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Prediction of the Risk of Capsize of Small Ships

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Prediction of the Risk of Capsize of Small Ships

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Declaration

No part of this thesis has been submitted for any award or degree at any other institute.

While registered as a candidate for the degree of Doctor of Philosophy the author has not been a registered candidate for another award of the C.N.A.A. or of a University.

Eric Deakins

Previously Published Material

Two papers have been published in connection with this research:

Capsize Prediction Using a Test-Track Concept;

Deakins E. Cheesley N.R. Crocker G.R. Stockel C.T.;
Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Volume 2, Addendum 1, pages 9 - 35; Gdansk, Poland; September 1986.

Critical Motion Simulation in the Random Marine Environment;

Deakins E. Cheesley N.R. Stockel C.T.;
Proceedings of the 1987 Summer Computer Simulation conference, pages 55 - 60; Montreal, Canada; July 1987.

Previously published material is included at the end of the thesis.

Advanced Studies Undertaken

Attendance at a course in Probability and Spectral Techniques at the University of Newcastle upon Tyne.

Guided reading in computer programming using the Fortran 77 language.

Simulation Computer Program

A copy of the computer program used in this research is available on magnetic tape from the Computing Service at Plymouth Polytechnic.

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Prediction of the Risk of Capsize of Small Ships

E. Deakins, B.Sc. (Hons)

Abstract

The lack of a necessary rational framework for assessing ship stability was the main concern of this research. The aim was to develop a rational philosophy and a logical procedure of assessing intact stability in order to ensure a consistent and unified approach to design for operation and for survival.

The method uniquely brings together a linearised analysis for assessing a potentially dangerous roll motion with a probabilistic assessment of ship performance in rough seas on a standard test-track. This represents a significant advance on previous research.

A novel feature of the analysis was that prediction of the extreme capsize roll motion was not attempted per se. Instead a reduced level of roll response termed "potentially dangerous" roll motion was selected (based on discussions with seagoing personnel) beyond which there was evidence that loss of the vessel is likely.

Validation of the linear spectral analysis used in the simulations was performed using full scale trial results of a fisheries protection vessel. Provided that measured values of roll damping coefficient were used, the predicted values of extreme roll closely matched the maximum values experienced on sea trials up to the chosen value of critical roll angle of 30 degrees.

Particular attention was paid to the realistic modelling of total system behaviour in rough seas. Families of wave spectra were used to represent the complete range of wave conditions encountered in nature. Avoidance and pacifying seamanship were incorporated based on the results of available trials data and discussions with serving masters.

Independent (Bernoulli) trials procedures were used to calculate the cumulative probability of a critical roll motion being exceeded at least once during the vessel's passage through the test-track.

The value of critical motion exceedance obtained was 5×10^{-2} for the fisheries protection vessel which has a large metacentic height and is reported to have good seakeeping characteristics.

Chapter 1

Introduction

1.1. The Need for Stability Assessment in the Marine Environment

> "....in any engineering enterprise, particularly where human life is exposed to dangerous conditions, it is the responsibility of the designer as well as the statutory authorities concerned to ensure that the structure, vehicle etc. is safe, -judged by the scientific knowledge of the day."
>
> Bird et al (1982)

For as long as man has ventured onto the sea there has always been present the possibility that his craft might capsize and be lost. This is still the situation today. Shipbuilders from the oldest times understood that in order to survive in the hostile marine environment their ships had to be stable. They developed, by trial and error, the practical knowledge of how to build comparatively stable ships although there was still no guarantee that the vessel would safely complete the voyage. In more modern times an understanding of the basic laws of the ship's geometry has enabled the naval architect to make calculations of its static stability during the design stages. Developments in ship hydrodynamics assisted the calculation of the behaviour of the ship in a seaway and the effect of external forces on stability. Nevertheless the survival of a vessel in heavy seas as a result of extreme motions, and roll motions in particular, remains one of the fundamental requirements still to be satisfactorily considered by the naval architect when designing a ship.

The problem remains how to model the complex, irregular, six degrees of freedom vessel motion with sufficient accuracy to predict when a "dangerous" roll motion may be experienced. Dangerous motion might give rise to cargo shifting, progressive flooding and damage to vessel and crew and possibly even to the loss of the vessel itself. Of course, the aim of the designer is to achieve the required degree of safety economically. The vessel must be functional, reliable and of reasonable first cost as well as being safe. Thus it is not surprising, particularly in the absence of appropriate guidelines, that a designer will occasionally step across the hazy borderline between safety on the one hand and disaster on the other. In any event perfect safety can never be guaranteed and one is forced to consider degrees of safety, or of risk, even on the rare occasions when there are no economic constraints on the design.

For more than two decades the International Maritime Organisation (IMO)[1] has attempted to establish international stability requirements. In 1968 the "Recommendation on Intact Stability for Passenger and Cargo Ships under 100 metres in length", Resolution A167 (1968), was adopted. Similar recommendations were adopted in 1975 for fishing vessels in excess of 12 metres registered length with some provisions applying to smaller vessels, Resolution A168 (1975). However these recommendations, for reasons which are explained in Chapter 2, are generally recognised to be not fully satisfactory and IMO is continuing its work towards development of more rational criteria, Plaza et al (1986).

Fundamental research into vessel stability continues to attract considerable international attention. Since 1975 three international stability conferences have been held to enable researchers and practitioners in the field to meet and discuss at length research programmes and results achieved and to consider how best to apply these rules in practice. The first of these was held in Glasgow in 1975, entitled the "First International Conference on Stability of Ships and Ocean Vehicles". Further conferences were held in Tokyo (1982) and Gdansk (1986). The venue for the next international stability conference will be Naples in 1990. In addition there have been several nationally funded stability projects including the United Kingdom SAFESHIP Project, which concluded in 1986, to which this work at Plymouth was officially affiliated, and the SIS (Ships in Rough Seas) Project in Norway.

In spite of these many efforts there is still a lack of fundamental understanding and of an adequate mathematical description of the basic physical phenomena which may lead to a ship capsizing. This lack of a mathematical model (or of experimental data) upon which to base criteria for judging the survivability of a particular design, when coupled with the philosophical and practical problems associated with establishing a rational approach to the problem (based on the assurance of an acceptable risk), has tended to concentrate research into small specialist aspects of the overall problem.

It is this lack of the necessary rational framework for assessing stability that is the main concern of this research.

In order to assess the severity of the capsize problem it is instructive to consider the casualty rates of vessels and men. In this context data from the fishing industry provides useful information to compare these mortality rates with the corresponding figures for other industries.

[1]The International Maritime Organisation (IMO) was known as the Intergovernmental Maritime Consultative Organisation (IMCO) until 20th May 1982.

1.2. Casualties to U.K. Fishing Vessels and Accidents to Fishermen

Commercial fishing has long been recognised as a hazardous occupation e.g. Schilling (1966). From time to time a disaster would occur that would cause people to focus on the risks being faced. For instance the loss of two vessels off Greenland in 1955 due to icing led to an investigation of this hazard and resulted in recommended design changes to mast structures, BSRA (1957). The loss of the Hull trawlers St.Romanus, Kingston Peridot and Ross Cleveland during the winter of 1968 within a few days of one another, when 56 lives were lost, led to an examination of the major factors affecting the safety of deep sea trawlers and their crews. This Committee of Inquiry into Trawler Safety (CITS) under the chairmanship of Admiral Sir Deric Holland-Martin (1969) reported its findings and recommendations 18 months later. These were mainly concerned with vessels in excess of 80 feet (24.4 metres) registered length.

On 1st May 1975 as a direct consequence of the Holland-Martin report "The Fishing Vessels (Safety Provisions) Rules 1975" came into effect covering the safety features which had to be incorporated into all fishing vessels in excess of 12 metres registered length -with some provisions applying to smaller vessels.

1.2.1. Fishing Vessel Casualty Rates

Reilly (1984) analysed the safety record of fishing vessels and their crews for the period 1961-1980 to assess whether the action that was taken since CITS was having any effect.

Chaplin (1986) has carried out a similar analysis using additional data for 1974-1985 inclusive to see if the rates and trends noted by Reilly still apply. Chaplin's premise was that the safety measures introduced in the mid 1970's, resulting from the CITS inquiry, did not become fully effective until after 1980 because of the inevitable phasing-in programme to survey all new and existing vessels. This phasing-in programme was not completed until the mid 1980's and it was suspected this would be reflected in the casualty figures after 1980.

The principal data sources used by Reilly and Chaplin were:

1. "Casualties to Vessels and Accidents to Men" published annually by the Department of Transport (Marine Division), hereafter referred to as D.Tp.
2. "Sea Fish Industries Statistical Tables" published by the Ministry of Agriculture, Fisheries and Food (MAFF) and the Department of Agriculture and Fisheries for Scotland (DAFS).

Casualty data as published by D.Tp. is of three categories. These are "total losses", "serious casualties" and "minor casualties". The term "total losses" is self explanatory but "serious casualties" is defined where:

(a) the vessel in in danger of becoming a total loss, for instance where salvage assistance is required; or

(b) serious damage is sustained so as to affect the seaworthiness of the vessel; or

(c) the vessel sank, but is known to have been subsequently raised and repaired ; or

(d) human life is lost; or

(e) serious financial loss occurs in relation to the size and value of the vessel.

"Minor casualties", although not defined by D.Tp, clearly do not meet the above criteria.

The "Seafish Industries Statistical Tables" detail the number of fishing vessels on the UK register but can give no indication of whether a vessel is fishing part-time or full-time. Large variations which occur in the number of vessels registered, particularly of those below 12 metres, are due mainly to part-time activity brought about by better economic conditions in the industry, Chaplin (1986). Thus any statistics in which the total number of vessels below 12 metres is a factor should be regarded with caution.

1.2.2. Total Losses

Figure 1.1 which was compiled from results by Reilly (1984) and Chaplin (1986) indicates a sustained and increasing casualty rate (for Total Losses) for fishing vessels of all lengths for the years 1960-1982 inclusive. The peak of 7.4 casualties per 1000 vessels at risk (7.4×10^{-3}) achieved in 1982 (Table 1.1) fell to 5.4×10^{-3} in 1985. Subdivision of the data by vessel size revealed that the hump after 1980 was almost entirely due to a significant increase in the rate of loss of vessels of less than 12 metres. This arises because for vessels in excess of 12 metres the rate of total loss has fallen from a maximum of 15.0×10^{-3} in 1978 to 10.2×10^{-3} in 1985, a reduction of 32 percent (Table 1.2 and Figure 1.2).

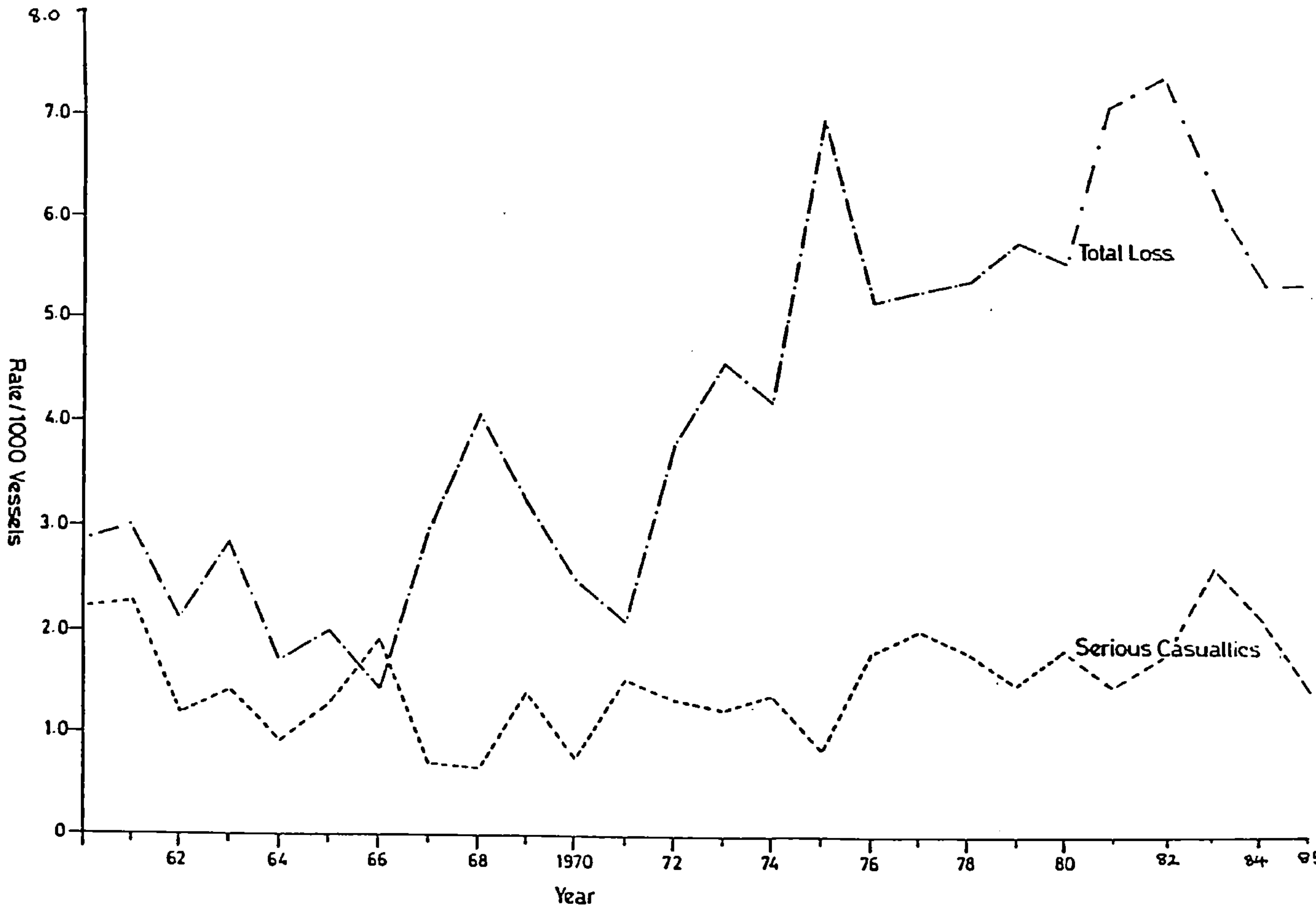


Figure 1.1 Total Loss and Serious Casualty Rates for 1961/1985
All Vessels

YEAR	REGISTERED* VESSELS	TOTAL LOSS		SERIOUS CASUALTIES		LOSS + CASUALTIES	
		VESSELS	PER 1000	VESSELS	PER 1000	VESSELS	PER 1000
1974	6916	28	4.0	8	1.2	36	5.2
1975	6691	47	7.0	5	0.7	52	7.8
1976	6740	35	5.2	12	1.8	47	7.0
1977	6953	37	5.3	14	2.0	51	7.3
1978	7067	38	5.4	13	1.8	51	7.2
1979	7242	42	5.8	11	1.5	53	7.3
1980	6890	39	5.7	13	1.9	52	7.5
1981	7351	52	7.1	11	1.5	63	8.6
1982	6797	50	7.4	12	1.8	62	9.1
1983	7010	43	6.1	18	2.6	61	8.7
1984	7584	41	5.4	16	2.1	57	7.5
1985	7354**	40	5.4	10	1.4	50	6.8

* Sea Fisheries Statistical Tables MAFF
** Estimated

Table 1.1 Total Loss and Serious Casualties for 1974/1985
All Vessels

YEAR	REGISTERED* VESSELS	TOTAL LOSS		SERIOUS CASUALTIES		LOSS + CASUALTIES	
		VESSELS	PER 1000	VESSELS	PER 1000	VESSELS	PER 1000
1974	2833	16	5.6	7	2.5	23	8.1
1975	2538	36	14.2	5	2.0	41	16.2
1976	2433	25	10.3	11	4.5	36	14.8
1977	2352	29	12.3	13	5.5	42	17.9
1978	2335	35	15.0	12	5.1	47	20.1
1979	2364	31	13.1	10	4.2	41	17.3
1980	2378	29	12.2	10	4.2	39	16.4
1981	2381	28	11.8	7	2.9	35	14.7
1982	2312	30	13.0	11	4.8	41	17.7
1983	2204	23	10.4	13	5.9	36	16.3
1984	2151	21	9.8	10	4.7	31	14.4
1985	2054**	21	10.2	9	4.4	30	14.6

* Sea Fisheries Statistical Tables MAFF
** Estimated

Table 1.2 Total Loss and Serious Casualties for 1974/1985
Vessels Over 12 metres

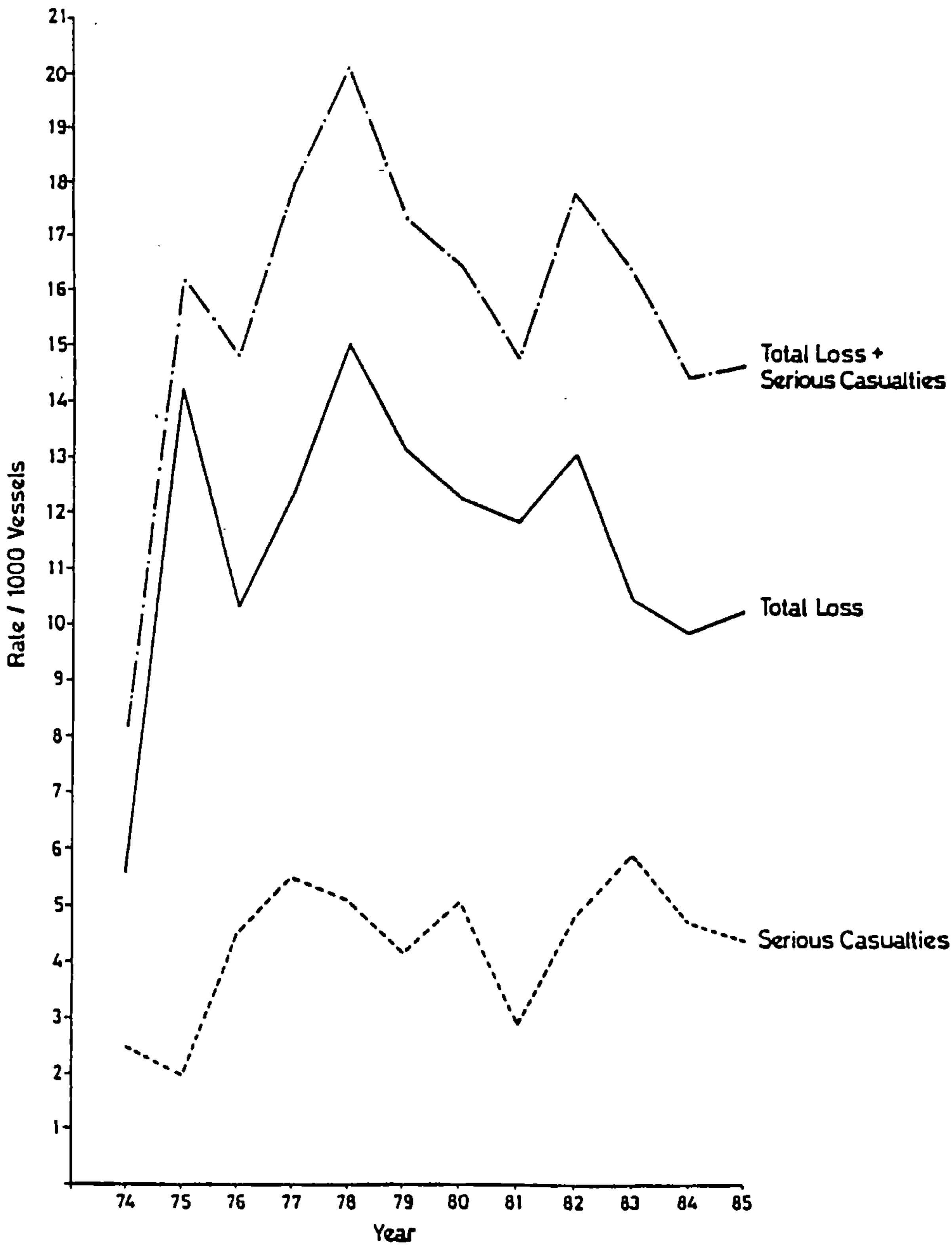


Figure 1.2 Total Loss and Serious Casualty Rates for 1974/1985
Vessels Over 12 metres

There was a corresponding reduction of 35 percent for vessels in the size range 12 - 24 metres where the rate was 14.3×10^{-3} in 1979 and 9.2×10^{-3} in 1985 (Table 1.3).

YEAR	REGISTERED* VESSELS	TOTAL LOSS		SERIOUS CASUALTIES		LOSS + CASUALTIES	
		VESSELS	PER 1000	VESSELS	PER 1000	VESSELS	PER 1000
1974	2378	10	4.2	3	1.3	13	5.5
1975	2139	32	15.0	2	0.9	34	15.9
1976	2087	23	11.0	9	4.3	32	15.3
1977	2023	21	10.4	11	5.4	32	15.8
1978	2033	26	12.8	6	3.0	32	15.7
1979	2092	30	14.3	9	4.3	39	18.6
1980	2132	29	13.6	7	3.3	36	16.9
1981	2136	26	12.2	6	2.8	32	15.0
1982	2073	28	13.5	9	4.3	37	17.8
1983	1973	20	10.1	12	6.1	32	16.2
1984	1934	18	9.3	8	4.1	26	13.4
1985	1855**	17	9.2	6	3.2	23	12.4

* Sea Fisheries Statistical Tables MAFF
** Estimated

Table 1.3 Total Loss and Serious Casualties for 1974/1985
Vessels Between 12 and 24 metres

There has been some small increase for vessels in excess of 24 metres but the number of such vessels was so low that a difference of one loss results in a change of 5 per 1000 (Table 1.4). Thus Chaplin (1986) concluded that any increase in casualty rates (total losses) apply to vessels which are of length less than 12m and which therefore do not fall within the 1975 Safety Rules. For those vessels which do fall within the 1975 Rules he concluded that the loss rate has improved for the "major segment" of the fleet which consists of vessels in the range 12 to 24 metres. However Chaplin noted that "it is reasonable to assume that the 1975 Safety Rules are having some impact.... this is not to say that the position is now satisfactory since the rate for these vessels is still significantly greater than that which applied up to the early 1970's (figure 1.2) and further improvement should be sought". The rise in the loss rate since 1981 for vessels below 12 metres is emphasised by Chaplin (1986). However it is noted that many of these may be open boats used primarily for angling and that their inclusion could be distorting data as far as vessels seriously engaged in fishing are concerned.

YEAR	REGISTERED* VESSELS	TOTAL LOSS		SERIOUS CASUALTIES		LOSS + CASUALTIES	
		VESSELS	PER 1000	VESSELS	PER 1000	VESSELS	PER 1000
1974	455	6	13.2	4	8.8	10	22.0
1975	399	4	10.0	3	7.5	7	17.5
1976	346	2	5.8	2	5.8	4	11.6
1977	329	8	24.3	2	6.1	10	30.4
1978	302	9	29.8	6	19.9	15	49.7
1979	272	1	3.7	1	3.7	2	7.4
1980	246	0	0	3	12.2	3	12.2
1981	245	2	8.2	1	4.1	3	12.2
1982	239	2	8.4	2	8.4	4	16.7
1983	231	3	13.0	1	4.3	4	17.3
1984	217	3	13.8	2	9.2	5	23.0
1985	199**	4	20.1	3	15.1	7	35.2

* Sea Fisheries Statistical Tables MAFF
** Estimated

Table 1.4 Total Loss and Serious Casualties for 1974/1985
Vessels Over 24 metres

Caldwell et al (1986) presented the results of a study into worldwide casualties to ships of all types (1970-1980), Table 1.5. This table confirms the loss rate of 4.9×10^{-3} obtained for all fishing vessels using Reilly's casualty values for (1970-1980) in figure 1.1.

Class	Risk
World Fleet (1970 – 1980)	6.0×10^{-3}
Oil Tanker	4.0×10^{-3}
Roll–on Roll–off Ships	3.0×10^{-3}
Fishing Vessels	5.2×10^{-3}

Table 1.5 Risk of Vessel Casualty for World Fleet (1970-1980)

1.2.3. Vessel Losses by Cause of Loss

Figure 1.3, taken from Reilly (1984), illustrates the causes of fishing vessel losses and serious casualties (1961-1980 inclusive) and shows that Founderings (35.6%) have been the major cause of casualty followed by Strandings (25.5%), Collisions (15.7%) and Fires (10.9%).

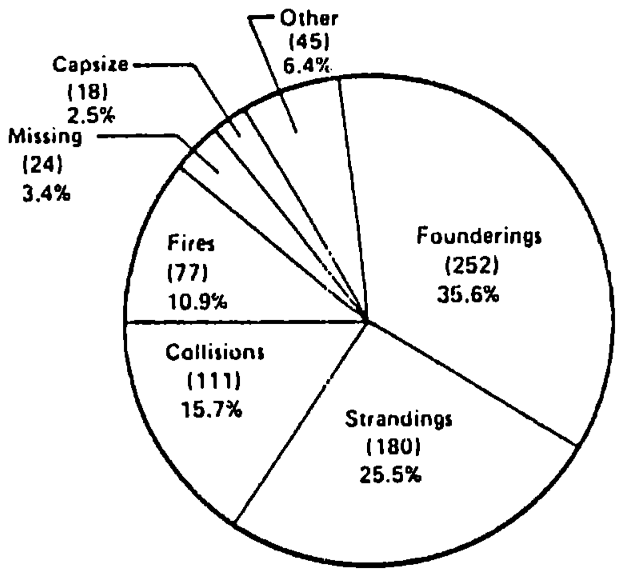


Figure 1.3 Total Losses and Serious Casualties by Cause of Loss 1961-80

It is noted that Fires, Collisions, Strandings and "Other" together account for 58.5% of all total losses/serious casualties. The remaining 41.5% due to Foundering, Capsize and Missing may therefore be reasonably attributed to the vessel becoming overwhelmed by the seaway. This lack of seaworthiness will, in general, be either due to a capsize or a foundering. Missing vessels may reasonably be associated with a foundering or capsize in heavy weather conditions or to a rapid explosion, fire or collision which prevents a distress message being sent.

Foundering is related to the vessel's freeboard and to its watertight integrity; thus foundering might be considered as a loss of the weathertight integrity of the hull. By contrast capsizing occurs when upsetting influences, -wind and waves, act upon a vessel which is deficient in transverse stability. It is also likely that a vessel may appear as a founder statistic even though the initial casualty was caused by deficient stability which is not always readily apparent, and this will affect the statistics to an unknown degree.

Figure 1.4 clearly indicates that the increasing total loss/serious casualty rate (TL/SC) when subdivided into its seven constituent causal rates was particularly influenced by changes in the rates of founderings, collisions and fires/explosions.

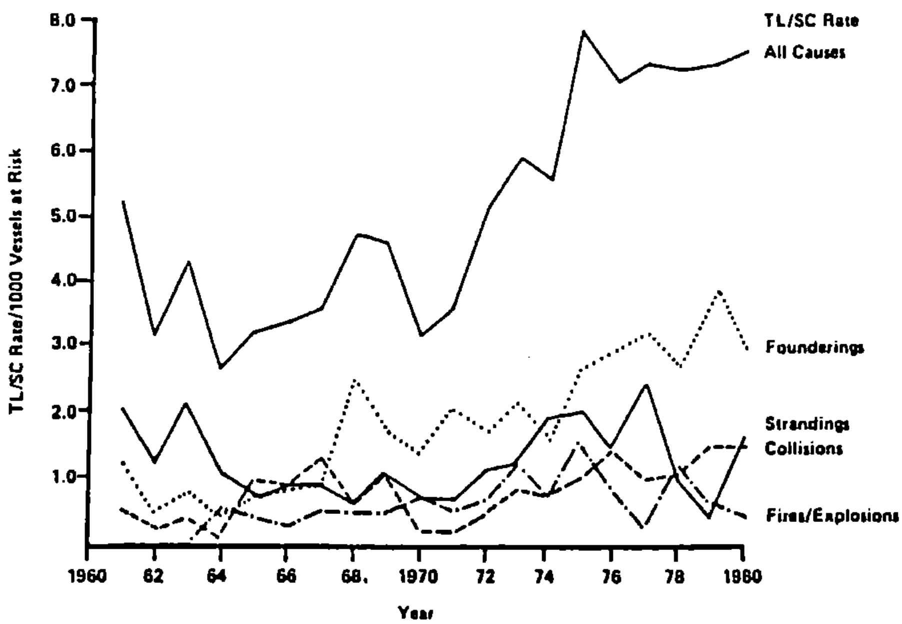


Figure 1.4 Total Loss and Serious Casualty (TL/SC) Rates and Component Causal Rates (Reilly, 1984)

The individual increases/decreases in the different causes of loss are detailed in Table 1.6 which indicates that 64 per cent of the increase recorded could be accounted for by the corresponding increase of founderings alone. This compares with an increase of only 20 per cent for collisions and approximately 17 per cent for fires and explosions. Capsize recorded an increase of 8 percent.

Cause of loss/ casualty	Regression coefficient	Increase/decrease (%)
Foundering	+0·154	+63·64
Stranding	+0·004	+1·65
Collision	+0·049	+20·25
Fire/explosion	+0·042	+17·36
Missing	+0·002	+0·83
Capsize	+0·020	+8·26
Other	−0·029	−11·99
All causes	+0·242	100·00

Table 1.6 Rates of Change in Causal Loss Rates 1961-80 (Reilly, 1984)

Reilly also states that the overall increase in the TL/SC rate was the product of separate trends for inshore vessels (length less than 80 feet) and larger vessels and that the inshore vessels accounted for much of this trend. Thus in terms of loss of vessel, combining the results of figure 1.1, "Total Losses for all Fishing Vessels", with the percentages in figure 1.3, "Total Losses by the Cause of Loss", it is apparent that the overall risk of capsize among fishing vessels is of the order of 10×10^{-5} to 18×10^{-5} (14×10^{-5} average) for the period 1970-1985. The corresponding figures for foundering are 1.4×10^{-3} to 2.6×10^{-3} (2.0×10^{-3} average) for the same period.

1.2.4. Deaths to Fishermen

Considerable doubt exists as to the actual numbers of fishermen at risk and the death rates must be treated with some caution. In a second paper Reilly (1985) analysed the deaths of fishermen on board fishing vessels for the years 1961-1980 inclusive. Again Chaplin (1986) has extended this survey and noted some encouraging trends in the mortality rates for the subsequent years 1981-1985 inclusive.

a) Fishing Vessels of Length > 24 metres

While the death rate for personal accidents (1.47×10^{-3}) on board vessels of length > 24 metres has shown no improvement (Table 1.7) the death rate due to vessel loss has fallen from 1.75×10^{-3} (1971/1980) to 0.27×10^{-3} (1981/85), an improvement of 84 percent. This, in turn, has reduced the annual death rate from all causes on these vessels from 3.21×10^{-3} (1971/80) to 1.74×10^{-3} (1981/85), an improvement of 46 percent. However vessels in this category currently comprise only 3 percent of the total fleet (1985 figures) with only 10 percent of the total serving manpower of 19,000 men, Chaplin (1986).

b) Fishing Vessels of Length < 24 metres.

For vessels of less than 24 metres registered length again the death rate due to personal accidents has been virtually constant (5.6×10^{-4}) since 1971 (Table 1.7). The death rate due to vessel loss has improved by 13 percent from 6.7×10^{-4} (1971/80) to 5.8×10^{-4} (1981/85). This has reduced the annual death rate from all causes by 8 percent from 1.23×10^{-3} (1971/80) to 1.13×10^{-3} (1981/85).

c) All Fishing Vessels

The annual risk of death due to personal accident (all fishing vessels) is currently 6.3×10^{-4} (1981/85) compared with 7.7×10^{-4} (1971/80). The death rate due to vessel loss has improved by 41 percent from 9.3×10^{-4} (1971/80) to 5.5×10^{-4} (1981/85). This has reduced the overall annual death rate (all vessels) from all causes by 30 percent from 1.7×10^{-3} (1971/80) to 1.18×10^{-3} (1981/85).

Thus the mortality risk due to ship capsize (all fishing vessels) is of the order of 3.6×10^{-4} assuming that the majority of "missing" casualties (Table 1.8) are due to capsize (average figure 1971/85). The corresponding figure for foundering is 2.4×10^{-4} (average figure for 1971/85 in Table 1.8).

CAUSE OF DEATH GROUP	VESSEL LOSSES			PERSONAL ACCIDENTS			ALL CAUSES		
	1961/70	1971/80	1981/85	1961/70	1971/80	1981/85	1961/70	1971/80	1981/85
On Vessels >24 Metres	1.33	1.75	0.27	0.98	1.46	1.47	2.31	3.21	1.74
On Vessels <24 Metres	0.44	0.67	0.58	0.84	0.56	0.55	1.28	1.23	1.13
All Fishermen	0.78	0.93	0.55	0.89	0.77	0.63	1.67	1.70	1.18

Table 1.7 Accident Death Rates Per 1000 Men At Risk

CAUSE OF LOSS CONTRIBUTING IN DEATH	ON VESSELS >24 METRES						ON VESSELS <24 METRES						ALL FISHERMEN					
	1961-70		1971-80		1981-85		1961-70		1971-80		1981-85		1961-70		1971-80		1981-85	
	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate	No.	Rate
Foundering	43	0.55	18	0.46	1	0.13	10	0.08	25	0.16	22	0.28	53	0.26	43	0.21	23	0.26
Fire/Explosion	17	0.18	23	0.43	1	0.13	4	0.03	8	0.06	1	0.01	21	0.09	31	0.15	2	0.02
Stranding	9	0.09	0	0.00	0	0.00	8	0.07	7	0.04	0	0.00	17	0.09	7	0.03	0	0.00
Collision	0	0.00	3	0.05	0	0.00	8	0.05	9	0.06	0	0.00	8	0.04	12	0.05	0	0.00
Other	0	0.00	0	0.00	0	0.00	3	0.03	1	0.01	3	0.04	3	0.01	1	0.01	3	0.03
Missing	42	0.51	45	0.81	0	0.00	25	0.18	53	0.34	20	0.25	67	0.29	98	0.48	20	0.23
All causes	111	1.33	89	1.75	2	0.27	58	0.44	103	0.67	46	0.58	169	0.78	192	0.93	48	0.55

Table 1.8 Accident Death Rates Per 1000 Men At Risk: Vessel Losses

1.2.5. Comparison of Risk Level with Other Risks

Table 1.9 indicates the various levels of risk involved in other activities and occupations. The concept of an acceptable level of risk is addressed in chapter 9. For the moment it is useful to compare the risk levels obtained in the previous section to the values given in the table.

Class	Risk
Mountaineering	2.7×10^{-3}
Distant Water Trawling	1.7×10^{-3}
Air Travel (crew)	1.2×10^{-3}
Coal Mining	3.3×10^{-4}
Car Travel	2.2×10^{-4}
Construction site	1.7×10^{-4}
Air Travel (passenger)	1.2×10^{-4}
Home accidents (all persons)	1.1×10^{-4}
Home accidents (able bodied)	4.0×10^{-6}
Manufacturing	4.0×10^{-5}
Structural failure	1.0×10^{-7}

Table 1.9 Occupational Accident Rates, Caldwell et al (1986)

It can be seen that the above value for distant water trawling (1.7×10^{-3}) is identical to the overall fishing vessel mortality rate obtained in the previous section for the years 1971/80 (some improvement has been demonstrated for 1981/85). These are very similar to the accident rate figure for air crew (1.2×10^{-3}). Values are an order of magnitude larger than shore based risk activities of both a voluntary and an involuntary nature.

The above results indicate that there is a real need to improve fishing vessel casualty rates. This requires a survivability framework for assessing risk to be established. Such a framework would enable the risk of foundering and capsize for <u>any vessel</u> to be assessed and pinpoint areas for improvement. The remainder of this chapter briefly outlines the steps that were taken and the methods of approach used to solve the problem of assessing a lifetime of risk.

1.3. The Present Work

In chapter 2 this work is placed into context by consideration of the principal developments in ship stability theory. In particular the complex nature of the capsize phenomenon is emphasised together with how different researchers have tackled the various aspects of a multi-faceted problem. Finally, chapter 2 concludes with a critical review of certain of the more important current and proposed stability criteria that have resulted from the many studies.

Chapter 3 illustrates and emphasises the stochastic nature of the capsize problem in contrast to the deterministic method of stability assessment which is embodied in the current IMO stability criteria. The need for a truly rational probabilistic motion prediction method is argued. This is followed by a description of modern reliability and safety assessment methods which were considered for this research with special reference made to the hindcast methods which are being used in high risk activities such as the nuclear and petro-chemical industries. It is argued that the lack of suitable marine casualty information limits the usefulness of such studies and leads one to conclude that the formulation of a suitable prediction method is to be preferred to take account of the many complex interrelated parameters (including the effects of human behaviour) which affect vessel response to the environment.

The difficulties of assessing the actual lifetime risk of capsize are discussed in chapter 4. Capsize phenomena are considered in some detail and the point is made that a vessel should ideally be tested for all of these in any considered operational scenario. The present study utilises the superposition principle of St. Denis and Pierson (1953) for predicting vessel response. It is argued that the full study would consider all of the appropriate methods necessary for predicting the capsize phenomena. These would simply "plug into" the method which is being proposed for evaluating risk. However, because the main aim is to formulate an overall framework for assessing risks, this question is not pursued in detail. Finally in chapter 4 the concept is introduced of the test-track and proving ground for systematically assessing vessel performance. The analogy to the road vehicle test-track is drawn and the advantages of standardising procedures from a regulatory viewpoint are discussed. Statistical derivation of the test-track and proving ground probabilities of critical motion exceedence are presented.

Chapter 5 considers the use of linear seakeeping theory for predicting vessel capsize. A brief survey is made of the theoretical models which are available for analysing large angle roll motion. It is argued that the capsize phenomena are non-linear in nature, -particularly at the large capsize roll angles. The concept of a "potentially dangerous" roll motion is introduced to represent the onset of capsize and possible objections to this approach are presented. Finally, chapter 5 introduces the subject vessel used for the investigation and presents the results of computer-predicted responses obtained from the British Maritime Technology Ltd (BMT) "Britsea" suite of linear seakeeping programs against available model and full scale sea trials in both regular and irregular waves.

Key factors which must be included within the proposed procedure, in order to accurately assess the risk of capsize, are considered in chapter 6. Particular emphasis is laid on their appropriate treatment from a regulatory viewpoint. Fundamentally each test-track can be reduced into the four main considerations of route, climatology, seamanship and (resulting) response for any given vessel of a particular displacement condition. These factors are described in detail.

Chapter 7 considers the development of the computer simulation and presents the algorithms used, including the represention of master's action in a severe seaway. Assumptions made and their limitations are given particular consideration. Finally a worked example is presented, for a particular scenario which gave rise to a large response level, in order to demonstrate the probability calculations.

The sensitivity of vessel motions to various key parameters is considered in chapter 8. Parameter values used in the main simulation are described which incorporate the sensitivity information. Results of the final calculation are presented for an as-built vessel condition making use of information obtained from the serving masters whenever possible. Some possible future improvements to the computer model are described.

Chapter 9 considers the future of safety studies which are based on achieving an acceptable level of risk. Conclusions and details of required further work are presented which would enable a full implementation of the risk framework proposed in this study.

Chapter 2

Review of Principal Developments in Ship Stability Theory

2.1. Introduction

> "As in other branches of engineering, safety rules have grown up from cumulative experience of failures and in the case of ship stability such an entirely empirical approach has led to simple but rather crude statical stability criteria which are of questionable value in assessing safety."
>
> Bird et al (1986)

Stability is a property of ships and other marine vehicles which is not amenable to simple definition. To naval architects 'stability' means safety against capsizing in a very general sense, and the development of the relevant theory has had a long period of evolution which is still far from complete.

Seagoing vessels, during their lifetime, are required to operate in a great variety of seastates with different cargoes and with different displacements. Speed and heading to waves are variable and are dictated both by the operating routes and the skill of the ship's officers in avoiding or pacifying the effects of severe weather conditions.

Dangerous roll motion could lead to cargo shifting, progressive flooding into the hull through unsecured openings and bodily damage to the vessel and its crew. Ultimately the vessel could even capsize (usually very rapidly) due to a complete loss of stability. The problem is further compounded by the vessel responding to the external excitations in 6 degrees of freedom. Essentially the problem facing the designer and the regulatory authorities is to safeguard the stability of a ship or other marine vehicle which must necessarily operate in such a regime.

Because the overall problem is so complex there have been numerous studies into the various related aspects of ship stability. In order to place the present study into context a brief review of the principal developments will now be presented, followed by a critical review of certain of the current and proposed stability criteria that have resulted.

One could possibly group the studies as follows:

1. Studies into 'conventional' ship stability that are based on stability in still water (statical stability).
2. Studies relating to the form of the roll motion equation.
3. Motion stability methods.
4. Studies into suitable stability criteria.

2.2. Stability Studies

2.2.1. Stability in Still Water

This first group of studies assumes that the stability of a ship can be determined from its geometry and its weight distribution.

The couple formed by weight and buoyancy, in still water when the ship is heeled, is taken as a measure of stability and the lever of the couple GZ is chosen as the representative quantity, Figure 2.1. Certainly the understanding of this concept of ship stability is very old.

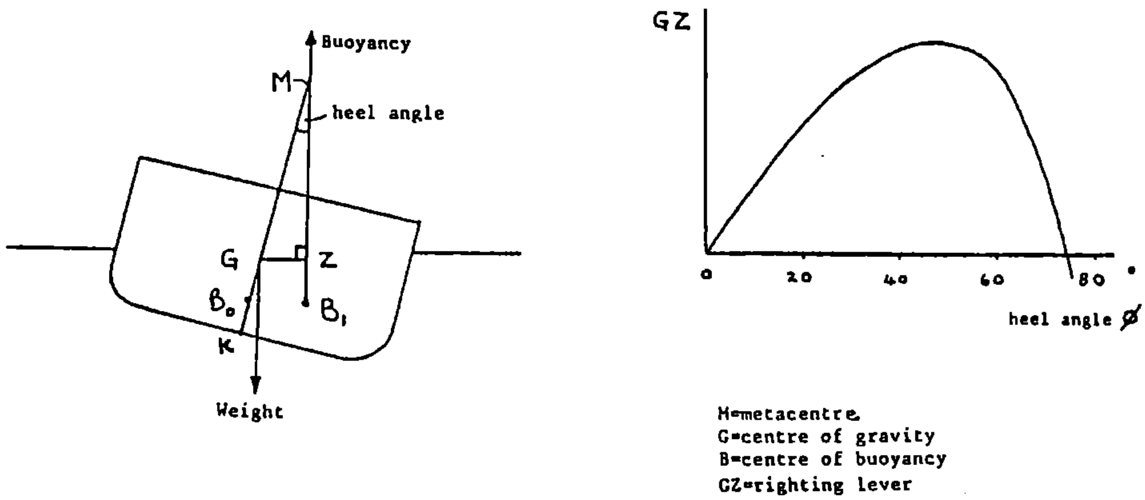


Figure 2.1 Stability (GZ) Curve

Pierre Bouguer (1746) defined the metacentric radius B_0M (shown in figure 2.1) as the ratio of waterplane moment of inertia I to the immersed volume V ; $B_0M=I/V$. Thus the metacentric height, GM, which is used as a measure of stability was defined by:

$$GM=KB_0+B_0M-KG$$

where KB_0 is the vertical coordinate of the centre of buoyancy and KG is the vertical coordinate of the centre of gravity. The righting lever, GZ, was approximated by:

$$GZ=GM\sin\phi$$

where ϕ is the heel angle in radians.

Attwood (1796) derived his celebrated formula for more accurate calculations of the righting levers which was given as:

$$GZ=vh_1h_2/V-B_0G\sin\phi$$

where v is the volume of the immersed or emerged wedge, h_1h_2 is the horizontal component of the shift of volume, V is the underwater volume and B_0G is the vertical distance between the centre of buoyancy and the centre of gravity.

Canon Mosely (1850) introduced the idea of "dynamical stability". He derived the expression for the work done by the ship under the influence of some potential external forces and expressed this work as the area under the righting moment curve, where the righting moment is simply the value of the product of GZ and ship displacement. So long as the inequality:

$$\int_0^{\phi_{max}}(M_r\phi - M_e\phi)d\phi > 0$$

held, the ship was assumed to be stable. Here $M_r\phi$ and $M_e\phi$ are the righting and heeling moments respectively and ϕ_{max} is the maximum angle of heel.

The significance of this early study was its attempt to relate the stability of ships to their rolling motion although, as with previous works, the results obtained were a significant step away from the case of a rolling ship in actual seawaves.

2.2.2. Roll Motion Equation

This group of studies endeavoured to define the rolling motion of ships in a general sense but without considering the stability of the motion itself. Again, the important developments may be summarised as follows:

Neglecting the damping effect, W.Froude (1861/1862) derived the expression for rolling motion in regular beam seas as:

$$\frac{d^2\phi}{dt^2} + \omega_\phi^2\phi = \omega_\phi^2\alpha_{max}\sin\omega_w t$$

where

ϕ	is the roll angle
ω_ϕ	is the ship's natural roll frequency
ω_w	is the regular wave frequency
α_{max}	is the maximum effective waveslope

He assumed that the beam and draft of the ship were small in comparison to the wavelength and that the presence of the ship did not alter the wave form. In 1874, Froude also introduced the effect of roll damping by using the best empirical damping as:

$$\frac{-d\phi}{dn} = a\phi + b\phi^2$$

where n is the number of oscillations and a,b are constants to be determined from experiments. Krylov (1896) gave a more comprehensive representation of the theory of ship oscillations and the theory of ship rolling was further developed on the basis of the Froude-Krylov equation of motion. This assumes that the ship behaves as a "phantom hull" which is disturbed by the seawaves without itself disturbing the surrounding flow.

In order to improve the estimate of motions for normal ship forms the effect of added mass was included e.g. Lewis (1929) and Ursell (1949).

Manning (1939) included the effect of ship speed and heading to waves by introducing the period of encounter.

In 1953 St Denis et al presented a statistical approach for analysing ship motions in irregular seas by a superpositon of its response to an infinite number (in theory) of regular sinusoidal waves. This development opened up the field of ship motions. The majority of this research was concerned with determining the longitudinal responses heave and pitch in head seas (surge being neglected). Korvin-Kroukovsky et al (1957) presented such a strip theory based on heuristic arguments which was later modified by Gerritsma et al (1967).

Transverse motions (roll, sway, yaw) were presented by Vugts (1971) and Salveson et al (1970). These later theories were formulated with a velocity potential (Ursell(1949), Tasai (1961)) so that the effect of viscosity was not included. The roll damping coefficient thus derived was usually modified to account for this by using empirical results e.g. Ikeda (1978).

2.2.3. Motion Stability Studies

The relevance between ship motions and their stability was recognised a long time ago and through the end of the 19th century A.M. Lyapunov derived the conditions for stability of motion of a freely floating rigid body (Lyapunov (1892)). Unfortunately the potential importance of that novel study was not recognised at that time.

During the early 1950's Grim (1952) and Wendel (1954) both introduced the effects of the variations with time of the ship's restoring moment in a seaway, but used this variation for different purposes. In fact the basic idea was not new, Pollard and Dudebout (1892) and Kempf (1938) had mentioned the importance of the subject.

Statistical analysis of casualty records indicated that an important part of capsized ships, especially those between 30 and 60 metres in length, were under the action of following or quartering seas with 5 - 7 Beaufort wind forces. Inspired by this fact Wendel concluded that the most critical stability condition arises when the ship is acted on by a wave which has length and velocity the same as those of the ship, and that the worst case occurs when the wave crest is at amidships. In order to make the magnitude of these results more realistic Arndt and Roden (1958) proposed the introduction of Smith effect (Smith 1883) in the wave pressure computations to account for the orbital motion of water particles. Further studies by Paulling (1961), Upahl (1961) and many others have followed e.g. Hamamoto (1986).

Grim considered the equation of rolling as:

$$I\,\frac{d^2\phi}{dt^2}+\Delta(GM+\delta GM\cos\omega t)\phi=0$$

where

I is the virtual mass moment of inertia about the rolling axis
ϕ is the roll angle
Δ is the displacement
GM is the metacentric height
δGM is the maximum variation in metacentric height
ω is the wave frequency
t is the time

By making use of the known results on the stability of Mathieu's equation, he pointed out the possible instability regions. Grim (1954) further considered more general rolling as:

$$I \frac{d^2\phi}{dt^2}+\Delta\, GZ(\phi)=M$$

where M is the excitation. He showed that the time dependent variation of the restoring moment may result in severe roll motion resonance in following seas, a phenomenon known as 'parametric excitation'. This attempt to relate the stability of a ship to its motions forms the basis of a large amount of todays research activity e.g. Skomedal (1982), Boroday (1986).

While the deterministic case was being studied extensively, the behaviour of a ship in random sea conditions was also examined. Following the work of St.Denis and Pierson in 1953, Cartwright et al (1956) paid more attention to rolling motion. Kato (1957) presented an experimental study for irregular wind and wave conditions. Hasselman (1966) and Vassilpoulos (1967) showed how to treat the nonlinear systems under random excitations. Kastner extended this application (1969) and studied the behaviour of phase trajectories, Figure 2.2.

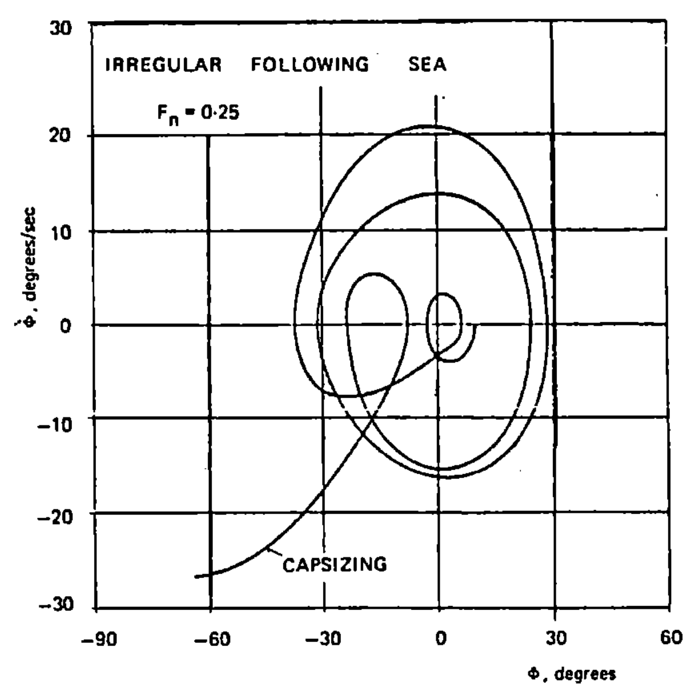


Figure 2.2 Example of a solution for a stochastic roll motion at random parametric seaway excitation plotted in the $(\phi\text{–}\phi')$ plane.

De Jong (1970) tried to solve the problem with the aid of Fokker-Planck-Kolmogorov equations (Arnold 1973) and defined the stability with the probability of threshold crossing. Similar studies have been carried out both theoretically and experimentally by many research centres, e.g. Haddara (1971), Dalzell (1971) and Roberts (1982).

One of the most important features of all this work was the tendency towards solving the single or coupled nonlinear roll equations and then searching for the stability with the aid of the determined solution. When the equations of motion are severely non-linear the approximation methods which linearise them in one way or another may not yield reliable solutions. To overcome this difficulty, Odabasi (1973) re-introduced Lyapunov's Direct Method into the stability computation of ships. Later the general definition of stability has been further studied by Odabasi (1982) and Caldeira Saraiva (1986) among others.

2.2.4. Stability Criteria

This group of studies is aimed at determining a safe minimum amount of stability for devising stability criteria. It is known that load line rules existed as early as the 11th century, but the real efforts for establishing rules in ship stability came after 1870. In 1870 a British warship "Captain" capsized and this accident brought forward the question of safe minimum stability, Brown (1981).

One of the first measures for judging the stability was the initial metacentric height. In the beginning of the 20th century, depending on the type and size of vessel, an initial metacentric height of between 0.2 - 0.6 metres was considered sufficient. Efforts were also made to establish principles based on the main dimensions of vessels for judging stability but these proved unsuccessful in practice. The use of the righting arm curves for judging stability was first proposed by Reed (1868) but its use followed the paper by Denny (1887). This type of stability criterion was in frequent use in the design of vessels and there were various standard curves suggested by different authors, Figure 2.3.

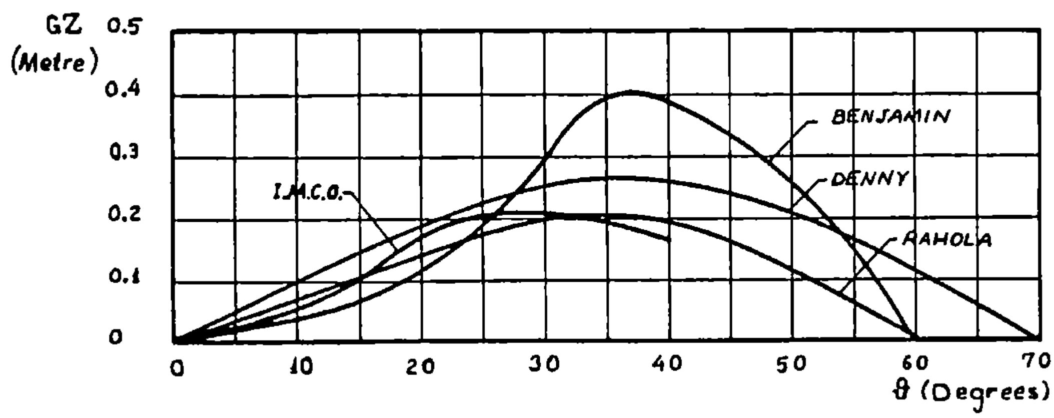


Figure 2.3 Standard Stability Curves

The following features were considered to be significant:

1. The initial part of the righting arm curve up to an angle of heel of 10 degrees, which depends on the initial metacentric height;
2. The angle ϕ_m at which the righting arm curve reaches its maximum value is very important;
3. The vanishing angle ϕ_v where the righting angle becomes zero is also important;
4. Magnitudes of the righting arms at 20, 30 and 40 degrees have a strong influence on the vessel's stability.

Rahola (1939) made a significant contribution towards achieving workable stability criteria. His study was based on the results of official inquiries into some 30 capsizes and, by selecting a level of stability which exceeded that of most of the casualties, he proposed the following combined criteria:

$GZ \geq 0.14$ metres for 20 degrees
$GZ \geq 0.20$ metres for 30 degrees
$GZ \geq 0.20$ metres for 40 degrees
$\phi_m \geq 35$ degrees

and $e = 0.08$ metre-radians for ϕ_r

where the limit angle ϕ_r was defined as the smallest of ϕ_m , angle of heel for immersion of non-watertight openings, angle of heel for shifting of cargo or 40 degrees. Rahola, himself had reservations about proposing the standards for general use on the grounds, inter alia, of the "unsuitablility of the same standard stability arm curve for large and small vessels". However, such statical stability criteria formed the basis for several national criteria, amongst them the current IMO Res.A167 (1968) for ships less than 100m in length and Res.A168 (1975) for fishing vessels of length 12m and over.

The original Rahola stability criteria are illustrated in Figure 2.4, and the current stability criteria for fishing vessels (Res.A168) shown in Figure 2.5.

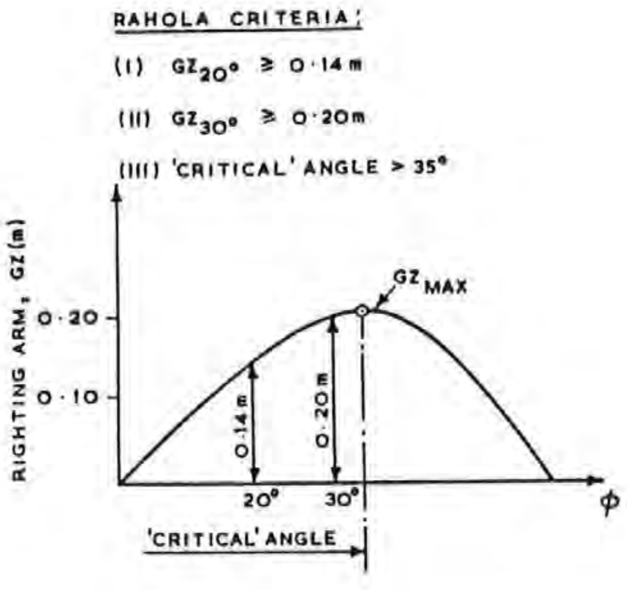


Figure 2.4 Original Rahola Stability Criteria, Rahola (1939)

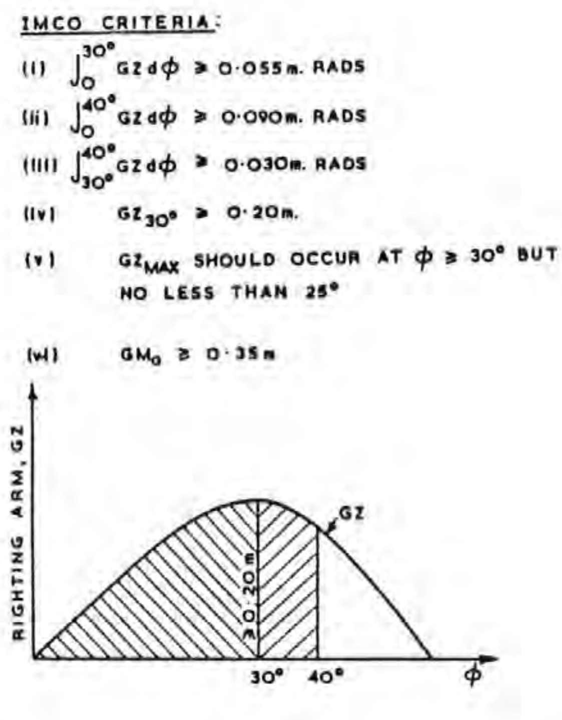


Figure 2.5 Current Fishing Vessel Stability Criteria, Res.A168 (1975)

Statical stability criteria of this kind have the chief advantage of being simple to apply by naval architects and ship's officers, being based on hull form geometry and weight distribution. They involve no explicit use of external forces or motion characteristics so that for the regulatory authorities the advantage is that there is no commitment to difficult decisions about wind and wave parameters and the possibility of giving false guarantees of safety in any particular sea conditions, Bird et al(1986). Their disadvantages are that they cannot give any indication of safety margins or of likely motion behaviour in any seastate except still water. Additionally when some significant departure from previous design practice occurs, for example as occurred with the twin hulled SWATH ships and mobile oil drilling rigs, no recourse can be made to previous experience and a different approach to intact stability assessment is required.

Further approaches to ship stability attempt to account for the external forces affecting behaviour of the vessel in an assumed environmental condition. Steel (1956) analysed several casualties of specific ship types and stated that the minimum standards must only be accepted with due consideration given to the type of ship service and the nature of the cargo.

The so-called moment balance methods advocate a static balancing of restoring and upsetting moments for assessing stability. Among these include methods by Steel (1956) and Abicht, Kastner et al (1977). Wendel's criterion is illustrated in Figure 2.6.

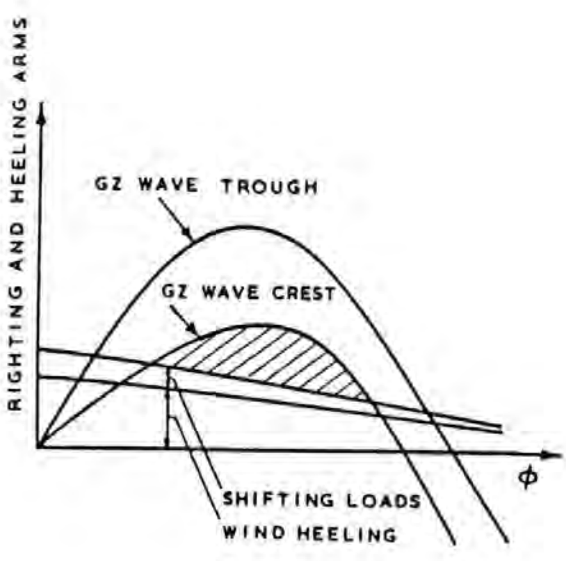


Figure 2.6 Balancing of Righting and Heeling Curves proposed by Wendel (1977)

The dynamical lever curve, which is the integral of the righting arm curve is also used as a stability criterion. Originating with Moseley's (1850) work proposals were made, both on the basis of vessels which had operated successfully Benjamin (1913), and on theoretical bases which attempted to take account of the work done by wind, waves, centrifugal force and the movement of passengers on board, Pierrotet (1935). These were known as energy balance methods.

Sarchin et al (1962) introduced one form of a dynamic windheel or 'weather criterion', Figure 2.7. This type of criterion is intended to provide sufficient stability for a vessel to withstand the dynamics of being subject to a sudden wind gust while rolling. The recent IMO weather criterion, A14/562 (1986) which is intended to supplement rather than to replace Res.A167, is illustrated in Figure 2.8.

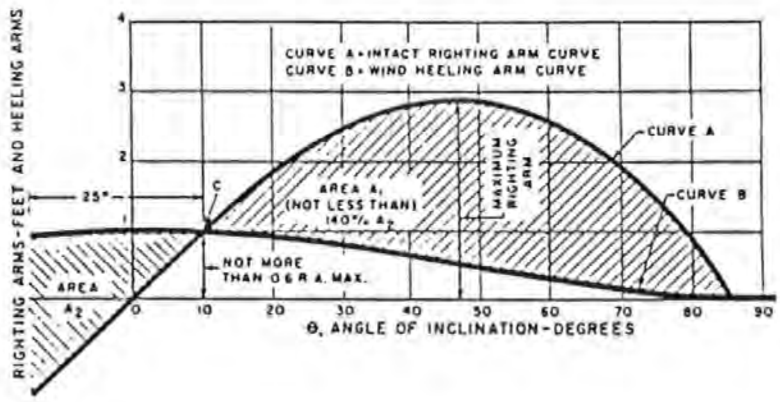


Figure 2.7 The Classical 'Weather Criterion' (1962)

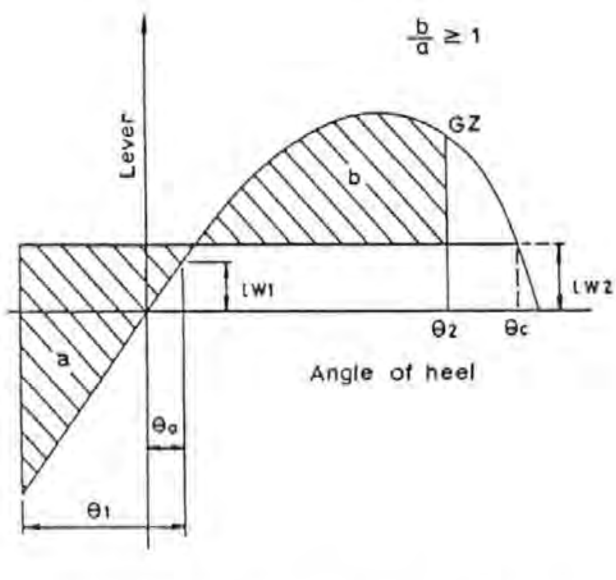


Figure 2.8 The IMO Weather Criterion (1986)

A natural development of the weather criterion, which has been developed by Vassalos (1986) at Strathclyde University within the U.K. Safeship Project, is illustrated in Figure 2.9. This has become known as a 'butterfly diagram'.

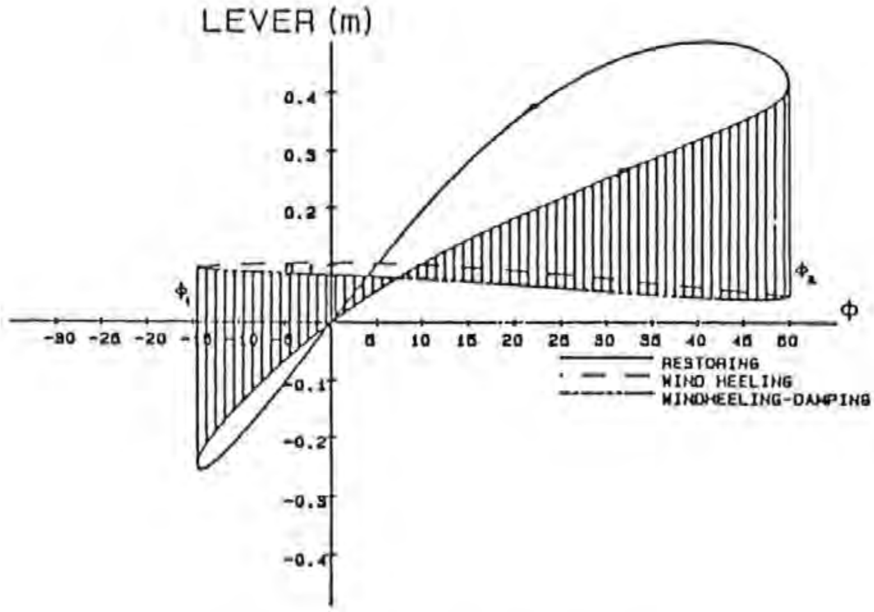


Figure 2.9 The Butterfly Diagram (1986)

This criterion is concerned with the pure loss of stability in following seas and the effects of wind, waves and motions is accounted for in a quasi-dynamic manner. The energy balance is considered between restoring and upsetting moments during an extreme half roll cycle to discriminate between 'safe' and 'unsafe' ships.

Although moment and energy balance methods take account of the external forces affecting behaviour of the vessel in an assumed environmental condition, they are at best fairly simple models of the real world and present only a quasi-dynamic picture, especially of the influence of wave motion.

Such criteria use conventional principles and procedures which are familiar to naval architects.

Because of the inadequacies in the two preceding approaches attempts have been made to develop stability criteria based on Lyapunov's Direct Method, Caldeira-Saraiva (1986). Lyapunov theory is applied to the equations of motion which can be made to account for coupling effects, wave diffraction, parametric excitation, linear and non-linear damping and wind effects. A simplified stability criterion, Figure 2.10, is then derived from the vessel's region of motion instability in the phase plane.

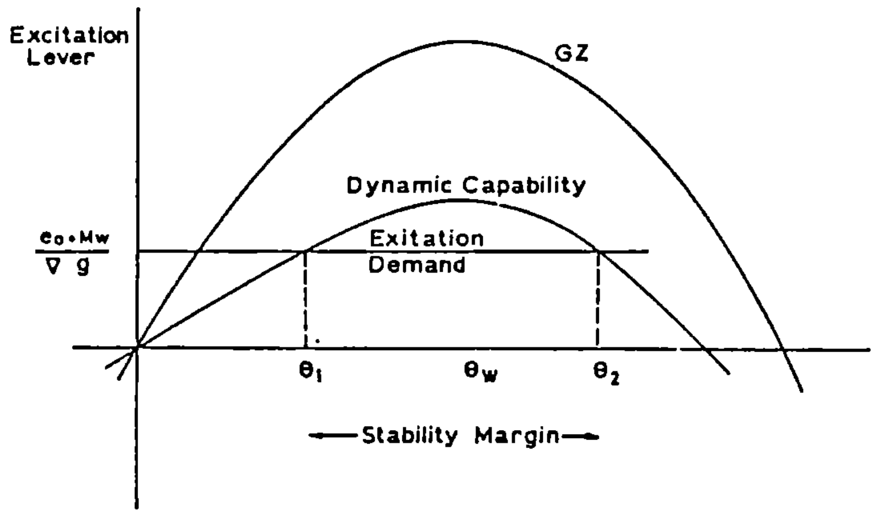


Figure 2.10 Criterion proposed by Caldeira-Saraiva(1986)

The main (present) disadvantages are that, while the resulting criteria are simple to apply, naval architects are not yet familiar with the basic concepts. Such new forms of stability criteria may need considerable validation from practical experience to be generally accepted.

Table 2.1 summarises the comments of this section.

<table>
<tr><th>Criterion Type</th><th>Regulations</th><th>Regs.Apply To</th><th>Advantages and Disadvantages</th></tr>
<tr><td>Rahola</td><td>IMO Res.167 [1968]</td><td>Shiplength < 100m</td><td rowspan="2">Simple to understand and apply

Takes no account of external forces due to wind, waves or current

Gives no idea of likely motions or safety margins

Expected to apply to all load conditions and all shiptypes and lengths (within the respective rules)

Difficult to extrapolate to novel ship forms</td></tr>
<tr><td>Rahola</td><td>IMO Res.168 [1975]</td><td>Fishing Vessels of Length > 12m</td></tr>
<tr><td>Moment Balance Methods</td><td>-</td><td>-</td><td rowspan="2">Simple to understand and apply

Attempts to account for external forces acting on the vessel in an assumed environment

Quasi-dynamic treatment of motions given by Strathclyde method</td></tr>
<tr><td>Energy Balance Methods</td><td>IMO RES.A14 /562 [1986]</td><td>Shiplength < 100m</td></tr>
<tr><td>Lyapunov Method</td><td>-</td><td>-</td><td>Resulting criteria simple to apply

Based on principles unfamiliar to designers

May require much validation for acceptance</td></tr>
</table>

Table 2.1 Summary of Different Types Of Stability Criteria

2.3. Related Studies: United Kingdom SAFESHIP Project

Ship stability continues to attract considerable research effort. The SAFESHIP Project, to which this work was officially affiliated, ran from April 1981 and culminated in a conference held during April 1986 (Rina Safeship Symposium 1986). The extensive programme of work was as indicated in Figure 2.11.

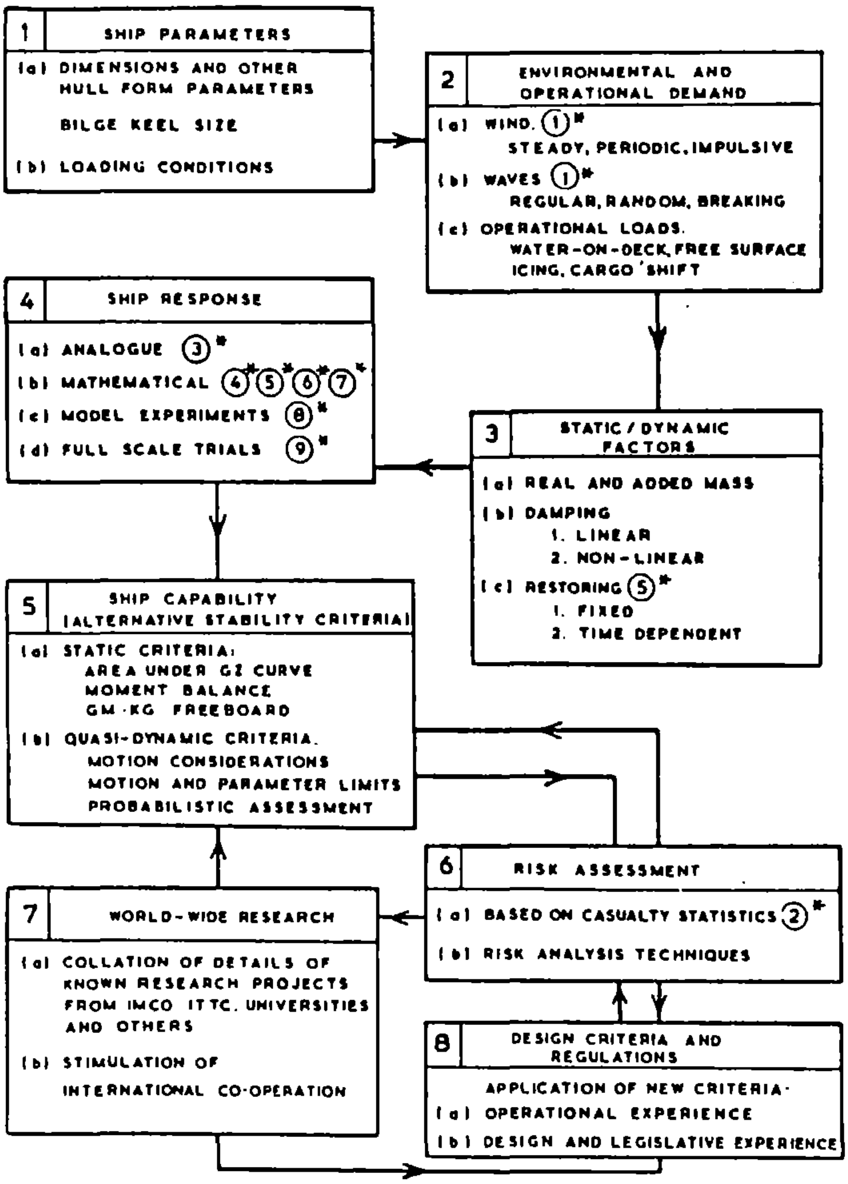


Figure 2.11 Safeship Project Areas

* Circled numbers were SAFESHIP project numbers

The SAFESHIP Working Group identified that one of the specific projects should be concerned with exploring the feasibility of developing and applying risk analysis methods as a basis for assessment of ship safety from capsize. The need for such methods, which are central to this study, are discussed in Chapter 3.

Chapter 3

Assessment of Capsize Risk in the Marine Environment

3.1. Introduction

> "Traditionally the stability is deemed adequate depending on compliance with certain parameter values of the still water statical stability curve .....
>
> Since these parameter values are the same for all ships regardless of size, type, operating and weather conditions, the margin of safety must vary considerably and is unknown".
>
> Bird et al (1982)

The current I.M.O. Resolution A167 "Recommendation on Intact Stability for Passenger and Cargo Ships under 100 m in length", which recommendations have been adopted by many countries, embodies the current deterministic approach to assessing ship stability. This is in spite of advances made in the various aspects of the stability problem as well as the fact that ship stability is fundamentally a dynamic and stochastic phenomenon. To illustrate this latter point, Table 3.1 is included. This is a non-exhaustive list of parameters which are likely to have a greater or lesser effect on ship stability. They may cause the vessel to respond in six degrees of freedom or may influence the vessel's ability to return to the upright following a response (these may be referred to in terms of 'demands' made on the vessel and 'capability' of the vessel to resist the demands respectively). It may be argued that any study which seeks to quantify ship "stability" should ideally take into full account all of these parameters in a rational way. Further it will be necessary to take into account the variability of these as they occur in practice. For example it is readily apparent that the environmental factors wind, waves and current display great variability and prediction error is likely to be present (uncertainty) particularly when data is sparse. Other studies indicate that certain of the factors that have hitherto been treated deterministically, such as the metacentric height and vertical centre of gravity, actually vary in a random way during the life of a vessel, Tucker (1978). These types of argument have led various researchers to suggest that the long-term future of marine safety lies with methods that may be used to allow for the intrinsic uncertainties and to assure acceptable standards and levels of risk, e.g. Caldwell (1983), Kastner (1982), Krappinger (1975).

This chapter examines the prospects for a rational assessment of vessel stability in the light of the available methods and data. The subject of acceptable risk and its assurance is discussed in chapter 9.

VESSEL DESIGN	Principal dimension ratios, length Beam, roll gyradius Age, structural deterioration Mass accretion Freeboard, watertight integrity Coaming and sill heights Extent of freeing ports Bow and stern form Provision of deck shelters Bilge keels or active fins Extent of superstructure Lateral area Provision of hold subdivision
ENVIRONMENTAL PARAMETERS	Wave height, period, energy spread Wind strength, gusting effects Breaking waves, shallow water effects Steep waves, Icing
OPERATIONAL PARAMETERS	Displacement, KG, draught, trim Stability curve (roll stiffness) Range of stability, angle of vanishing stability Free surfaces, suspended weights Autohelm
SEAMANSHIP	Speed and heading to waves Storm avoidance Training, experience, information available
ACCIDENTAL	Cargo shift, slurries Engine failure Steering loss Sudden structural failure Fire or collision admitting water into the hull

TABLE 3.1 Parameters For Consideration (Ideal Simulation)

3.2. Reliability and Safety Assessment Methods

The 'core' of any risk analysis is to establish the risk level. This fundamentally involves the assessment of the probability of hazardous events and the assessment of the severity of the events. The evaluation of the two properties can be carried out in a number of ways.

An extensive review of the available literature revealed several promising risk analysis methods, -promising from the point of view that they may be suitable for transfer of application to ship stability. Although it subsequently became apparent that certain of these methods were not appropriate (for reasons given below) they have been included for completeness. Methods have been classified as follows:

1. Methods used predominantly in the defence, nuclear, petro-chemical and electronics industries which combine component probabilities to obtain the probability of failure of the undesirable 'top event'.
2. Structural reliability methods which seek to evaluate the probability that the demands (loads) on the structure will be greater than the capability (strength) of the structure to resist the demands.

3.2.1. Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA)

Reliability methods, per se, were originally evolved during the Second World War in connection with electronics and guided weaponry. They became the norm in the defence and aerospace industries and, particularly during the last decade, have been used extensively in the higher risk industries, petro-chemical and nuclear for instance, where large communal databases of reliability data were created e.g. Kletz (1982), Griesmeyer et al (1981).

The key to successful failure analysis lies in the application of basic tools which discipline the analyst to subdivide the design and its operation into discrete parts. For a petro-chemical or nuclear plant, particularly where there has been no previous experience in the design process, the structural and engineering drawings are broken down into significant parts and events which may interact during operation. Failure Mode and Effect Analysis (FMEA), US Dept of Defence (1973), is a qualitative analysis tool which is designed to observe the possible failure states of components of a system and to identify all possible consequences within the design during normal, but also including abnormal, operation. It is ideal for identifying the need for corrective measures in a single random failure analysis, Aldwinckle et al (1983). Table 3.2 illustrates an example FMEA Sheet.

Failure Mode and Effect Analysis	
System:	
Subsystem:	
1. Component Name:	2. Function:
3. Mode of Operation:	
4. Failure Mode:	
5. Failure Cause:	
6. Effect of Failure:	
7. Failure Detection Method:	
8. Corrective Action:	

Table 3.2 Example FMEA Sheet

A FMEA is rarely adequate in projects involving large and complex arrangements of components. In these cases Fault Tree Analysis is used (FTA), Fussell (1976), to logically represent the many events which lead to the system failure or 'top event'. A complicated network of logic gates (AND or OR gates, Figure 3.1) results.

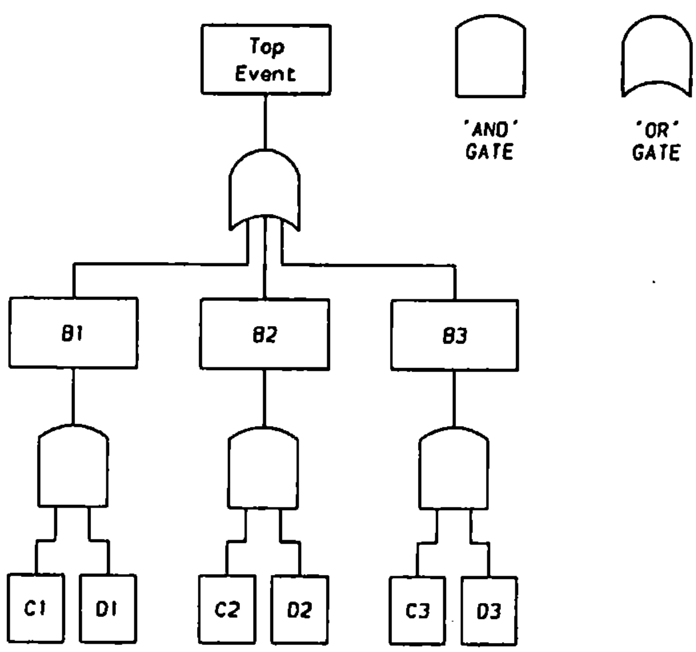


Figure 3.1 General Representation of a Fault-Tree

Working downwards the failure event tree structure is created terminating at basic events (which are usually independent). Once a tree has been created, a qualitative analysis can often reduce it into combinations of basic events (known as 'minimal cut sets') using Boolean algebra sufficient to cause the undesirable top event to occur. Following this procedure a quantitative analysis involves the transformation of the tree structure into an equivalent probability form from which the probability of the 'top event' may be evaluated very simply from the probability of occurrence of the basic events.

It was concluded that the practical value of this approach to the capsize problem is severely limited by the necessity to accurately determine these basic event probabilities. The data simply does not exist at this time. In addition this type of analysis is better suited to systems with large numbers of relatively simple discrete components having little or no interaction.

3.2.2. Structural Reliability Analysis

Structural reliability as a discipline is quite distinct from reliability engineering. Whereas FMEA and FTA are concerned with systems consisting of a large number of small elements of relatively simple modes of operation and with simple or no interaction, engineering structures are characteristically made up of complex elements with complex modes of operation and interactions, -thus in this respect there exists close analogy with the ship stability problem. Several approaches to marine structural design are now available. In the conventional 'safety factor' approach a single valued worst demand design or working load D_D is related to a similarly dimensioned failure or upper limit capability (strength) of the structure C_U by a scalar quantity F.

$$C_U \geq F D_D$$

In principle the strengths C_U can allow for interactive failure modes but the concept of a single unique scalar safety factor F is then illusory, Faulkner et al (1979). It is also usual for minimum specified material and section properties to be used so that, for example, a limiting strength is assumed when the stress reaches the yield stress. By direct analogy with the current (statical) stability regulations (Res.A167/68) the statutory rule section modulus approach to design, Lloyd (1976), is implicitly and explicitly based on the static wave balance principle coupled with still water loads, Muckle (1975). No allowance is made for different mission profiles or ship motion effects and thus no account is taken of the variability in either the strength of nominally identical structures or in the maximum loading to which they are subjected. The safety factor F is intended to account for all the unknowns in the load and strength and yields a structure that should have an acceptable performance based on past experience, though the degree of structural adequacy is unknown. In addition the approach is not entirely satisfactory for novel vessel forms and this, in parallel with scientific development, has led to the development of more rational concepts and approaches. These all have one common feature; that is the definition of the probability of failure p_f is given by 'adding' all probabilities that the failure governing load (D) exceeds the failure governing strength (C). Symbolically this is expressed as

$$p_f = p(C < D)$$

Faulkner et al (1979). This probability is represented by the area of the overlapping tails of the load (demand) and strength (capability) probability distributions shown in Figure 3.2. In principle this offers the opportunity to select an appropriate 'strength' on the basis of acceptable risk.

Another way to view this is that the failure will occur when the margin "M" between capability and demand is negative ($p_f = p(C < D) = p(C - D < 0) = p(M < 0)$). It follows that provided the probability density functions of demand and capability are known then the probability of failure can be evaluated from:

$$p_f = 1 - \int_0^{\infty} (F_D(x))\, f_C(x) dx$$

Where $f(x)$ are the probability density or frequency distributions and $F(x)$ the distribution functions of two uncorrelated[2] random strength and load variables C and D, Freudanthal (1956).

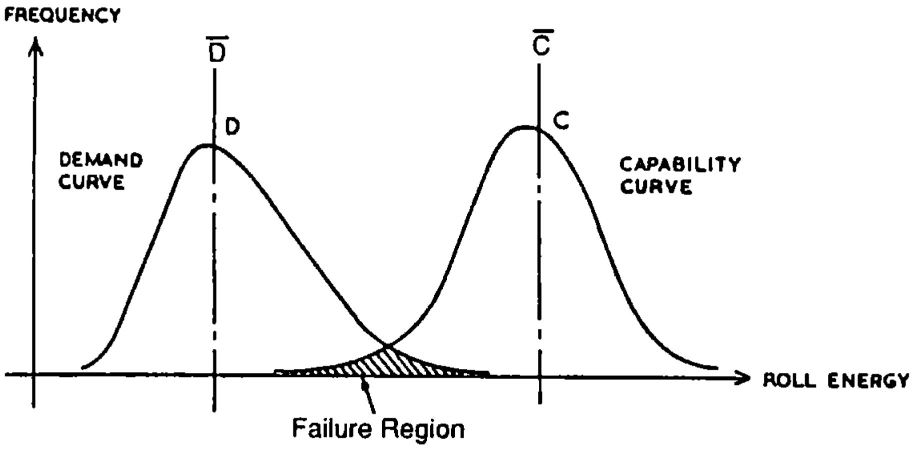


Figure 3.2 Demand and Capability Curves

Because of the difficulty associated with the determination of these failure governing load and strength functions and distributions a number of semi-probabilistic approaches have evolved:

- **Safety Index Approach**

Mansour (1974) used an approximate semi-probabilistic design method which required that only the means and variances of the load and strength be known. This approach expresses the safety index $\bar{\gamma}$ as:

---

[2]In fact it is known that certain of the demand and capability parameters which affect ship stability in Table 3.1 are not independent of each other. For example as a wave crest passes down the shiplength the sealoads (demand) will vary. So too will the capability since the righting levers are modified by the varying buoyancy forces as the wave crest progresses.

$$\bar{\gamma} = \frac{\bar{M}}{\sigma_m}$$

$$= \frac{\bar{C} - \bar{D}}{\sqrt{\sigma_c^2 + \sigma_d^2}}$$

$$= \frac{\theta - 1}{\sqrt{\theta^2 \delta_c^2 + \delta_d^2}}$$

where

$\bar{M}$ is the mean safety margin $\bar{C} - \bar{D}$

σ_m^2 is the variance of the safety margin

$\approx \sigma_c^2 + \sigma_d^2$

$\bar{C}$ σ_c δ_c are the mean, standard deviation and c.o.v. of strength respectively

$\bar{D}$ σ_d δ_d are the mean, standard deviation and c.o.v. of load respectively

θ is the central safety factor $\frac{\bar{C}}{\bar{D}}$

Obviously the equation will yield a different safety index for each mode of failure and, lacking an adequate method to combine such indices, the minimum safety index $\bar{\gamma}$ should be used comparatively as a measure of structural safety of the hull.

• Partial Safety Factors

Regulatory bodies have for many purposes adopted a slightly varied form of the above explained pure probabilistic approach. Instead of considering the overlapping tails directly on a basis of acceptable risk (figure 3.2), the concepts of design values have been introduced for both demand and capability. The relationship between the characteristic loads $\langle D_k \rangle$ and strengths $\langle C_k \rangle$ will generally be of the form:

$$\langle C_{kj} \rangle \geq \gamma_c \gamma_s \left\{ \sum_{i=1}^{n} \gamma_{di} \langle A \rangle \langle D_{ki} \rangle \right._j$$

-Faulkner et al (1979)

The subscripts i refer to the different loads factored by the correct transformation matrix $\langle A \rangle$ to give the load-effect for load combination j in the n-dimensional space.

By ignoring interactive effects between different failure modes and adopting a weakest-link model for ultimate collapse of the ships hull, Mansour (1974), and by making use of the fact that the probability of failure p_f is dominated more by variability in load than in strength the amount of work is dramatically reduced to one (weakest-link) case and the equation reduces to:

$$C_k / D_k = \gamma_c \gamma_d \gamma_s (C_d / D_d)$$

where C_d and D_d are design values for strength and load and are usually assumed to be equal when applying the partial safety factor concept. Then:

$$C_k = \gamma_0 D_k$$

where $\gamma_0 = \gamma_c \gamma_d \gamma_s$ is an overall partial safety factor which is very similar in concept to the traditional (deterministic) safety factor F.

The subjective partial safety factors by which the objectively derived characteristic loads are multiplied to obtain the design loads are:

γ_d which takes account of the variability of the applied loading and its methods of determination.

γ_s which takes account of the nature of the structure (failsafe etc.) and the seriousness of failure in economic and loss of life terms, i.e. $D_d = D_k \gamma_d \gamma_s$

The partial safety factor by which the characteristic strengths are divided to obtain the design strength is:

γ_c which takes account of the differences between the strength of the material by testing and the effect of local defects, i.e. $C_d = C_k / \gamma_c$

The merit in using the Safety Index and Partial Safety Factor Concepts is that they rely on four parameters only; the mean values and variances of load and strength, which can be measured or assessed objectively and adjusted for subjective uncertainties. No knowledge is required of the nature of the distributions in the tails. All random uncertainties are treated uniformly through the coefficient of variation with systematic errors affecting the mean values.

Unfortunately semi-statistical methods cannot combine the risks of failure for independent modes of failure nor provide a rigorous procedure for proportioning a structure against different load combinations and multi-modal failures. Only a fully probabilistic approach can do this. Nevertheless, Kure(1979) has suggested that the Partial S.F. approach might be suitable for the ship stability problem once the subjective safety factors have been determined with sufficient confidence. Such information will be more forthcoming once 'black box' motion and stress recorders, similar to those on aircraft, are routinely provided on ships. Lloyds Classification Society is currently developing such a device, Spencer (1986).

3.3. The Role of Available Casualty Information

To a very large extent the approach that was finally adopted at Plymouth was governed by the lack of availability and the poor quality of casualty information which is currently available.

Initially it was considered that if sufficiently detailed casualty information could be obtained then a hindcast probability analysis could be undertaken (FMEA,FTA or Demand/Capability). In fact it soon became apparent that where casualty data did exist it was generally poorly detailed and was probably not very accurate, a not unexpected result given that a characteristic feature of all forms of capsizing is the great speed at which the vessel founders, together with the fact that the only wreckage which is found as a rule are those objects which are loosely stowed and which are able to float to the surface after the vessel has sunk, Hanssen (1982).

Casualty data for the years 1973-1984 (inclusive) were obtained from the Department of Trade, Marine Division, together with summary statistics provided by 'Casualties to Vessels and Accidents to Men' published annually by the department of Transport. The fact that the format of the published data has not always been consistent from one year to another and that large variations in the number of vessels on the register is apparent ensures that absolute judgements are not possible unless elaborate steps are taken to assess the actual numbers at risk. Fortunately this is not a problem when comparative judgements are required regarding the actual total number of casualties. For example, Figure 3.3 illustrates the breakdown of founderings and capsizals by vessel for all years 1973-84 inclusive and shows that vessel loss through foundering and capsize is largely a 'small ship' problem.

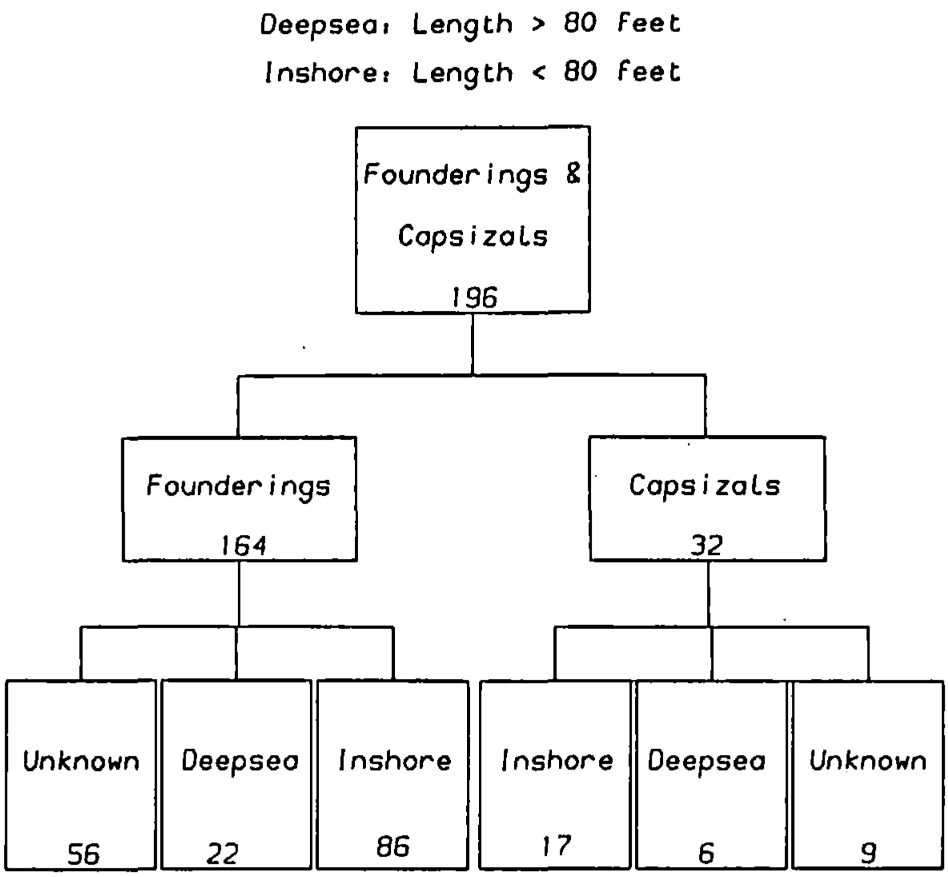


Figure 3.3 Total Number of Founderings/Capsizals with respect to Vessel Length (1973-1984)

Similarly by examining Figure 3.4 it may be stated (regarding the environmental conditions):

- A great majority of founderings and capsizes occur in estuaries, port approaches and coastal waters.
- Casualties are likely to happen all year round with almost equal likelihood of occurrence.
- Except in those cases of dangerous loading or water inrush, almost all founderings and capsizes occurred in moderate or rough weather conditions.
- Mild/Moderate wind strengths are as dangerous as strong wind strengths.

Regarding the operational conditions:

- Light load condition and ballast conditions appear to be more hazardous than the fully laden condition.

Such a qualitative analysis of casualty records can lead towards a better understanding of capsize which will eventually guide one to the appropriate methods of stability assessment. Unfortunately, this level of information is not sufficient for such an analysis as failure mode and effect analysis or fault tree analysis when information is required on the sequences of events giving rise to capsize as well as the probability of each of the 'base events' occurring. Structural reliability methods, that have been outlined, also require greater detail (means and variances of demand and capability) than is currently available in the casualty records before the safety indices or partial safety factors may be used for (especially) new ship types - when no recourse is possible to past design values. Indeed an extensive survey of current risk analysis methods including Cox (1981) and Fairley (1981) leads one to the conclusion that, whatever method is chosen, the confidence in the final estimate of output uncertainty depends on the confidence one can place in the basic estimates of parameter uncertainties. Thus poor estimates would be expected with the current state of knowledge.

Another approach, fuzzy set theory, has been developed to cater for significant parameters which are difficult to quantify, Yao(1985). Thus linguistic descriptors are used to describe the damaged state of certain structural components in a subjective manner, such as 'the structure is moderately damaged' or 'the structure is severely damaged'. These descriptors may be assigned numerical values (known as 'membership functions') which are logically manipulated to provide an answer to the question "How severely damaged is the total structure?". This would be couched in such terms as "the total structure has a weak/moderate/strong membership of the severely damaged set".

It was felt that, although such theory might be very useful for assessing certain values such as damage states or the nature of human behaviour for example, unfortunately lack of knowledge of the interrelationships between the highly individual critical parameters (as evidenced by Table 3.1) would undermine the value of such an approach to the capsize problem.

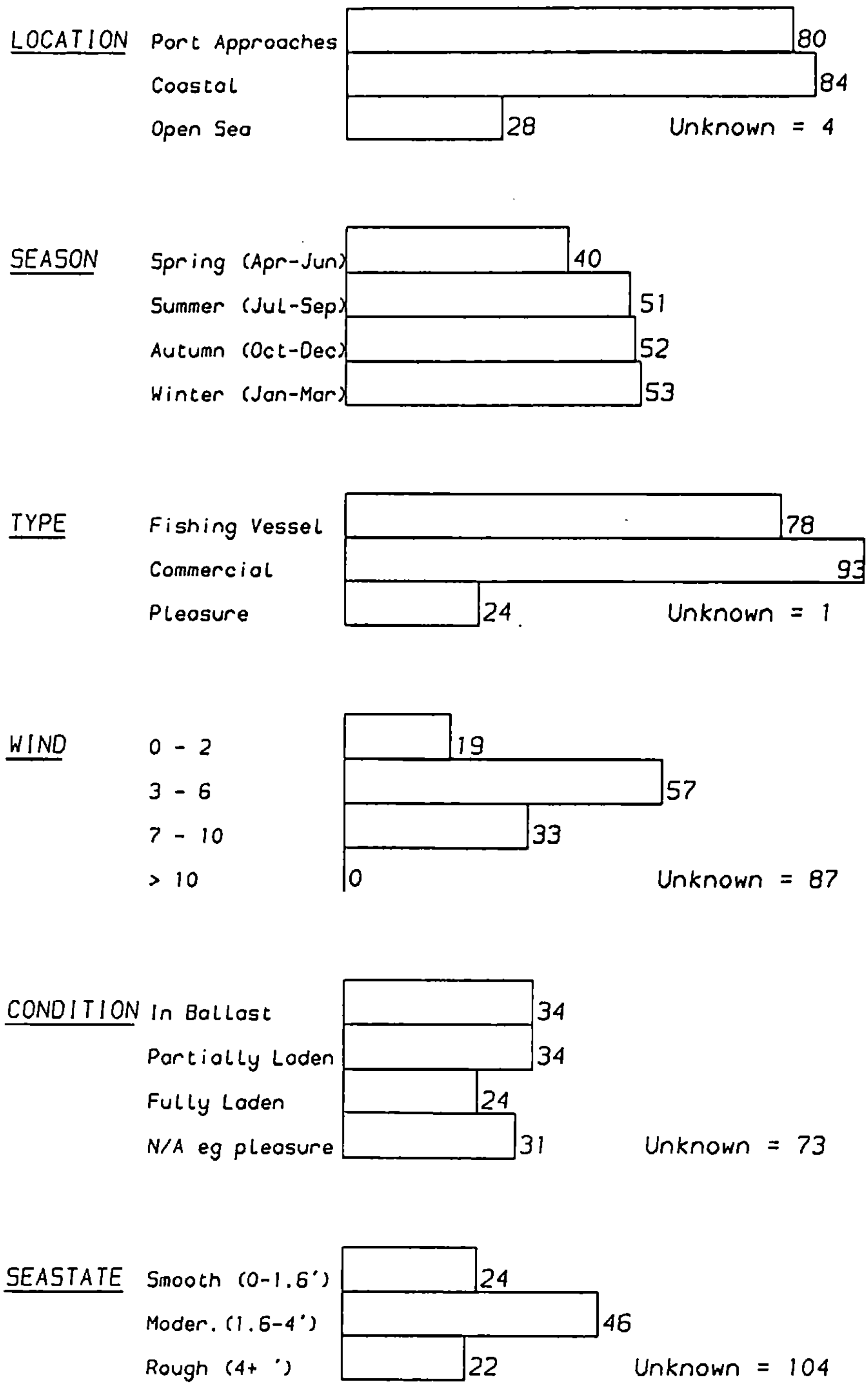


Figure 3.4 Casualty Breakdown for Foundering and Capsize

The alternative to the aforementioned hindcast/retrospective approaches is to develop a prediction method to forecast the probability of occurrence of extreme roll motions judged dangerous or undesirable for continued safe operation.

Chapter 4 describes the framework of risk that was adopted in this research and Chapter 5 discusses how the problem of predicting extreme roll motion in a seaway was tackled.

Chapter 4

Managing a Lifetime of Risk

4.1. Introduction

> "...It is essential to develop a rational philosophy and a logical procedure of assessing intact stability in particular wherein the essential steps and decisions are clearly indicated. Such a procedure when applied to a conventional or novel vessel will not only ensure a consistent approach to design but will show clearly where the uncertainties lie and where further research is most needed".
>
> Morrall (1982)

Most of the noteworthy papers on intact stability of ships have concentrated in recent years on the theoretical aspects of an apparently intractable problem to predict large angle roll motion very accurately in idealised wave conditions e.g. Roberts(1984). Little or no reference has been made to safety and ship performance in rough seas in order to develop a framework for future design and stability criteria.

The most universal stability criterion should be the probability of non-capsizing of a vessel during its lifetime but as Kastner (1982) points out:

"It would be an almost impossible task to solve for the real actual probability of capsizing for any ship during her lifetime, because of the many parameters involved such as ship characteristics, environment, service routes of ship etc".

A question also arises whether it is possible to calculate the capsize probability with sufficient accuracy since the occurrence of extremely severe conditions of wind and waves causing extreme roll motions is a very rare phenomenon which may not be accurately predicted on the basis of statistics at present. Unless this inaccuracy in the probability calculation is of a lower order than the final predicted value of risk the usefullness of this concept in assessing stability criteria may be questioned, Sevastionov (1970).

In spite of these observations, and in order to avoid a large safety margin which would be inappropriate to use throughout the entire life of the vessel and would lead, amongst other things, to poor seaworthiness and unsatisfactory economic factors, it has been suggested that it would be useful to analyse chosen critical situations (scenarios) of the vessel taking into account their probability of occurrence e.g. Kobylinski (1975). Thus, using this concept, logically the stability criterion is motion based -- being the probability of non-capsizal of the vessel during several selected dangerous seagoing scenarios. Such an approach requires the identification and proper selection of the potentially capsize-causing situations (combining features of design with environmental and operational factors) together with the probability of their occurrence and a realistic modelling of the total system (including human) behaviour. It is felt that, provided consistent and plausible assumptions and values are applied, the estimates of survivability which result should have meaningful comparative significance, Caldwell (1983).

In any event the limitations imposed by data availability and quality, which have been described previously in chapter 3, will inevitably lead to a comparative survivability assessment and it is probably most useful to ensure that all vessels are judged comparably safe for their respective intended modes of operation until the data quality improves.

To summarise, the probability approach to stability assessment that was finally adopted at Plymouth comprises three distinct but interacting parts:

1. Identification, selection and treatment of the critical (potentially capsize causing) scenarios
2. Evaluation and combination of the probabilities of the critical scenarios identified in (1) above
3. Modelling of total system behaviour comprising primarily vessel response but also containing aspects of human behaviour

The remainder of this chapter is concerned with the important parameters that should be included in the analysis and the handling of the associated probabilities to manage a lifetime of risk.

4.2. The Capsize Phenomenon

By consideration of the capsize phenomenon some useful pointers to the dangerous situations which are being sought may be found. Careful analysis of casualty records as well as observations of capsizing model experiments in rough seas has provided a good picture of capsize e.g. Boroday et al (1975), Takaishi (1982). For example Table 4.1 from Takaishi (1982) classifies the flooding and capsizing accidents of some 448 ships into 10 modes corresponding to ship and navigation conditions as well as environmental conditions. Similarly Table 4.2 also taken from Takaishi (1982) reveals the main factors causing capsize in rough seas. These tables reveal the great diversity of factors that may contribute to a capsize and the relatively high incidence of human factors having major contributory effect. An ideal analysis would seek to account for all of these factors but in practice some means of standardising them, particularly for regulatory purposes, is clearly both necessary and desirable.

Case	Causes or Conditions of Casualties	Number of Casualties		
		Fishing Boats	Cargo Vessels	Total
1	Navigating in Quartering or Following Seas	25 (19)*	26 (19)	51 (38)
2	Navigating in Head, Bow and Beam Seas	49 (37)	101 (64)	150 (101)
3	Navigating in Calm Water	5 (5)	15 (15)	20 (20)
4	Working as Fishing or Towing Ship	5 (5)	25 (20)	30 (25)
5	Hull Break Down	17 (1)	37 (5)	54 (6)
6	Mishandling of Piping or Valve System	24 (3)	22 (5)	46 (8)
7	Anchoring in Harbour When Storm or Typhoon	12 (3)	12 (4)	24 (7)
8	Misloading of Cargo	3 (3)	47 (45)	50 (48)
9	Icing or Drift Ice	8 (8)	0 (0)	8 (8)
10	Reasons Other Than 1-10	5 (2)	10 (6)	15 (8)
	TOTAL	153 (86)	295 (183)	448 (269)
*Note: Number in parenthesis indicates the number of capsizing accidents.				

Table 4.1 Classification of Flooding and Capsizing Accidents
Takaishi (1982)

Factors Causing Capsize	Fishing Boat	Cargo Vessel	Total
Over Loaded	9	8	17
Top-Heavy	13	11	24
Insufficient Lashing	1	20	21
Inferior Loading	7	17	24
Cargo Shift	13	41	54
Open Door	9	22	31
Inferior Hatch Cover	2	18	20
Hull Break Down	2	1	3
Shipping Water on Deck	29	26	55
Broaching	1	3	4
TOTAL	52	87	139

Table 4.2 Classification of Main Factors Causing Capsize
Takaishi (1982)

Closer examination of capsizals during model tests has shown that several distinct capsize mechanisms exist. These may be classified with respect to heading of vessel to the incident waves:

4.2.1. Capsizing Experiments in a Beam Sea

Experiments with models side-on to the waves have revealed that the large heel angles are the result of two mechanisms e.g. Morrall (1975 and 1978), Dahle et al (1980):

1. The impact of the wave as it strikes the superstructure and the hull.
2. The high front of the wave upon which the vessel may float.

It is this second factor which is the main reason for the vessel adopting large heel angles. Experiments have revealed that these will occur on the whole irrespective of the stability of the vessel and that the models lay at this large angle after the wave had passed. Whether or not the vessel 'survived' was dependent on the value of the righting lever (positive or negative) at the large heel angle.

In addition Takaishi (1982) and other researchers have demonstrated that shipping of water on deck and cargo shifting due to large lateral accelerations acting on the weight are major contributory factors to consider in the beam-sea situation.

4.2.2. Capsizing Experiments in a Following Sea

Three kinds of capsizing phenomena have been identified by experiments with models in following seas:

1. Pure loss of stability occurs when the model is moving with a speed nearly equal to the wave phase velocity, when a wave crest may assume a stationary position amidships, Paulling et al (1972). Reduction in waterplane area reduces the initial stability and GZ values at all angles of heel. The vessel capsizes in the same way as an unstable vessel in calm water i.e. in a non-oscillatory manner. The effect is exacerbated when the height of the wave is sufficient to wash over the deck, Takaishi (1982), Hanssen (1982).
2. Parametric excitation (or Mathieu effect) occurs when the encounter frequency of the ship to waves is around half the natural roll frequency. In the event of a wave crest being located amidships the vessel's righting levers will be reduced (as described above) and the vessel may heel over to a large angle. At complete synchronization as the vessel reaches maximum deflection the wave has moved on until there is now a trough positioned at amidships with consequent increase in righting levers. The vessel will return rapidly to the upright where its righting levers are again reduced as the wave crest approaches amidships. The vessel assumes larger and larger angles of heel until it may capsize if the initial stability is very low [GM/Beam = 0.0075 according to Paulling et al (1972)]. Regular choppy waves with a wavelength between 1 - 2.5 times the shiplength are frequently quoted for this phenomenon to occur.
3. Broaching occurs when the ship is overtaken by a large wave, (L_{wave}>>L_{ship}), accelerated on the waveslope and forced to move at the same speed as the wave.

The vessel is forced to yaw off her course suddenly and will come about only to heel over to leeward. Directional control is lost as a result of the low relative speed between the rudder and the wave and the vessel will tend to turn rapidly encouraged by the asymmetrical flow of water past the bow. The combination of dynamic forces exerted by the waves and the centrifugal force generated by the turning action produce large heel angles or capsize angles.

4.2.3. Capsizing Experiments in a Quartering Sea

Model experiments indicate that when the ship navigates in steep and short quartering waves with high speed the worst beam-sea and following-sea factors can occur simultaneously, Takaishi (1982). It is apparent that the vessel can be subject to all of the above mentioned phenomena if the conditions are sufficient, the difference being that the relative wave elevations on the ship's side become large in the quartering waves at amidships so that water can enter onto the deck easily. Because of these facts the quartering sea case deserves special attention in a motion based stability assessment.

4.3. Conceptual Model Outline

It follows that every seagoing situation should be analysed to take account of all the possible capsize phenomena described above. This is especially true of smaller vessels under investigation when, due to scaling effects, the ratio of exciting moment to restoring moment is likely to be larger than for a larger vessel. Consideration should also be given to the possibility of one phenomenon giving rise to another e.g. heavy seas from the beam causing cargo shifting or water ingress. With the current state of knowledge this would lead to the ideal demand/capability assessment indicated in Figure 4.1. This would be a mixture of analytical time and frequency domain techniques and experimental techniques to predict the occurrence of the various capsize mechanisms. The largest roll motion obtained from consideration of all of these would be recorded in this case.

Since the main aim of this study is to formulate an overall risk framework for assessing the safety of a vessel against capsize, only certain capsize phenomena are modelled in the present work as discussed in Chapter 5. Eventually it is envisaged that the appropriate motion prediction techniques for analysing all of the various capsize modes will simply 'plug-in' to the (modular) computer program which has been written and is described in detail in Chapter 7.

Major attention has been focussed on synthesising the component parts which must be given consideration so that a realistic assessment of the probability of extreme roll motions is obtained. This will provide an index of survivability for each vessel given the difficulties of accurately predicting the actual capsize probability that have already been noted.

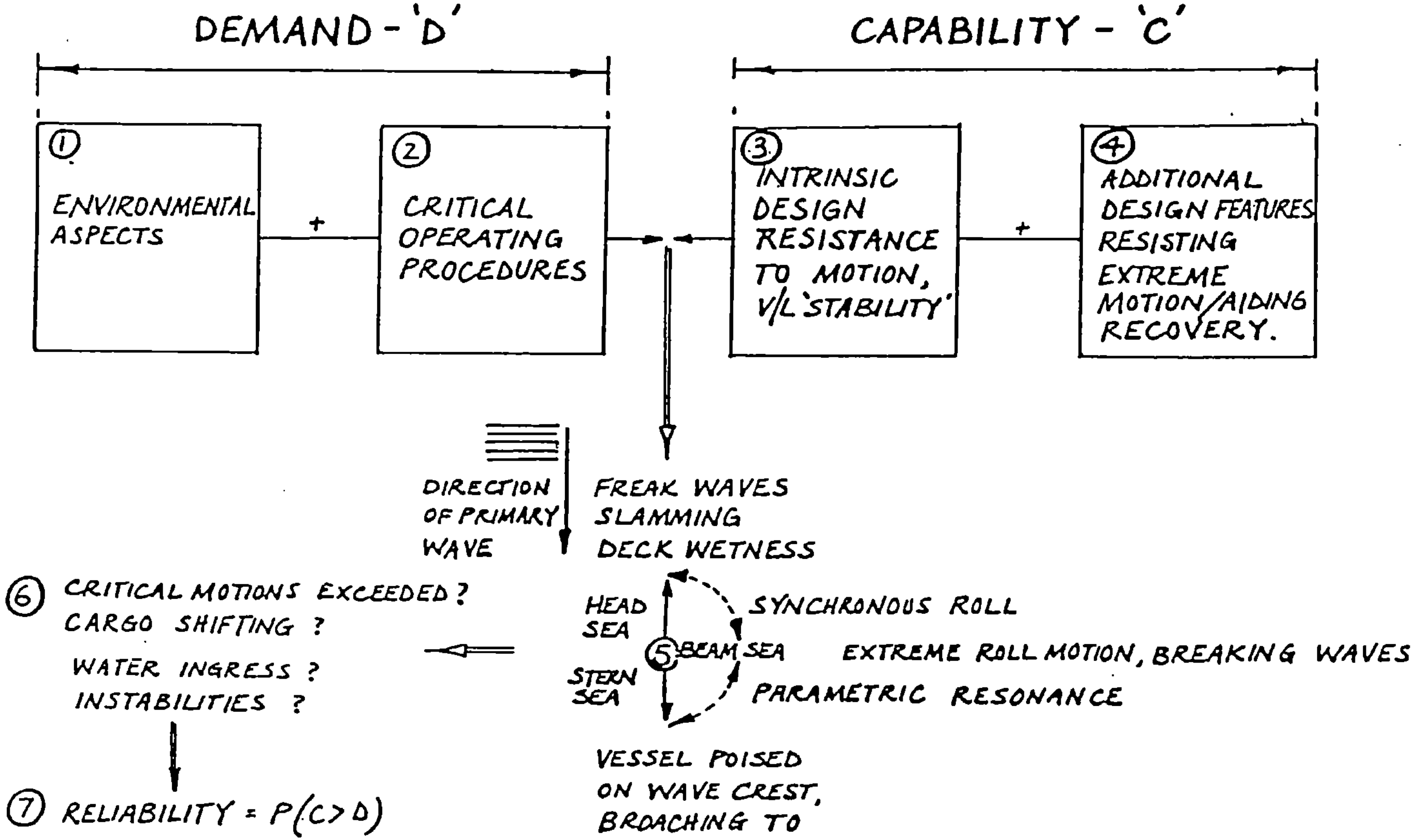


Figure 4.1 Ideal Demand/Capability Assessment

4.4. Short-Term versus Long-Term Analysis

There are two particular types of prediction method that may be generally considered for ship stability as advocated for the design of an offshore structure. These are:

1. the long-term prediction method, which considers all variations of the responses for every cycle of wave encounter in the ship's lifetime regardless of their magnitude, Ochi (1976a).
2. the short-term prediction method which considers only certain of the wave encounters, usually the severest which are likely to occur in a vessel's lifetime, Ochi (1978a).

4.4.1. Long-term Analysis

In operability-type studies such as a fatigue analysis it is necessary to consider every cycle of vessel response during its lifetime since all cycles contribute to structural fatigue failure. However, for estimating extreme values this long-term method has the serious disadvantage that because a significant percentage of vessel response are of small magnitude in relatively mild seas these do not contribute to the extreme values. The magnitude of vessel response will not reach a critical level irrespective of how long she operates in mild seas, while the magnitude will reach the critical level within a short period of time in moderate/severe seas. Indeed for certain classes of vessel it has been shown that the inclusion of responses in mild seas in predicting extreme values introduces a significant inaccuracy in establishing the probability function used for the prediction, Ochi (1976b).

4.4.2. Short-term Analysis

It is thus considered appropriate to consider only severe seas and several others below the severest since quite often only the severest seastates will cause the extreme motions. Provided that the relatively rare catastrophic responses in mild seas can be accounted for then the amount of computation can be reduced. Obviously it is not sufficient to seek the worst cases in an ad hoc manner and some ordered approach is desirable:

4.5. Test-tracks and Proving Ground

In an attempt to 'trap' the worst-case scenarios, the proposed method consists essentially of a subject vessel being required to successfully (i.e. without capsizing) negotiate a series of "test tracks" which have been designed to represent the range of critical (potentially capsize causing) scenarios that it will encounter during its lifetime.

In the automobile industry, in particular, this type of procedure is common. A road vehicle is caused to perform a series of manoeuvres over varying terrain in a variety of conditions (environmental, load, speed etc.) where each test-track represents one such set of conditions. For example there will exist a handling and stability test-track, a steep gradient test-track and so on. The total test-track set is termed the "proving-ground" and its overall nature reflects the vehicle's intended use and type. Thus a sports car will have a different set of test-tracks to negotiate than an articulated lorry, though some will be identical, Figure 4.2.

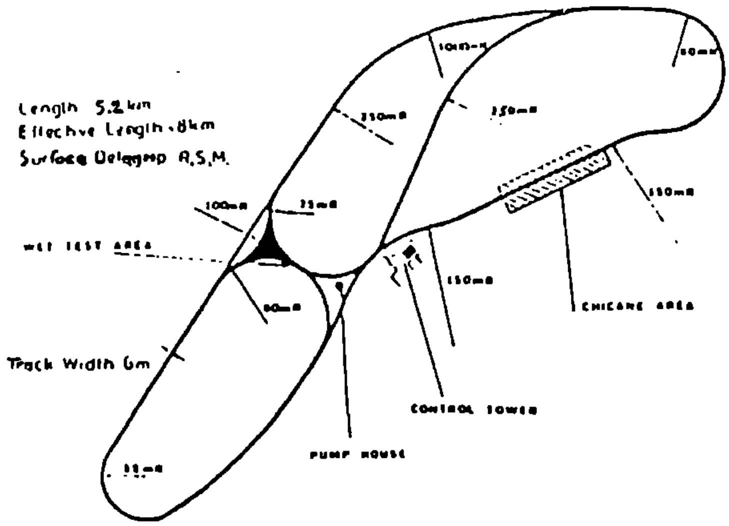


Figure 4.2 Handling and Stability Circuit at MIRA, Williams (1983)

The main advantages to the vehicle designer of using this approach are:

1. The full range of operating conditions, including the very important severe conditions, can be reproduced in a manner which is difficult to achieve on the open road; thus making repeatability of results possible.
2. Vehicles are tested under tightly controlled conditions where individual characteristics such as handling can be assessed, in isolation if necessary, and compared against previous and other vehicles' performances.
3. Attention is focused on individual elements e.g. vehicle suspension settings so that if a poor performance characteristic manifests itself on one particular test-track the design can be precisely retested after suitable modification.

It is believed that these are valuable procedures which can be used to assess the capability of a seagoing vessel to perform its duty in safety. However, leaving aside the immense difficulty of physical modelling of severe sea conditions, expense would preclude the use of a purely physical marine proving ground for every single vessel, even if the conditions could be precisely and routinely recreated. Thus it is envisaged that at first the test-tracks will be largely analytical in nature with some experimental back-up for certain difficult aspects until, as the theory improves, eventually no physical experimentation would be required (?)

4.5.1. Choice of Test-Track

As with the road vehicle case, the vessel type and intended zone or zones of operation dictate the nature of the proving ground that the seagoing vessel will be required to negotiate successfully by regulation. Thus a vessel which is intended for operation in a sea-area which is well sheltered or has shelter to hand will not have to 'negotiate' certain of the more stringent test-tracks required of a vessel which is intended for extended operation in high icing latitudes for example. A vessel which is intended for unlimited international operation would be subjected to the worst possible weather conditions.

Indeed, some form of licensing (or alternatively an appropriate equipment level) might be envisaged for individual operational zones since this would avoid the potential overdesign (or underdesign) of vessels which the current 'blanket' regulations may encourage.

By direct analogy with the case of a road vehicle which is made to perform a series of manoeuvres over varying terrain, during which time various measurements of handling, vibration, stability, power etc. may be taken simultaneously, the subject vessel proving ground is subdivided with due consideration of:

a) distinct climate conditions

b) distinct wave conditions

c) distinct operating procedures

d) distinct displacement conditions.

The vessel is examined over the same sea areas (the same circuits for the road vehicle) for different capsizing phenomena and thus the concept of a "layered test-track" approach may be considered. Figure 4.3 illustrates this for a single operation.

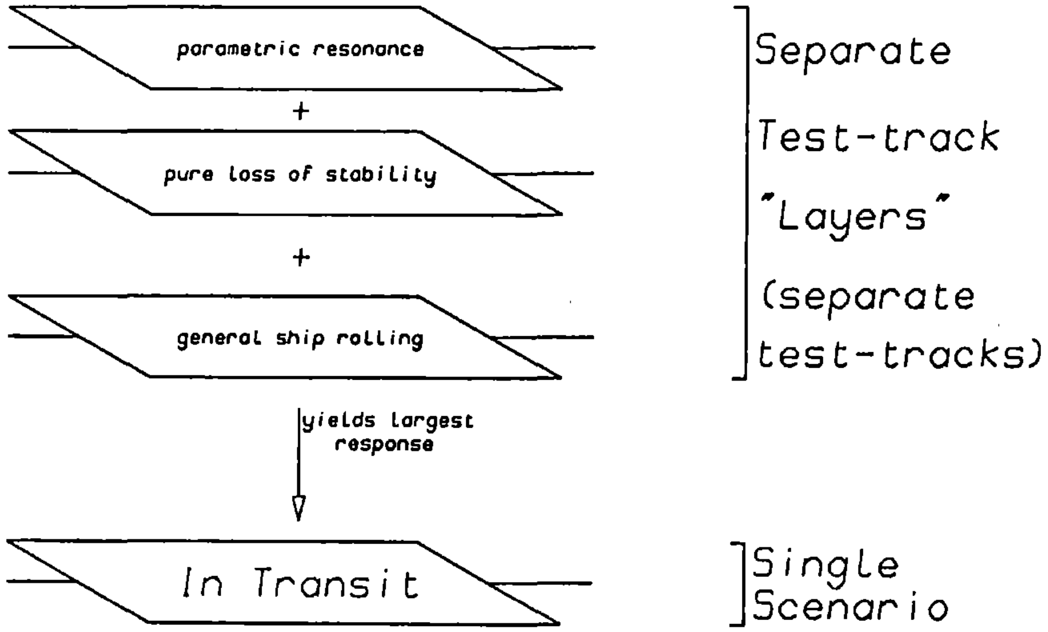


Figure 4.3 Layered Test-Tracks

These test-track layers may be overlayed to give the largest roll response for any individual scenario as indicated in figure 4.3. Alternatively, by separating the layers and considering individual test-track performance (for pure loss of stability as an example) the effect on the performance of selected design and operational features can be considered in detail. This concept would allow detail design improvements to be made for any of the layer characteristics.

Overall proving ground performance will allow comparison of total performance and safety levels across a fleet of vessels for example, though this 'average' value should be treated with caution.

In this study the single test-track which is concerned with "general ship rolling" is being studied and the other test-track layers are not considered due to the constraints on available time. In general less calculation will be necessary for the other capsize phenomena since they tend to be very heading/speed dependent and thus many scenarios could be eliminated on this basis at the outset.

A typical subject vessel can be expected to operate, over its lifetime, in a wide range of environmental and displacement conditions and to be subject to different masters' action. The correct choice of test-tracks to isolate the potentially capsize-causing scenarios from amongst all possible operating scenarios encountered by the vessel, during its lifetime, is vital if certain critical operations are not to be overlooked along the way. Whereas it is computationally desirable that the proving ground should encompass (only) all of the possible scenarios which could cause capsize, it is obviously not possible to pre-define them all and it is thus necessary to initially consider that all scenarios are potentially capsize causing. However, if an initial assumption is made that only the severest seastates cause the severest responses then the amount of computation for any scenario is reduced if the order of severity of seastates to which the vessel is subjected (everything else remaining unchanged) is progressively reduced from the most severe possible to the least severe in the operating zone being considered. It was intended that the results of multi-variate (pattern recognition) analysis of casualty data (for the broad vessel type and size under consideration) could be used to ensure that no proven (frequently recurring) capsize scenarios have been missed, particularly in mild seas. These positively identified "capsize nuclei" (each one representing a distillation of many similar casualties) form critical scenarios for consideration and are embedded in the test-tracks with respect to time and location, Figure 4.4.

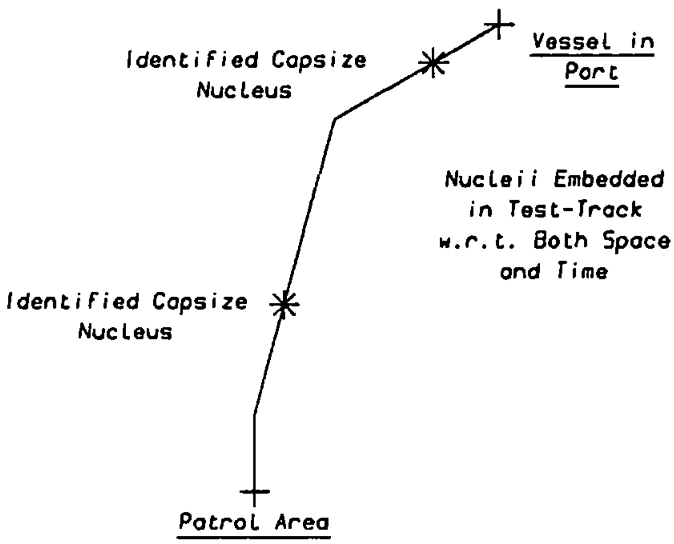


Figure 4.4 Capsize Nucleii

4.5.2. Managing the Lifetime of Risk

The process of handling all of the scenarios comprising a lifetime of risk is best described with the aid of an example. The subject vessel being used for the present study is a fisheries protection vessel which has an operational area encompassing the northern North Sea and north-eastern Atlantic in the region of the 100 fathom line around north west Scotland. There are also occasional sorties of up to 200 miles into the open North Atlantic.

Essentially, the adopted prediction method aims to calculate $p(\phi_c < \phi)$ the cumulative probability of a 'critical roll motion' ϕ_c being exceeded, at least once, during the vessel's lifetime of operation. This value is represented by the proving ground result.

Probabilities of motion exceedance due to the individual capsize phenomena, represented by individual test-track performance, is also being sought.

The cumulative probability $p(\phi_c < \phi)$ can be obtained from a knowledge of the underlying lifetime response probability density function $p(\phi)$. This in turn can be found by computer-predicting independent trial samples of roll response over the vessel's lifetime together with the independent single trial probabilities of occurrence. These independent trial results are then combined using Bernoulli trial procedures, Appendix A4.

A preliminary analysis is necessary to determine a vessel's intended missions (operating practices and operating areas). From the known mission profile for the vessel which, in this case, is already built and operating it is assumed that the vessel will only ever operate in the sea areas labelled 2 and 4 in Figure 4.5.

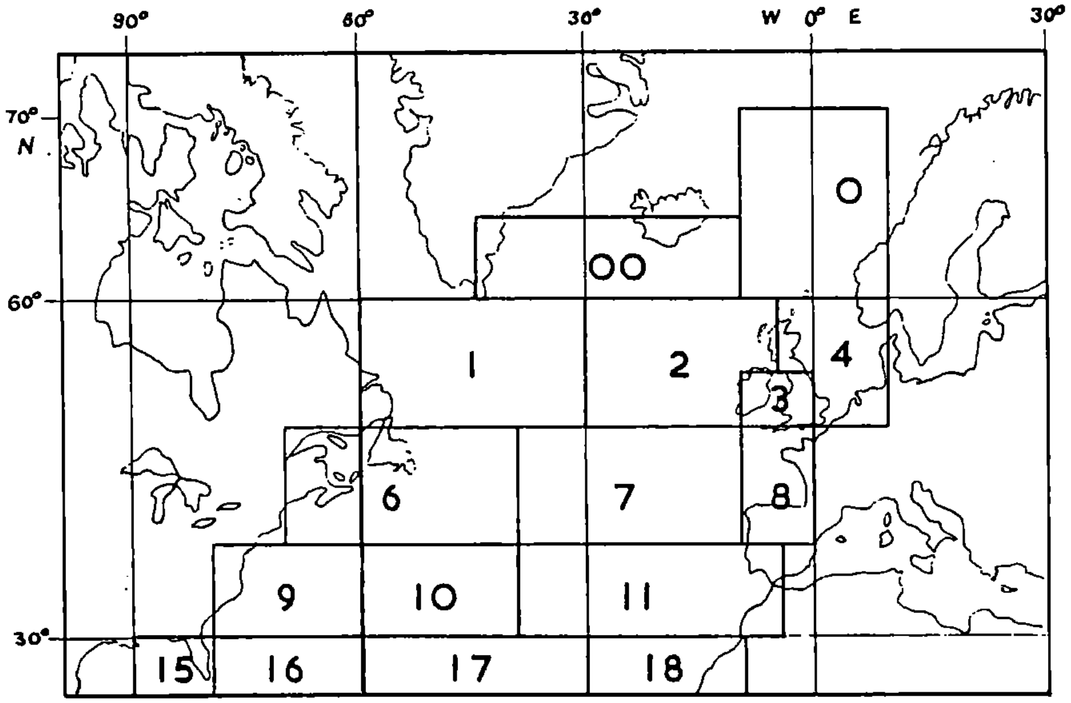


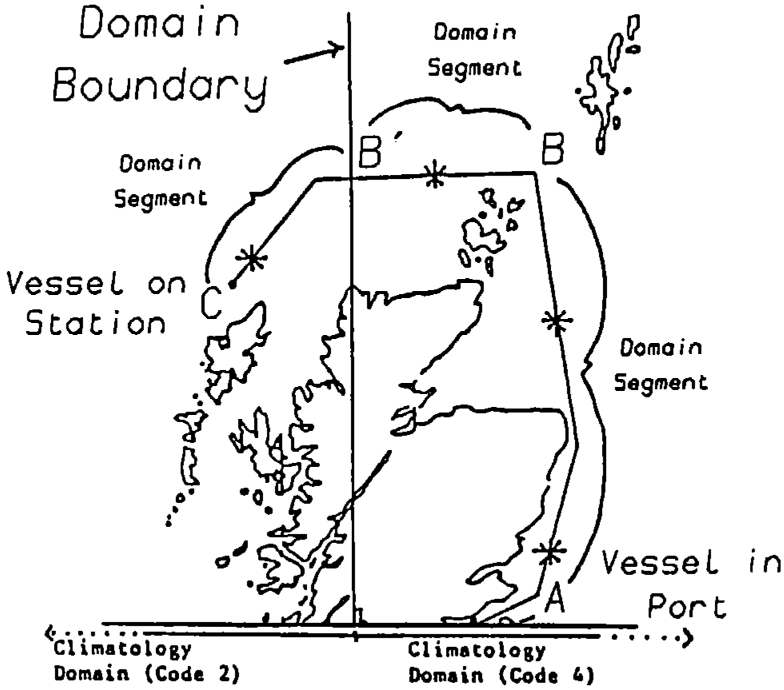
Figure 4.5 North Atlantic Basin Climatology Regions
Bales et al (1981)

This figure indicates the boundaries, called domain boundaries, of the sea-areas in the North Atlantic basin into which the chosen climatology data is divided, Bales et al (1981).

It is assumed that each sea-area has its own distinct climatology and that this is homogeneous (uniform) within the domain boundaries shown.

Thus the sea-areas 2 and 4 together comprise the proving ground for the subject vessel.

Typical missions indentify routes within the proving ground. One of these is shown in Figure 4.6.



Key: Test-Track = ABB'C

Assumption: Displacement is constant between legs AB and BC. Leg BC crosses the domain boundary at B'. * indicates independent trial sampling points.

Figure 4.6 Identification of a Typical Test-track Location

4.5.3. Application of the Method

For the remainder of this chapter the term "test-track" is referring to the frequency domain "general ship rolling" test-track unless otherwise stated.

A typical mission is involved in proceeding from the home port (Position A in the figure) to the patrol area at position C where time is spent on station before returning to A by the same route. It can be seen that the intended course track is ABB'C which crosses the domain boundary at B'. Thus this test-track comprises 2 separate spatial domains where the climatology is assumed homogeneous. In order to reflect the varying wave conditions within the same climatology, each domain may be divided into sub-domains. This is only necessary if it is required to model different wave conditions, such as open-sea and fetch-limited wave conditions, within the bounds of a single domain.

Each spatial domain/sub-domain is further subdivided into domain segments which are segments along the intended track where the vessel's displacement condition ($\Delta k_{xx} k_{yy} k_{zz}$)can be assumed constant. Thus in figure 4.6 between AB and BC the displacement conditions are assumed constant and different. (For convenience, and to facilitate comparison of performance with the existing stability criteria, the actual load conditions which are used are based upon values given in the vessel's stability booklet to represent the complete range of vessel capability in operational practice).

4.5.4. Independent Trial Samples

In order to be able to use the simple procedures for manipulating probabilities, which are given in Appendix A4, for risk and operability studies it is necessary to ensure that all the predicted responses (trial samples of the underlying lifetime response probability density function) are independent. This necessitates that the response obtained from one scenario shall not have been influenced by any previous responses obtained in the domain segment i.e. the response obtained should have no 'memory'.

Thus it is required to know how many independent trial samples of the underlying response distribution can be taken in each domain segment since this has an important bearing on the probabilities obtained. For this purpose an independence interval was introduced by Hutchison (1981). This 'interval' represents the minimum distance in time and/or space that a vessel must travel before the seastates (and by inference the resulting responses) can be considered independent trial samples of the underlying seastate probability density function. This is an important concept since conditional information concerning the seastate (and thus the responses obtained) at one instant strongly alters the probability distribution for seastates (responses) at nearby times or locations. The influence of the conditional data diminishes as one moves further away in time or space until eventually the underlying seastate (response) probability distribution is again dominant.

Hutchison proposed a simple form of metric for the number of independent ship exposure cycles, N:

$$N=\sqrt{(T/T_*)^2+(VT/L_*)^2}$$

where

T_* = independence period, hours

L_* = independence distance, nautical miles

T = exposure time, hours

V = average vessel speed

The independence period/distance is the time/distance required between two observations for them to be independent. These are indicated as a * symbol in figure 4.6. Further work is required in this area but values for the independence period of between 13 and 24 hours have been quoted based on some available seastate process sampling rates on a scale significant to ship routeing, Hutchison(1981). In fact a simpler measure:

$$N = \frac{Exposure\ Distance\ R}{VT_*}$$

is more appropriate if vessel speed relative to the advancing weather conditions is used.

4.6. Applied Probability Concepts

A particular vessel design which is operating in a domain segment (i.e. of a particular load condition) will have a motion response dependent upon the combination of factors route, climatology and seamanship. These factors are considered in detail in chapter 6.

It is apparent that the single trial probability of obtaining a roll response level (ϕ) is equal to the single trial probability of encountering the particular load condition, route, climatology and seamanship giving rise to the response.

Thus the single trial probability of obtaining the predicted roll response (ϕ) given the domain Location (L), Season (S) and load condition (Δ) is:

$$p^1(\phi / L S \Delta)$$

where p^1 indicates the single trial probability equal to the single trial probability of encountered seastate ($H_s^{\prime} T_m$), relative heading to waves (μ) and speed (V) given the domain location (L), season (S) and load condition (Δ) i.e.

$$p^1(\phi / L S \Delta) = p^1(\mu V H_s^{\prime} T_m / L S \Delta)$$

The value of $p^1(\mu V H_s^{\prime} T_m / L S \Delta)$ is obtained by manipulation of the component probabilities given in Table 4.3 from chapter 6.

Probability	Description
$P(L,S)$	Joint Probability of V/L location and season
$P(C,V_0/L,S)$	Joint Probability of intended course and speed given the location and season
$P(H_s',T_m,F,\Phi/L,S)$	Joint Probability of encountered significant waveheight and mean wave period, wave family spectrum and predominant wave direction given location and season
$P(H_s'/H_s)$	Probability of encountering a seastate of severity H_s'after taking avoidance action given that H_s would have been encountered if no bad weather avoidance had been attempted
$P(V,\mu/H_s',T_m,V_0,\mu_0)$	Joint Probability of new speed and new heading to waves after master's alteration in response to excessive motions caused by seastate severity and original speed and heading

Table 4.3 Component Probabilities Required in the Analysis

There are several ways of combining these probabilities but in the present study the adopted procedure is as follows:-

a) <u>For a Given Domain Segment (Δ constant)</u>:

The desired relative heading to waves μ_0, before any modifying seamanship, is given by $[\mu_0 = C - \Phi]$ where C is the course and Φ the predominant wave direction.

Now the joint probability of seastate, desired heading, wave spectrum and speed (prior to seamanship) given the location L and season S (for a given load displacement Δ) is:

$$p(\mu_0 V_0 H_s T_m / L S)$$

$$= p(C V_0 / L S) \, . \, p(\Phi H_s T_m / L S)$$

$$= \int_c p(C V_0 / L S) \, . \, p([C-\mu_0] H_s T_m / L S) \, dC$$

$$= \int_c p(C V_0 / L S) \, . \, p([C-\mu_0] H_s / L S) \, . \, p(F / L) \, dC$$

where F is the wave spectrum family member $[F=f(T_m)]$ described in chapter 6.

b) Incorporating the avoidance type seamanship, $p(H_s^{'}/H_s)$, gives after avoidance:

$$p(\mu_0 V_0 H_s^{'} T_m / LS)$$

$$= \int_{Hs} p(H_s^{'}/H_s) \cdot p(\mu_0 V_0 H_s T_m / LS)\, dH_s$$

c) Incorporating the pacifying type seamanship $p(\mu V / \mu_0 V_0 H_s^{'} T_m)$ yields the required joint probability of seastate, heading and speed (after seamanship action) given the location and season:

$$p(\mu V H_s^{'} T_m / LS)$$

$$= p(\mu V / \mu_0 V_0 H_s^{'} T_m) \cdot p(\mu_0 V_0 H_s^{'} T_m / LS)$$

This is the single independent trial probability of obtaining the predicted roll response ϕ resulting from this scenario in a given domain segment for one set of conditions. There are many such sets or combinations of conditions which must be considered.

At this stage of combining all the possible combinations the opportunity is taken to obtain directly the single trial probability of roll response ϕ exceeding the critical value ϕ_c, $p^1(\phi_c < \phi)$. To every scenario a response level ϕ is predicted, such as the expected maximum roll angle, which has a value dependent on the duration of exposure to each seastate. If a counting functional is constructed from:

$$\gamma_\phi = \begin{cases} 1 & \text{for } \phi_c < \phi \\ 0 & \text{otherwise} \end{cases}$$

the cumulative single trial probability of exceeding the critical roll angle ϕ_c in the domain segment (for a given load condition, location and season) is given by:

$$p^1(\phi_c < \phi / LS)$$

$$= \int_0^{2\pi} \int_0^{2\pi} \int_0^{\infty} \int_0^{\infty} \int_{f=1}^{f=F} p(\mu V / \mu_0 V_0 H_s^{'} T_m) \cdot p(H_s^{'}/H_s) \cdot p(C V_0 / LS) \cdot p([C-\mu_0] H_s / LS) \cdot p(F/L) \cdot \gamma_\phi$$

$$dC\, d\mu_0\, dV_0\, dH_s\, df$$

If required, further counting functionals can be added to this equation, e.g.

$$\gamma_\phi^{''} = \begin{cases} 1 & \text{for } \phi_c^{''} < \phi^{''} \\ 0 & \text{otherwise} \end{cases}$$

would give the cumulative single trial probability of roll angle ϕ exceeding ϕ_c with a roll acceleration $\phi^{''}$ exceeding $\phi_c^{''}$:

$$p^1(\phi_c < \phi,\ \phi_c^{''} < \phi^{''})$$

The number of independent trials in the domain segment is found from:

$$N = \frac{R}{VT_*}$$

where

R is the distance along the course track between entrance and exit boundaries of a domain segment e.g. distances AB, BB', B'C in figure 4.6

V is the vessel speed relative to the weather speed of advance

T_* is the independence period

Then the probability of $(\phi_c < \phi)$ in N independent trials in the domain segment is given by (Appendix A4):

$$p^N(\phi_c < \phi / LS) = 1 - (1 - p^1(\phi_c < \phi / LS))^N$$

Since the $p^N(\phi_c < \phi)$ processes are independent processes in each domain segment Δ, domain/sub-domain location (L) and season (S) the probability that ϕ exceeds ϕ_C at least once is given by:

$$p_P^1(\phi_c < \phi) = 1 - \left\{ \prod_L \prod_S \prod_\Delta \quad 1 - p^N(\phi_c < \phi / LS) \right.$$

This final expression yields the proving ground result i.e. the overall probability that ϕ exceeds ϕ_c for a lifetime of operation.

For a vessel having a mission profile which involves multiple sea, displacement and operational conditions it may be more convenient to partition the operating locations into totally separate contiguous regions. Alternatively it may be desired to extend the proving ground at a later stage. In this case the required probability is given by;

$$p^{\sum_P Q_i}(\phi_c < \phi) = 1 - \prod [1 - p_P^1(\phi_c < \phi)]^{Q_i}$$

where Q_i is the number of distinct proving-ground partitions of type i.

A worked example of the probability calculation is included in chapter 7. Quantification of the actual test-tracks used in the study is described in chapter 8.

Chapter 5

Linear Seakeeping Theory for Capsize Prediction

5.1. Introduction

"A complete mathematical description of the rolling motion of a ship in waves, taking all possible factors into account, is at present well beyond the state of the art."

Roberts (1984)

When a vessel capsizes, from whatever cause, it assumes a large angle of inclination from which it cannot recover.

In order to proceed with the probability analysis described in Chapter 4, a reliable method of predicting the magnitude of the large roll motion of a ship capsizing in waves is required. Indeed, ideally the chosen method should have the following main attributes:

- It should be capable of predicting the large capsize roll motion while taking account of the non-linearities inherent in the roll damping and restoring moments, as well as in the extreme wave excitations.
- The stochastic nature of the wave excitation and the roll response should be recognised.
- Roll, sway and yaw coupling effects must be included, particularly when considering the case of a vessel operating in following or quartering seas. Roll-sway coupling in particular leads to significant roll damping e.g. Vugts (1969).
- In addition, for risk analysis purposes, the method should take into account the various design features and operational effects such as varying displacement, speed and heading to waves as well as the effects of waves themselves.

The capability simultaneously to predict pitch, heave and surge as well as the manoeuvring characteristics of the vessel and the various capsize phenomena which were identified in Chapter 4, would enable a totally integrated approach to capsize risk assessment.

Consideration of human behaviour and fallibility as well as any exceptional circumstances such as the occurrence of freak waves or equipment failure would complete the picture.

Unfortunately such a general theory for non-linear system response to stochastic processes which is suitable for a risk analysis does not currently exist. An extensive review was made of the available methods which might be suitable for the extremely daunting task outlined above. At that time there appeared to be four main methods worthy of consideration:

1. Mathematical Simulation

2. Fokker-Planck-Kolmogorov (FPK) Method
3. Lyapunov Method
4. Linear Spectral Analysis

5.2. Theoretical Methods Available for Capsize Prediction

5.2.1. Mathematical Simulation

The most obvious approach to the problem is to use numerical simulation, thus including all relevant non-linear terms. The simulated motion history is analysed as if it were an experimental record and the resulting histogram approximates to the motion probability density function. Estimates may be made of:

1. Probability of a given roll angle being exceeded
2. Likely maximum roll angle (probable-extreme roll angle)
3. Roll angle with a certain percentage chance of being exceeded in a particular number of samples (design-extreme roll angle).

These values may be obtained by fitting an appropriate distribution, such as a double-exponential distribution, to a histogram of a number of peak (extreme) roll angles which occur in N samples e.g. Brook (1986).

The problems are exactly the same as with other methods in that the equation/s of motion for large amplitude waves and motions are unknown. It is also very expensive to perform simulations to represent several years of sea conditions.

5.2.2. Fokker-Planck-Kolmogorov (FPK) Method

This method which is not derived from linear theory is capable, in principle, of predicting the form of the response distribution for non-linear responses. The F.P.K. method, Caughey (1963), is related to the general theory of Markov processes and Roberts has introduced the concept of stochastic averaging to allow a solution with non-linear damping and restoring forces, Roberts (1982).

This approach makes certain very restrictive assumptions which devalue its worth for the proposed risk analysis procedure. For example, the conventional (single degree of freedom) roll equation is assumed valid up to the large roll angles and coupling effects, although possible in principle, would involve complex mathematics and a lengthy solution. In addition the effects of forward speed and heading can only be approximately accounted for, Roberts et al (1983). However, parametric excitation can be evaluated.

It was concluded that this Markov technique will require further development before it may be used as the <u>central</u> prediction method for the analysis. Nevertheless, for the case of a vessel at zero speed of advance in irregular beam seas, close agreement with experiment has been demonstrated when the roll damping is light, Roberts (1984).

5.2.3. Liapunov Method

The concept of relative stability, which is particularly important for small ships, can be related to Liapunov's theory of the stability of motion, Caldwell et al (1986). It can be shown that a sufficient condition of dynamic stability follows directly from a theorem on the extent of asymptotic stability using Liapunov's direct method, Odabasi (1978).

Liapunov's so-called "second" method of investigating the stability of non-linear dynamic systems, without solving the differential equation, requires the formation of a function of the state variables having a special property such that its time derivative is negative along the trajectory of the system. If such a function can be found, then it can be said that the system is stable, since it is known from the properties of the function that the energy of a stable system will decrease after a disturbance. This function is termed a "Liapunov Function", $V(x)$, and is often represented as the sum of the kinetic and potential energies of the system. Hence it can be used to determine the explicit bounds on a perturbed motion from an energy point of view.

From this is defined an energy bound as a stability margin 'M' for a system under transient excitation. This is a measure of the disturbance in the exciting force that a ship in an equilibrium state can withstand before that state becomes one of unstable equilibrium. M is defined, using a Liapunov function expressed in energy terms, as an energy bound determined in relation to the relative positions of two equilibrium points (one stable, one unstable) at which the static stability curve is intersected by a steady heeling moment. The latter is taken here to be a constant wind moment; the additional excitation could then be due to wave and/or wind gust moments.

As an example consider Figure 5.1, from Caldwell et al (1986), which illustrates the results for a vessel under a steady wind heeling moment.

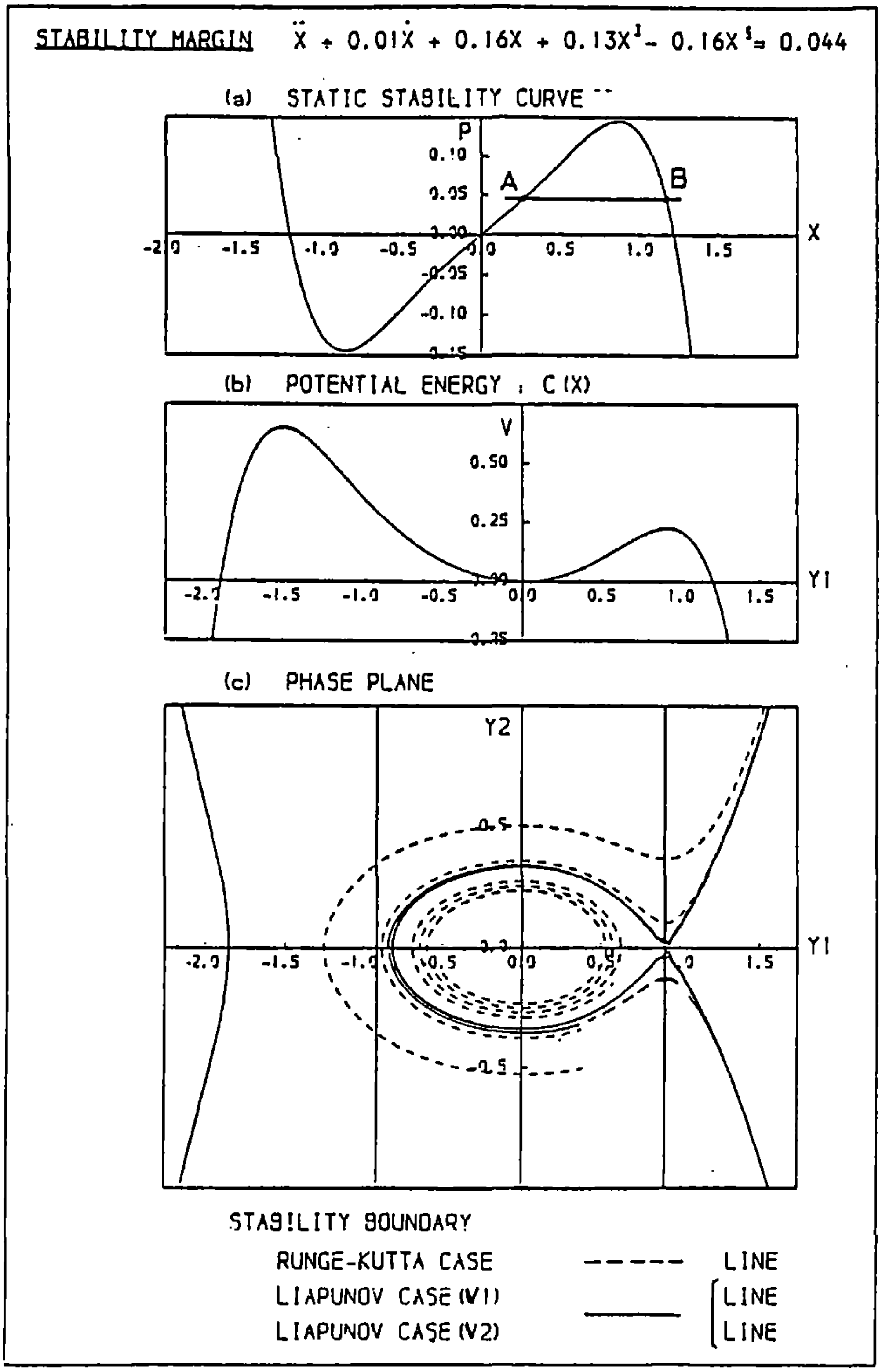


Figure 5.1 Stability Boundaries

If the single degree of freedom roll equation is, for example, that shown at the top of figure 5.1 and the static stability curve as in figure 5.1 (a), then figure 5.1 (b) is the potential energy $V = G(X)$

corresponding to any displacement $Y1$. A subdomain of asymptotic stability is drawn in the phase plane, figure 5.1 (c), in which trajectories of the motion (initiating at various positions) are shown to illustrate the usefulness of the energy bound concept in stability problems. Here the use of the two functions $V1$ and $V2$ gives similar results, which also agree closely with that obtained using a Runge-Kutta solution of the roll equation.

From the definition of marginal stability at the stable equilibrium points, the reserve of energy of the ship can be determined, using the Liapunov function, as the difference between the nearest unstable equilibrium state (B) and the stable equilibrium state (A) in figure 5.1 (a). This energy value, which is the minimum energy the system must acquire to escape from the equilibrium state, can be regarded as the reserve stability corresponding to point A. Comparison of this reserve energy with the energy of wave excitation provides a measure of the stability margin "M" for the ship at this point A on the curve i.e.

$$M = \frac{\textit{energy required to make the ship unstable}}{\textit{excitation energy}}$$

Unfortunately, mathematical stability theory also depends heavily on the equations of motion for stability assessment. In its present form it is not really suited to a probabilistic assessment of capsizing since it is mostly concerned with conditions under which an initial perturbation becomes unbounded e.g. Odabasi (1982), whereas in the present study of capsizing we are concerned with conditions under which motion exceeds a prescribed practical bound. This aspect is currently being addressed by Caldeira-Saraiva (1986). There are further drawbacks to the use of Liapunov functions, including their lack of uniqueness (giving a sufficient but not necessary condition for stability) and the absence of a general method for their construction.

However, more recently, work has been reported which is addressing the problems of non-linear damping, parametric excitation and coupling with the other modes of motion, Caldeira-Saraiva (1986), Phillips (1986). This will make Liapunov methods a very powerful tool for assessing stability of motion, once the unfamiliar methods on which the above procedure is based become understood and accepted by naval architects.

5.2.4. Linear Spectral Analysis Approach

Although extensive efforts have been made in recent years to develop a more realistic theory for rolling motion, by treating the wave input as a stochastic process, e.g. Salveson et al (1970) and Schmitke (1978), the linear spectral analysis is not really suited to predicting the large capsize roll angles. This is due to the non-linear nature of the roll damping and restoring moments with changing roll angle as well as non-linearities in the wave excitation. Since the analysis is performed in the frequency domain, certain capsize phenomena such as broaching and parametric resonance cannot be predicted - being more suited to a time-domain analysis. Unfortunately, a general theory for non-linear system response to stochastic processes, having the same scope as linear theory is not yet available.

Linear theory can include motion coupling terms together with the effects on response of underbody hull features and sectional properties and operational features such as load condition and vessel speed and heading. The importance of roll-sway coupling in following and quartering seas has already been mentioned and, in addition, the ability to (accurately) predict coupled vertical (pitch and heave) motions is important from the viewpoint of predicting excessive sea-loads and motions. For example slamming may influence the master to subsequently alter heading or speed to seek acceptable motion/sea-loading limits.

The linear approach can yield useful information on the probability distribution of roll angle (usually obtained by assuming the response is a narrow-band process) but not on extreme motions.

To summarise this review it is apparent that motion prediction methods which are available tend to either give accurate prediction of uncoupled large roll angles for an intact vessel stopped in beam seas, or else to have the scope for a risk analysis study but not the capability to predict the large roll angles. The linear superposition principle of St Denis and Pierson falls into the latter category. Whilst it can give reasonably good results for coupled pitch and heave motions the prediction of large amplitude coupled lateral motions is less satisfactory because of the inherent motion non-linearities.

5.3. Basis for the Investigation

5.3.1. Potentially Dangerous Motion

It is apparent, from the preceding discussion, that a great deal of work is necessary before large-amplitude rolling motion can be routinely and accurately predicted. The development of more advanced theory for fluid active and reactive forces that vary with amplitude, together with mathematical models describing the coupled roll-sway-yaw motions is required. This would appear likely to take a very long time.

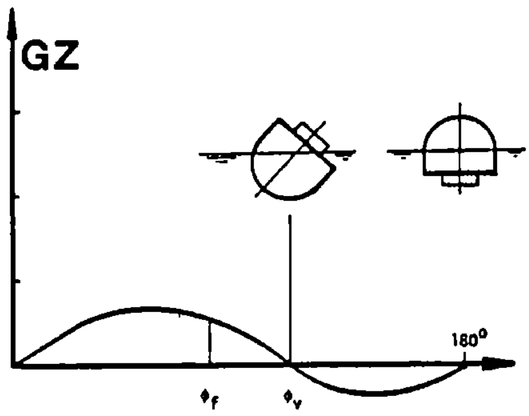
Thus a further important feature of the present analysis is that the prediction of the actual large-angle capsize is not attempted per se. Instead a lesser roll angle termed the "potentially dangerous" roll angle is selected, beyond which it is assumed that a capsize is likely. Thus the potential for disaster is being predicted rather than the disaster itself. This novel approach can be justified for the following reasons:

- Long before the vessel reaches its capsize angle there is often great likelihood of cargo shifting.
- Simultaneously there is great likelihood of water downflooding into the hull as well as water trapped on deck.
- Large changes in the hydrodynamic coefficients occur as the deck edge is immersed. Further changes occur as the superstructure becomes immersed.

The distinction is extremely important because, now, there is no necessity to describe the large motions themselves and the use of a linear theory may be defensible in certain circumstances. It is being proposed that linear theory be stretched to its prediction limits in order to estimate the occurrence of a roll motion judged to be potentially dangerous.

5.3.2. Value of Potentially Dangerous Roll Angle

For many vessels the range of statical stability, as evidenced by the GZ curve, typically takes the form indicated in Figure 5.2.



where

ϕ_f is the flooding angle

ϕ_v is the angle of vanishing stability

Figure 5.2 Typical Stability Curve

If the heel angle ϕ exceeds ϕ_v, $\phi > \phi_v$, the vessel will theoretically capsize and probably turn over to the stable position at $\phi = 180$ degrees.

If $\phi = \phi_f < \phi_v$ and the opening in question is allowing large quantities of water to flood into the hull there is no longer a case of intact stability. The further turn of events depends on several factors but the ultimate result may well be a capsizing if the ingress of water cannot be controlled, Hanssen (1982). The prospect of having to predict accurately large angle damage stability in these circumstances is extremely daunting, bearing in mind the state of the art for the intact case.

Similarly, the possibility of cargo shifting, which can be the direct cause of the capsize has great implications for accurately predicting actual capsize angles. At the present time little is known about the dynamics of cargo shifting, particularly for the case of slurry cargoes, and urgent research is required, Green et al (1981).

The angle of downflooding is considered an important factor in the regulations, Res.A167

(1968). Unfortunately the value of this parameter is unique for every vessel as are the values of roll angle/lateral acceleration which would cause cargo to shift. In addition the cargo shifting values are frequently unknown and will vary from one cargo to the next.

Thus from these considerations it was felt difficult to justify adopting a single critical roll motion based on strict analytical considerations.

The alternative was to consult with seagoing personnel in order that (possibly) some realistic subjective measure of vessel performance could be obtained based on experience. During lengthy discussions with Mr. J. Tvedt, an ex-trawler skipper active in the SAFESHIP project arena, it was concluded that attained angles of roll up to about 60 degrees (i.e. 30 degrees from the upright, Figure 5.3) were not considered too serious for the ship's safety provided that:

- openings into the vessel leading to large spaces are not submerged for too long before the vessel rights itself
- all loose objects are adequately lashed and the (fish) cargo properly pounded
- motion is not too severe for the crew, Tvedt(1983).

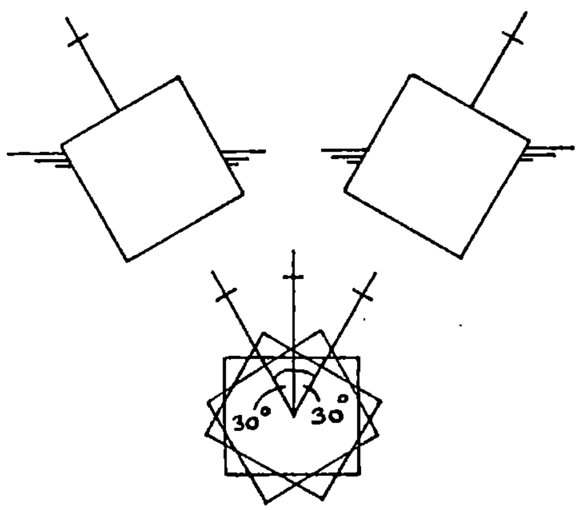


Figure 5.3 Potentially Dangerous Roll Angle

Beyond this 30 degree threshold value it was felt that there is increasing cause for concern. This was not to say that roll angles less than 30 degrees were treated with complete impunity. Indeed it was felt that there was increasing unease to the skipper and crew around the 30 degree level, although this may be compounded by the effects of lateral acceleration acting in conjunction with the roll. As the number of occurrences of roll angles greater than 30 degrees from the upright increases there is increasing cause for concern.

In these discussions no distinction was made between apparent roll values which, due to lateral acceleration, would be greater at the bridge position than in the engine room, say. Thus 30 degrees is assumed the value at the ship's centre of gravity.

For the purposes of the present work, and in the absence of solid evidence to the contrary, it was decided to make this roll angle of 30 degrees the threshold value beyond which it may be assumed that 'a large potential for danger' exists. Thus the reliability of the vessel ($R=p($capability $>$ demand$)$) is given by the probability that the attained roll angle is less than 30 degrees, $p(\phi < \phi_c)=p(\phi < 30°)$, during a lifetime of operation.

It was necessary to consider a limiting roll angle rather than a limiting roll velocity or acceleration because no references could be found which even indicate what these values might be.

5.3.3. Possible Objections to the Approach

Bishop et al (1982) presented a paper concerning the role of encounter frequency in the capsizing of ships at the 2nd international stability conference. In their rather specialist area of research, they too advocated predicting when capsizing can become a possibility using linear theory and cited the following criticisms of their approach by others:

1. that no attempt is made to describe the process of actual capsize is held to be a basic weakness of the approach;
2. since actual capsize is governed by non-linear equations it is possible that some crucially important behaviour is altogether missed by a linear analysis.

At this stage for the research investigation the author can only be reassured to some extent by the response to these questions:

1. "The first objection seems to be little more than an injunction not to try what was set out to be done".
2. "The theoretical possibility is accepted that something vital is missed. However in the apparent total absence of any solid evidence on the point the authors could do no more than keep open minds".

The next problem was to assess the suitability of using a coupled-linear system for the risk analysis. The advantage of the spectral technique for predicting the threshold value is that it can account for motion cross-coupling, varying displacements, speeds, headings to waves etc. Thus it can readily provide the necessary scope sufficient for it to be the central core of a realistic stability risk assessment, even though certain of the 'time domain' capsize phenomena will require incorporation at a later stage. A further important advantage is that the method is widely understood and is readily available to the profession.

5.4. Application of Linear Motion Theory

Previous papers have described how the operability of ocean-going vehicles and structures may be assessed using the linear superposition principle e.g. Hutchison (1981).

By predicting the magnitude of the vessel motions/sea-loads in seas which are representative of the selected operational site or route the probability of motions and loads remaining within acceptable limits, throughout a period of time sufficient to permit completion of the operation, can be estimated e.g. Hoffman et al (1978).

A valuable extension of these techniques, if viable, would be the ability to use the same linear spectral analysis techniques to assess the ultimate survivability of the marine vehicle.

The ultimate survival of the vehicle would be assessed by predicting the probability of a potentially dangerous motion being exceeded during a wholly contrived 'proving voyage' comprising a series of test-tracks, as described in chapter 4. Thus it was first necessary to consider the accuracy of linear theory for estimating the occurrence of dangerous roll motions:

5.4.1. Britsea Seakeeping Computer Programs

Britsea is one example of a strip theory computer program. The ship, which is treated as a rigid body, is represented by a number of transverse strips. Each strip is considered as a part of an infinitely long cylinder with constant cross-section, whose axis lies initially on the still water surface. Two-dimensional hydrodynamic coefficients of added mass and damping for each strip are calculated based on results by Ursell (1949a, 1949b) and Tasai (1959, 1961) for a cylinder which is executing simple harmonic oscillations in still water. Stripwise integration is used to deduce the hydrodynamics of the whole ship taking due account of speed and heading to waves.

The equations of motion for the ship in regular waves are formed by combining the added mass and damping coefficients with the forces or moments created by sinusoidal waves moving past the ship and the hydrostatic restoring forces (or moments) due to the instantaneous heave , pitch and roll of the ship. The equations are solved in two sets with the vertical plane motions, pitch and heave, assumed to be independent of the lateral plane motions, sway, roll and yaw. Interactions within each set are taken into account. The effects of appendages such as bilge keels, fins and rudders may be taken into account in the lateral motions by using empirical data e.g. Ikeda (1978).

Solution of the equations of motion yields the heave, pitch, roll, sway and yaw of the ship in regular waves of unit wave amplitude.

These so-called transfer functions are combined with wave spectrum values to give motion spectra using:

$$\Phi_R(\omega_e) = |H(\omega_e)|^2 . \Phi_\zeta(\omega_e)$$

where

$|H(\omega_e)|^2$ is the Response Amplitude Operator (RAO)

$|H(\omega_e)|$ is the Transfer Function defined as the ratio of motion amplitude to unit wave amplitude (unit waveslope for rotational motions)

ω_e is the encounter wave frequency (rad sec^{-1})

Φ_R is the response spectrum ordinate

Φ_ζ is the encountered wave spectrum ordinate

Britsea is described in detail in Appendix A1.

5.4.2. Version of Britsea used in the Analysis

The Britsea programs are commercially available from British Maritime Technology (BMT) Ltd. As originally supplied they were not suitable for research application because of their 'black-box' nature which prevented variation of all but the most frequently used parameters such as vessel speed and heading. In addition it was necessary to create five data files containing details of hull and appendages, lightship condition, compartmentation and displacement conditions for each program run. Responses were only available to a long or short-crested Pierson-Moskowitz 'seaway' and the response range was limited to RMS motion values which were presented in normalised form.

Extensive dialogue and correspondence with staff at BMT was aimed at reworking Britsea for the risk analysis, although greatest emphasis was placed on improving the quality of the lateral responses and on streamlining the programs for ease of use in order to render them more commercially attractive, Gedling (1983-1988).

Suggested improvements to the suite of programs included:

- Changes to hull definition to improve quality of hydrodynamic coefficients
- Extensions to the range of wave spectra to cover fetch-limited seas in particular
- Extensions to the range of spreading functions
- Output of wave and motion spectrum moments and spectral bandwidth
- Ability to change coordinate origin to enable de-coupling of motions
- Extend range of wave frequencies and allowable headings to waves

- Direct input of key parameters to speed up program runs
- Improvements to output to include graphics output
- Extension of results into slamming and deck wetness calculations.

In fact many of these suggestions have subsequently been incorporated into the new suite of (BMT) programs known as SEADAS , Gedling (1988).

Eventually, in August 1987, following several improvements to the quality of the lateral responses (these were checked at Plymouth against model tests and full scale trials results), a modified set of lateral response computer programs was made available to the author. The vertical pitch/heave programs were found to give reasonable predictions and were not updated. Thus it was now possible to input directly to the lateral response calculations global values of:

- Displacement
- Vertical Centre of Gravity
- Longitudinal Centre of Gravity
- Roll gyradius
- Yaw gyradius
- Metacentric height
- Bilge Keels/Fin details.

This avoided the necessity to prepare lengthy input data files for different load conditions. In addition measured roll damping values were input directly. This is an important consideration given the tendency of current strip theory programs to underestimate these values (Section 5.5.4)

For the present research purposes a post-processor program has been written at Plymouth. This uses only the basic transfer functions (amplitudes and phases) from Britsea and operates on them to derive motion spectra. These are used in further simulation routines within the main program RISK.F77 described in Chapter 7.

5.5. Correlation of Linear Motion Theory (Britsea) with Model and Full Scale Seakeeping Trials

5.5.1. F.P.V. SULISKER

The Fisheries Protection Vessel "SULISKER" has been the subject of an extensive series of full-scale seakeeping trials conducted by NMI Ltd (now part of BMT). The same ship was used for model experiments and theoretical work under the SAFESHIP project and subsequent research into ship rolling for the Department of Transport.

SULISKER is one of the newest ships in the DAFS fleet, which undertakes the fisheries protection task in Scottish waters. She was designed by Hall Russell Shipbuilders, and was built by Ferguson Brothers at Port Glasgow in 1981. She is shown shortly after commissioning in Plate 5.1.

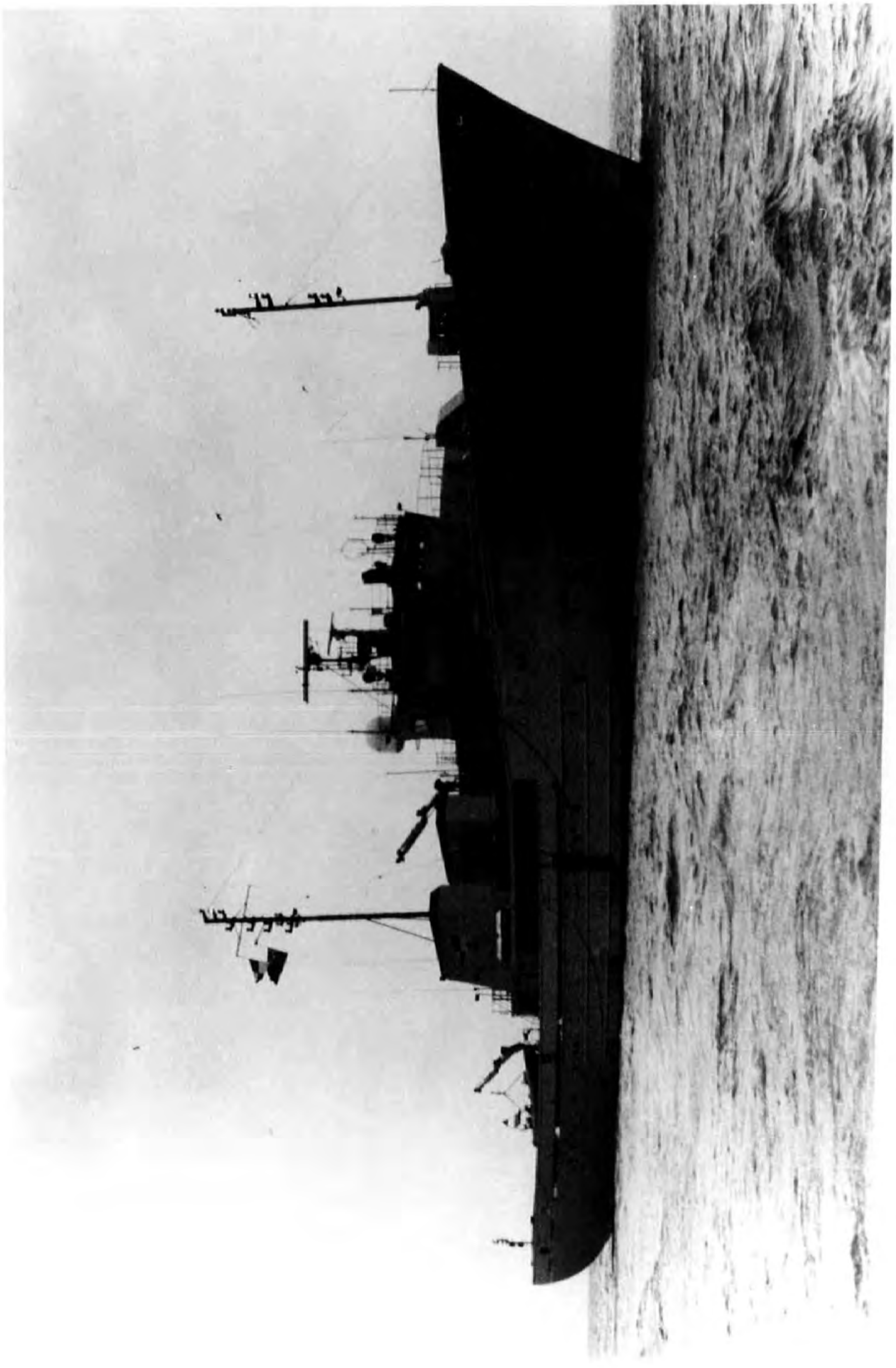


Plate 5.1 F.P.V. SULISKER

The SULISKER's principal particulars are given in Table 5.1. The ship has a 1.4 m designed rake of keel so that the zero trim condition has a 1.4 m aft keel trim. A simplified general arrangement is given in Figure 5.4. The body plan is shown in Figure 5.5. The bilge keels are 8.86m long and have a span of 0.38m. The ship is also fitted with a 0.16m deep bar keel, which runs along the length of the keel.

SULISKER has a complement of 9 officers and 14 crew. She is powered by two turbo-charged Ruston V12 diesels, with a 2820 bhp continuous rating, driving two 4-bladed Ulstein CP propellers. The shafts are supported by two large bossings and A-brackets, and the ship is steered by two large spade rudders. Her maximum service speed is 16.5 knots, with a cruising speed of 14 knots.

Length overall	71.33 m
Length B.P.	64.00 m
Beam mld.	11.60 m
Depth mld. to upper deck	7.32 m
Depth mld. to lower deck	4.95 m
Tonnage	1176.7 GRT
<u>Designed loaded departure condition</u>	
Displacement	1532.00 tonnes
Draught (full)	4.595 m
Draught (mld)	4.435 m
Trim of baseline (bow up)	0.055 m
Trim of keel (bow up)	1.455 m
KG	4.630 m
GM (solid)	0.849 m
GM (fluid)	0.778 m
LCG (aft of midships)	1.527 m
<u>Propeller dimensions</u>	
Propeller type	Ullstein twin 4-bladed CP
Diameter	2.90 m
Hub diameter	0.85 m
Mean pitch	2.66 m
Blade area ratio	0.50

Table 5.1 F.P.V. SULISKER General Particulars

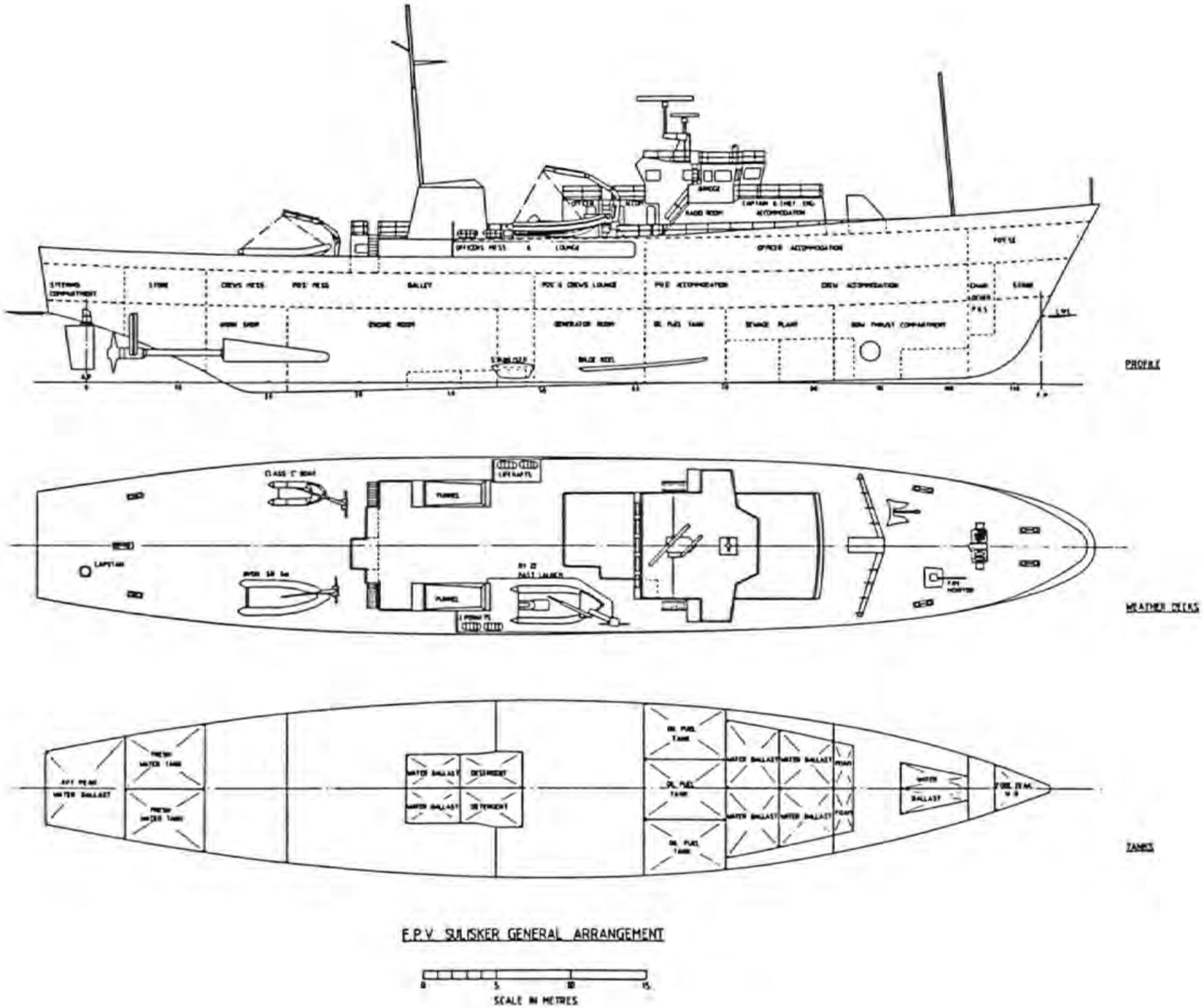


Figure 5.4 General Arrangement

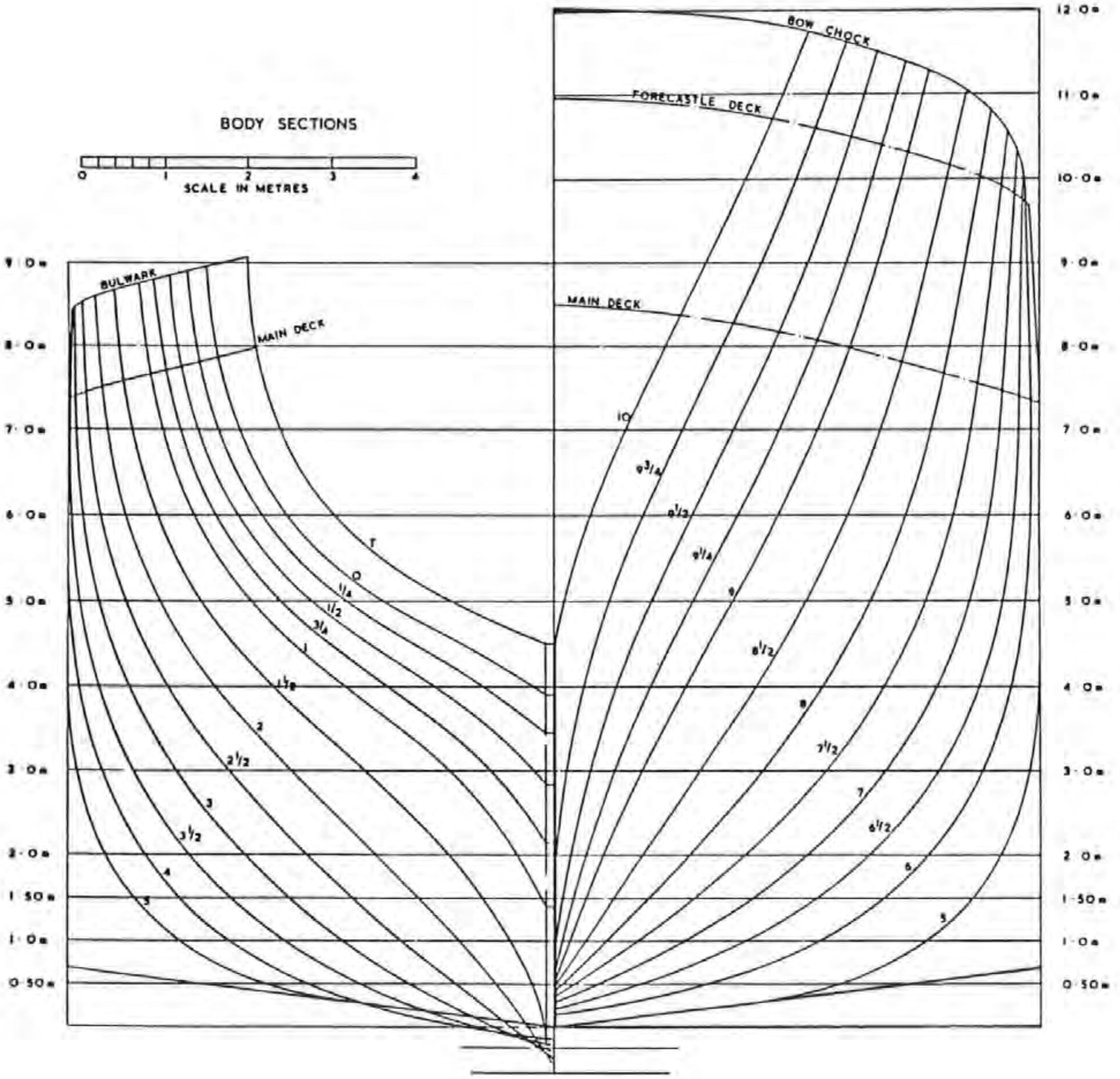


Figure 5.5 Body Plan

The GZ curve for the designed loaded condition is given in Figure 5.6. Curves are also given for three other GMs at the same displacement, which were used in the model tests.

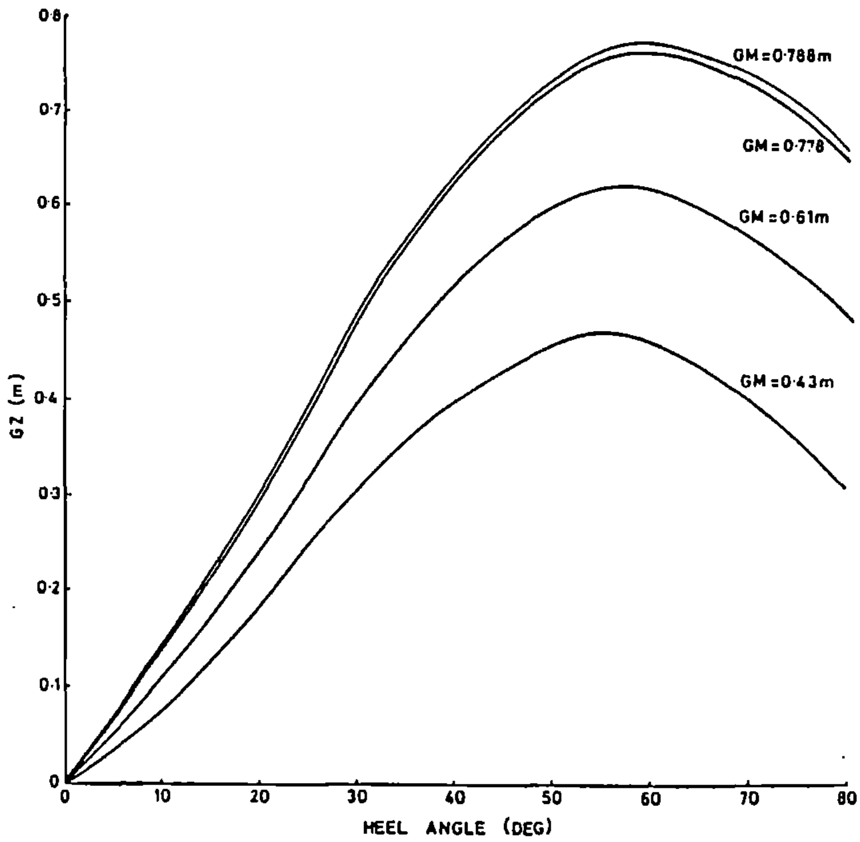


Figure 5.6 GZ Curves

The curve for the designed GM is markedly linear at low angles, and all the curves may be accurately represented up to about 30 degrees by linear plus cubic stiffness coefficients.

5.5.2. Correlation Tests

BMT Ltd has performed a series of model tests and full scale trials on the SULISKER to enable correlation of model measurement, theoretical predictions and full-scale measurements to be made for this vessel. Thus there are several sets of results available for comparison:-

- Model Scale trial in regular waves [designated 4SK-overweight, Freeman (1986]
- Model Scale trial in irregular waves [designated 4SK-overweight, Freeman (1986]
- Full scale trial in irregular seas [designated 4SK, BMT (1986a)]
- Full Scale trial in irregular seas [designated 8SK, BMT (1986b)]

The 1:30 scale model of F.P.V. SULISKER used in the rolling and seakeeping research was made to the moulded lines in figure 5.5, fitted with all appendages and ballasted to the scaled full displacement. The model was made of GRP with wooden decks. The hull was modelled up to the top of the bulwarks on the weather decks for use in the seakeeping experiments.

a) Model Scale Comparison

The 1:30 scale model that BMT used in the experiments was radio controlled and used radio telemetry to send the measured motions ashore. Speed and course were monitored using an ultrasonic tracking system.

It was not possible to obtain the same model displacement as used in both full-scale trials examined. The departure in displacement for the two trials from the achieved model condition is given in Table 5.2. The model was given the correct trim and metacentric height (equal to the ship's metacentric height including the effect of free-surfaces), and consequently had the wrong centre of gravity. The error in this is also given in table 5.2. The effect of these errors on the model motions was assessed by theoretical predictions and roll decrement tests, Freeman (1986).

		SHIP	MODEL	SCALE MODEL
Designed loaded departure condition				
Displacement	(tonnes)	1532		
Draught (full)	(m)	4.595		
Trim (bow up)	(m)	0.055		
KG	(m)	4.630		
GM (solid)	(m)	0.849		
GM (fluid)	(m)	0.778		
4SK condition				
Displacement	(tonnes)	1456	0.057	1578
Draught (full)	(m)	4.447	0.155	4.65
Trim (bow up)	(m)	0.280	0.010	0.30
KG	(m)	4.754	0.162	4.85
GM (solid)	(m)	0.723	0.02186	0.656
GM (fluid)	(m)	0.646	0.02186	0.656
8SK condition				
Displacement	(tonnes)	1500	0.057	1578
Draught (full)	(m)	4.527	0.155	4.65
Trim (bow up)	(m)	0.357	0.010	0.30
KG	(m)	4.690	0.159	4.77
GM (solid)	(m)	0.805	0.0245	0.735
GM (fluid)	(m)	0.732	0.0245	0.735

Table 5.2 Achieved Model Condition

Stationary and forward speed roll decrements were analysed by BMT (1986c) using the ROLAS suite of analysis programs, BMT (1986d), to give linear and quadratic or linear and cubic coefficients. Linear and quadratic damping coefficients used with Britsea are summarised in Table 5.3.

CONDITION	SPEED (m/s)	LINEAR COEFF K_1	QUADRATIC COEFF K_2
4SK Overweight	0	0.029	0.190
	0.3	0.039	0.186
	0.6	0.063	0.193
	0.9	0.102	0.146
	1.2	0.115	0.129
	1.5	0.115	0.126
8SK	0	0.030	0.240
4Sk Correct Disp	0	0.055	0.198

Table 5.3 Roll Damping Summary

Damped natural roll frequencies are shown in Table 5.4 which indicates a clear increase with increasing speed. Roll gyradius calculated from the GM and natural frequency values are also given in table 5.4. The roll gyradius decreases with increasing speed due to the decrease in added mass. The correct displacement 4SK condition had a roll gyradius 1.9% lower than the 4SK condition used for the forward speed tests.

CONDITION	SPEED (m/s)	GM (M)	PAIRED NATURAL FREQUENCY (rad/s)	GYRADIUS BEAM
4SK Overweight	0	0.02186	3.274	0.366
	0.45	0.02186	3.274	0.366
	0.75	0.02186	3.282	0.365
	1.05	0.02186	3.314	0.361
	1.30	0.02186	3.368	0.356
	1.40	0.02186	3.400	0.352
	1.60	0.02186	3.513	0.341
8SK	0	0.02450	3.561	0.356
4SK Correct Disp	0	0.02186	3.337	0.359

Table 5.4 Natural Roll Frequency and Radius of Gyration Results

5.5.3. Data Requirements for Theoretical Seakeeping Tests

Ideally, details of the following parameters are required for Britsea so that best accuracy may be obtained:-

a) General Particulars:

Length Overall and B.P.

Beam mld.

Block coefficient

Drafts and Trims Mld.

b) Hull Particulars:

Table of hull offsets and stem/stern profile data.

Rise of floor and half siding

Bilge keel/Fin extent

Shell plating thickness

c) Lightship Weight Distribution:

Ideally required as a weight distribution diagram, in order that the disposition of all structure can be taken account of, i.e. the program considers the lightship weight to be comprised of a whole series of 'fixed items' and the following information for each fixed item is required.

Weight

Length of the weight distribution

LCG and VCG

Distance of the after end of the fixed item from A.P.

d) Load Condition Details:

For each loaded compartment the following information is required:

Weight

VCG (Vertical centre of gravity)

LCG (Longitudinal centre of gravity)

FSM (Free surface moments)

The body sections of the ship are required at a sufficient number of stations to allow for curvature in the hull at the fore and aft ends. Manual digitisation was used to obtain sectional values of cross section area, beam, draught and vertical centre of buoyancy. Details of the weight distributions were obtained from DAFS Support Unit, Corse (1984).

This data is required to calculate the added mass and damping coefficients and also the wave exciting forces and moments in regular seas for a range of wave frequencies.

5.5.4. Results for Regular Wave Tests, Model Scale

N.B. The derived response curves for model scale and full scale trials in both regular and irregular waves are presented in Appendix A2.

BMT Ltd performed a series of seakeeping tests in regular waves on the model which was ballasted to the 4SK (overweight) condition. The model was run at 7.1 knots (full scale) at a range of 5 headings (0,45,90,135,180°) to the waves. The wave height was chosen to give reasonable motion amplitudes without significant non-linearities, Freeman (1986).

The regular wave response curves for the measured and theoretical (Britsea) roll, pitch and vertical accelerations are presented in Appendix A2, Figures A2.1 - A2.20 inclusive. Presentation is in terms of motion amplitudes for a 1 m wave amplitude. Error bars for 95% confidence limits are also indicated. Details of the error analysis are given in Freeman (1986).

Figures A2.1 and A2.2 show the effect of using empirical roll damping values on theoretical (Britsea) roll response. Peak roll amplitudes of 70 degrees and 40 degrees were obtained using Inoue roll damping and Ikeda (1978) roll damping respectively, at the natural roll frequency (0.6 rad sec^{-1}). Measured roll damping coefficients are presented in Figure A2.3. When these were used in the theoretical predictions a much better fit to the measured response values was obtained, peaking at a value of 10.4 degrees, Figure A2.4. Thus for roll motions, provided the measured roll damping values were used, good agreement between model results and theory was obtained for all headings.

The pitch theoretical results show good agreement with experiment for head and following seas. Reasonable agreement for bow and quartering seas was also obtained with most deviation from experiment at higher wave frequencies. It was demonstrated in a similar study that this discrepancy was due to differences between the model track and heading, Freeman (1986).

The measured accelerations show good agreement with theory for head, bow and beam seas although, as with the pitch results, some discrepancy due to leeway angles are present. For other headings at lower encountering frequencies the measured accelerations are greater then theoretical predictions. Freeman noted that additional errors due to shaft/motor vibration might have a significant effect on the (small valued) measured accelerations. In general bow acceleration results were closer to experiment than stern acceleration results, especially for incident waves forward of the beam.

Heave motion at amidships was calculated from the measured accelerations and these are shown in Figures A2.21 - A2.23 inclusive. Theoretical heave values using Britsea show good agreement with measured values at all headings.

5.5.5. Results for Irregular Wave Tests, Model Scale.

Freeman(1986) carried out a series of model seakeeping tests in irregular waves for the 4SK (overweight) condition. The wave spectrum used in the model tests was the idealised spectrum which most closely matched the actual wave spectra measured in the sea trials. This was the ISSC spectrum with the identical significant waveheight and modal period. A comparison with the measured trials spectra is given in Figure A2.24.

The model was run at 7.1 knots (full scale) over a range of 7 headings in both long-crested and short-crested seas (with cosine-squared spreading).

The RMS motion amplitudes for the 4SK tests are plotted against ship heading in Figures A2.25 - A2.30 inclusive. Error bars for 95% confidence limits are included on the measured data from Freeman (1986). The figures also show the Britsea theoretical predictions, for which the roll motions were obtained using the measured roll damping.

Theory and experiment for the 4SK (overweight) condition show good agreement for roll motion in long-crested waves. Theoretical predictions for pitch are in close agreement for waves on or abaft the beam and rather less agreement for waves forward of the beam (at high encounter frequencies), showing similar trends to the regular wave results previously discussed.

The accelerations are not in such good agreement. They demonstrate similar trends to the regular wave results i.e. good agreement is obtained at high encounter frequencies but high model results are obtained at low encounter frequencies (quartering waves).

The 4SK (overweight) results for short-crested waves are presented in Figures A2.29 and A2.30. The effect of wave energy spreading on responses can be seen by the increase in roll motion in head seas and the increase in pitch motion in beam seas. A large amount of scatter in the model results was noted by Freeman (1988). This is typical of predictions in short-crested waves when longer run times are required for consistent results. Again the roll results are in close agreement at all headings and the pitch results not so good, but reasonable agreement for waves abaft of the beam were obtained as for the longcrested case.

5.5.6. Results for Irregular Waves, Full Scale Trial (4SK)

The seakeeping manoeuvre 4SK was carried out on 20 September 1984 in the North Minch between the Butt of Lewis and Cape Wrath. There was a regular swell from ENE from a recent storm in the Atlantic with a wind-blown sea component running at 20 degrees to the swell direction BMT (1986a). Subsequent analysis revealed that the ship responded almost exclusively to the swell, Freeman (1986). Two wave buoys were deployed on a N-S line 1.7 miles apart, to monitor the variation in wave height that was apparent over the trials area. The degree of wave energy spreading was not monitored. A speed of 7 knots was chosen and a pattern of headings set in order to give head, bow, beam, quartering and following seas without moving too far away from the buoys, Figure A2.31. The fin stabilisers were turned off for the trial and the ship was steered manually.

The ship condition during the trial was calculated from the known state of the tanks and was given in table 5.2 (labelled "4SK" condition).

The variations in significant wave heights from the two buoys during the trial are reproduced in Figure A2.32 and the variations in wave period for buoy 1 is reproduced in Figure A2.33 (buoy 1 and buoy 2 measured periods were almost identical). Comparison of a sample wave spectrum with a theoretical (ISSC) spectrum having the same significant waveheight and modal period as the mean values is given in Figure A2.24, and demonstrates a good agreement.

Full scale results for the 4SK condition are presented in Figures A2.34 - A2.39 inclusive. Although no error bars are shown for the full scale data it was expected that they would be of a similar magnitude to the model errors, i.e. ± 10% on motions and ± 5 degrees on heading, Freeman (1986).

Despite the scatter in the results due to variations in waveheight (in particular) the 4SK full scale trials results for RMS roll, sway, pitch and heave show good agreement with theory at all headings to the waves when a cosine to the power 4 wave spreading envelope is used. Results for RMS yaw are less good and a program error is suspected to be responsible for this. Comparison of the maximum roll angle obtained on trial, taking account of duration, shows good agreement with the theoretical probable-extreme values calculated for the same time interval, Figure A2.39.

5.5.7. Results for Irregular Waves, Full Scale Trial (8SK)

Seakeeping manoeuvre 8SK was carried out on the 16th November 1984 in the North Sea 60 miles east of Peterhead. The fetch length was approximately 250 miles with water depth of 100 m. Conditions were quoted as being very rough with a gale force 8-9 wind with an associated long-crested seaway, BMT (1986b). A plan of the manoeuvre is given in Figure A2.40 and this also shows the position of the single (non-directional) wave buoy which was deployed. The ship (condition 8SK in Table 5.2) was run with the fin stabilisers off. A triangular pattern of 3 headings was manually steered to give head, beam and quartering seas and this was repeated twice at different speeds. Variation in significant waveheight and wave period for the single wave buoy is shown in Figures A2.41 and A2.42 respectively. Comparison of a sample wave spectrum with a theoretical (mean) Jonswap wave spectrum (significant waveheight 6.27m, modal period 12.22 sec.) is shown in Figure A2.43 and the fit is seen to be quite close, being more sharply peaked than a comparable ISSC spectrum (figure A2.24).

Full scale results for the 8SK condition are presented in Figures A2.44 - A2.55 inclusive. No error bars are shown but again these are expected to be of the order of ± 10% on motions and ± 5 degrees on heading, Freeman (1986). In spite of the limited amount of full scale data the RMS roll, pitch and heave results indicate close agreement with theoretical (long-crest) values for the trial speeds at the chosen headings to waves.

Comparison of the maximum roll angles obtained on trial taking account of duration are particularly encouraging when compared against the theoretical probable-extreme values calculated for the same exposure time to the seaway, Figures A2.53 - A2.55 inclusive. The largest value obtained on trial was 27.5 degrees.

5.5.8. Motion Results Summary

The results of a series of model tests and sea trials on the F.P.V. SULISKER have been compared with theoretical predictions for the same vessel using the Britsea suite of computer programs. The model tests were performed in both regular and irregular waves. The model experiments and sea trials have shown that the theory accurately predicts roll motions and heave motions to within experimental error provided that measured roll damping coefficients are used in the prediction of roll motion. Empirical formulae tend to underpredict the damping values. It should also be noted that the regular waveheights were chosen to avoid non-linearities, Freeman (1986). The theory accurately predicts the pitch motion provided the leeway angle due to wave drift is small.

The measured accelerations, particularly bow accelerations, are in good agreement with theory. Freeman reported that where differences do occur it is of a similar magnitude for all measurements and is thought to be due to the accelerometers picking up stray motion/shaft vibrations.

Wave energy spreading was not measured during the trials on the SULISKER and roll motion is particularly sensitive to this. Nevertheless the RMS roll values show good agreement when calculated using cosine to the power 4 wave spreading (4SK trial). Of course the relevance of this choice of spreading function is open to question in the absence of measured data. For the 8SK trial the seas were reported to be apparently long-crested and this is borne out by more accurate theoretical results being obtained without the spreading function.

It is worth noting that the restoring moment curve of this vessel is particularly linear up to about 30 degrees (figure 5.6). For many vessels the restoring curve is non-linear at much lower angles and consequently for these vessels the agreement between seakeeping and simulation results may not be as good for large angles of roll. However, for the SULISKER which does have a linear restoring moment curve it has been shown that, provided measured values of roll damping coefficient are used, the calculated values of probable-extreme value closely match the maximum values of roll obtained on trial. It was on this basis that the simulation was able to proceed with some degree of confidence.

Chapter 6

Important Factors for Consideration

6.1. Introduction

The approach to risk analysis, which was outlined in Chapter 4, is preferred because it enables a vessel's risk cycle to be assessed by the use of the test-track concept. This chapter is concerned with the treatment of key factors which must be included within the outlined procedure in order to facilitate the accurate determination of risk. Fundamentally each test-track reduces into the four considerations of route, climatology, seamanship and (resulting) response for any given displacement condition. These together define a particular scenario. A vessel actually encounters a large range of operational scenarios during its lifetime. Thus a consistent and plausible procedure for treating the key aspects is required so that the proposed method may be equally applicable to all seagoing vessels. Since a full treatment of these aspects is beyond the scope of this research the procedure finally adopted was governed by the desire to render it most useful for regulatory purposes (through simplification without undue loss of realism) and to provide a base for further work. In this way an acceptable stability assessment procedure might be developed to supplement the existing statical stability criteria.

6.2. Displacement Condition

Under this global heading, for convenience, may be grouped due considerations of:

a) Hull design features

b) Displacement

c) Cargo characteristics/loading condition.

a) Hull design features

This important area of the investigation is one of the most difficult to quantify. It is feasible that ultimately a form of indexing might be developed and the design parameters accounted for, possibly by the use of a semi-probabilistic procedure, Kure (1979). In this way if a vessel displays certain design features that improve its capsize resistance e.g. by the provision of bilge keels or fins to increase roll damping or has features that contribute to its recovery from the extreme roll motion e.g. by the provision of freeing ports to clear deck water, it will be "credited" within the analysis by appropriate adjustment of the partial safety factors (section 3.2). In this study the benefits of bilge keels are included within the motion prediction method and also only one vessel is being studied. For these reasons the above "semi-probabilistic" approach is noted but has not been incorporated at this time.

b) Displacement.

Variation in the loaded condition of the vessel will affect the wetted underwater surface of the hull as the draught and trim are altered. In addition different loading configurations influence the vertical and longitudinal centres of gravity, and to a lesser extent the various motion gyradii. Values of the righting levers are further influenced by the presence of free surfaces within the fuel, fresh water, ballast and cargo tanks.

Some element of poor seamanship may be present, possibly due to inexperience (or motion fatigue in the case of a fishing vessel which loads its cargo at sea), which leads to conditions of vessel stability outside of the acceptable limits.

In this study a relatively narrow range of displacement conditions is considered because the fisheries protection vessel under study has only a narrow range of load configurations, compared with say a fishing vessel, as evidenced by the vessel's stability booklet. To facilitate comparision of simulation results the load conditions actually used in the study are taken directly from the stability booklet, with the actual values of draught and trim used when deriving the hydrodynamic particulars.

c) Cargo.

Cargo shifting can be the direct cause of a capsize. It is necessary to consider the range and frequency of cargoes to be carried in order to ascertain typical loading conditions as well as to study the possible onset of a cargo shift. This latter aspect has a direct bearing on the choice of critical roll motion which should therefore ideally contain a lateral acceleration term. Unfortunately little is known about the magnitude of the critical values. While it is reasonably easy to set limit values of acceleration for cargo lashings, e.g. Varheim et al (1982), it is no simple matter to do the same for bulk cargoes, in particular those which demonstrate sliding liquefaction instability, Green et al(1981). Again it is noted that the semi-probabilistic approach may be ultimately appropriate but because the fisheries protection vessel has modes of operation more reminiscent of a naval vessel than of a merchant vessel, this aspect is not considered further since no cargo is actually transported. Although the vessel used in the study is not representative of a typical merchant vessel or fishing vessel it was felt that this disadvantage was outweighed by the large amount of full scale and model scale trials data which would enable some verification of simulation results to be made.

6.3. Route

The route embodies consideration of the geographical location (L), season (S), initial intended course (C) and initial speed (V_0). The problem of determining the route is to determine the joint probability distribution of the location, season, initial course and initial speed $p(C\,V_0\,L\,S)$. Consideration of the test-track segment being used governs the joint probability of location and season, $p(L\,S)$, where L is actually representing a distance along the vessel's intended track for which the displacement condition can be assumed constant. The test-track segment also governs the conditional probability distribution of initial course and speed given the location and season, $p(C\,V_0/L\,S)$.

Then the required probability is given by :

$$p(C\,V_0\,L\,S)=p(C\,V_0/L\,S)\,.\,p(L\,S)$$

Chapter 8 describes the database values used in the final calculation.

6.4. Climatology

Environmental demands made on the vessel are an essential element in any ship motion performance assessment, particularly when smaller vessels are being considered, Hanssen (1982). During their lifetime certain seagoing vessels will operate in a wide variety of sea areas while others will be confined to a single area. In all cases some coastal seastates will be encountered and these may be influenced by refraction and diffraction of waves by the coastline and seabed, Varheim (1982). This suggests that some differentiation by operating zone is possible and that certain vessels may be licensed to only operate in designated areas if desired. This would be an improvement on the current "blanket" regulations which take little or no account of likely areas of operation. Hogben et al (1967) divided the oceans into wave data collection areas and it is proposed that these areas could be extended and used for licensing purposes.

6.4.1. Spectral Representation of the Seaway

Since 1953, when the wave spectrum concept was first introduced to the ship design community, it has been most common to use idealised wave spectra (as opposed to measured spectra) in analytical studies of ship performance, due to their inherent simplicity and ease of calculation. These idealised spectra are used to represent the variety of shapes of wave spectra measured in the ocean which may be present at the desired sea severity. Wave spectrum formulations due to Pierson et al (1964), Bretschneider (1959) and Voznesenski et al (given in Mirskhin et al (1975)) may be used for evaluating responses in the open oceans. Alternatively, Darbyshire (1961) and Hasselman et al (1973) among others have presented spectral formulations appropriate for coastal, fetch-limited seas. In reality the shape of wave spectra observed in the seas and oceans varies considerably (even though the significant wave heights are the same). This is dependent on the geographical location, duration and fetch of wind, stage of growth and decay of a storm, and existence of swell. Because a ship encounters an infinite variety of wave conditions, which in turn significantly influence the magnitude of the response, there is some reservation on the reliability of the predicted responses unless the variability of wave conditions is reflected in the prediction technique. One way to cover the variety of spectral shapes is to develop a systematic series of wave spectra consisting of several members (called a family of wave spectra) for each sea severity. This concept of a family of wave spectra was considered by several researchers, e.g. Hoffman et al (1976), however Ochi et al (1978) derived three families of wave spectra using a statistical analysis of available data whereby each member of the family was weighted according to the frequency of its occurence. Two of these are appropriate for use with open sea areas and one is intended for use with coastal, fetch-limited sea areas, Ochi et al (1976c), Ochi et al (1977), Ochi (1979). The derivations of these wave spectral families will now be considered and the chief advantages for the present risk analysis study highlighted.

a) Two-Parameter Wave Spectrum Family.

The idea of expressing wind-generated wave spectra in terms of two parameters was first presented by Bretschneider (1959). The original spectral formulation was given as a function of the non-dimensional average wave height and period:

$$\Phi_{\zeta}(\omega)=3.437\frac{F_1^2}{F_2^2}\frac{g^2}{\omega^5}e^{-0.675(g/F_2 U\omega)} \qquad (1)$$

where

$\Phi_{\zeta}(\omega)=$ wave (frequency) spectrum

$F_1=$ non-dimensional wave height $=g\overline{H}/U^2$

$F_2=$ non-dimensional wave period $=g\overline{T}/2\pi U$

$\overline{H}=$ average wave period

$$=\frac{\int_0^{\infty}T\,.\,\Phi_{\zeta}(T)\,dt}{\int_0^{\infty}\Phi_{\zeta}(T)\,dt}$$

$\Phi_{\zeta}(T)=$ wave (period) spectrum

U = wind speed

g= gravity constant

The wind speed U in equation (1) essentially disappears and the spectrum can be expressed by two parameters, average wave height $\overline{H}$ and average wave period $\overline{T}$. If $\overline{T}$ is defined from the wave frequency spectrum then:

$$\Phi_\zeta(\omega) = 0.278\frac{\bar{\omega}^4}{\omega^5}\bar{H}^2 e^{-0.437(\bar{\omega}/\omega)^4}$$

where $\bar{\omega}$= average frequency $= \dfrac{\int_0^\infty \omega \, . \, \Phi_\zeta(\omega)\,d\omega}{\int_0^\infty \Phi_\zeta(\omega)\,d\omega}$

The spectrum can be further modified to be expressed in terms of significant wave height H_s and modal frequency ω_m. From the narrow-band spectrum assumption, in general:

$$H_s = \sqrt{8.0/\pi}\ \bar{H} = 1.60\bar{H}$$

$$\omega_m = \{(0.8)^{\frac{1}{4}}/\Gamma(0.75)\}\,\bar{\omega} = 0.77\,\bar{\omega} \qquad \text{thus}$$

$$\Phi_\zeta(\omega) = \frac{1.25}{4}\frac{\omega_m^4}{\omega^5}H_s^2\, e^{-1.25(\omega_m/\omega)^4}$$

(2)

In reality the magnitudes at the modal frequency and number of occurences in a given sea are random therefore statistical data on wave height and period are required to determine the modal period in a given sea. Wave statistics given in references by e.g. Hogben et al (1967) and Draper et al (1967) are extremely valuable for this purpose, however data for severe seas are sparse and no reliable information can be obtained. Ochi et al (1977) established the conditional probability of the modal frequency for a given significant wave height derived from statistical analysis of North Atlantic data. His results pertained to records taken at Weather Station India ($59°N, 19°W$), Draper (1967), and Weather Station Juliet ($52°N, 20°W$), Draper (1965), and to Walden's information obtained at nine weather stations (A,B,C,D,E,I,J,K and M) in the North Atlantic shown in Figure 6.1, Walden (1964).

It was found that the statistical properties of both wave height and period can be evaluated based on the log-normal probability distribution and this law appears to be valid in the range of the cumulative distributions up to 0.99 for both measured and visually observed data. This result contradicts the view held by some that the data can be better fitted by the Weibull distribution, Ochi (1976b), although Jasper obtained the same log-normal distribution result, Jasper (1956).

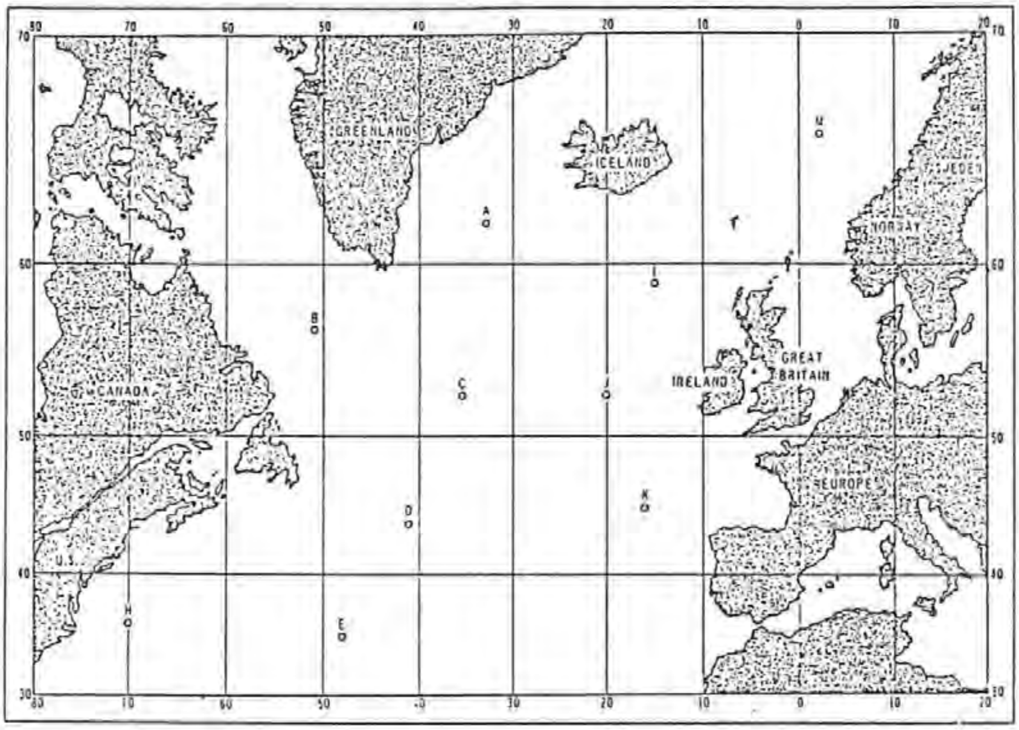


Figure 6.1 Weather Stations in the North Atlantic

A full description of the analysis method is given in Ochi (1978b) and the main results are given below. The log-normal probability distribution applicable for wave height can be written:

$$f(H_s)=\frac{1}{\sigma_{H_s}\sqrt{2\pi}H_s}e^{-\frac{1}{2}((\ln H_s-\mu_{H_s})/\sigma_{H_s})^2}$$

(3)

where μ_{H_s} and σ_{H_s} are parameters associated with the log-normal distribution of significant wave height H_s which, for simplicity, may be reduced to:

$$f(H_s) \sim \Lambda(\mu_{H_s},\sigma_{H_s})$$

(4)

Similarly for modal period:

$$f(T_m) \sim \Lambda(\mu_{T_m},\sigma_{T_m})$$

(5)

where $\Lambda(\mu_{T_m},\sigma_{T_m})$ is the log-normal probability density function with parameters μ_{T_m} and σ_{T_m}.

Since both wave height as well as wave period are log-normal distributed it can be derived that the combined statistical properties of significant wave height and modal period follow the bivariate log-normal probability law which may be written as:

$$f(H_s,T_m) \sim \Lambda(\mu_{H_s},\sigma_{H_s},\mu_{T_m},\sigma_{T_m},\rho)$$

(6)

where ρ is the correlation coefficient between wave height and period. This equation makes it possible to evaluate the joint probability of occurrence of a specified significant wave height and modal period particularly for severe seas (which is in contradiction to the statistical information given in the original data).

The conditional log-normal probability distribution gives the statistical properties of the modal period T_m for a specified significant wave height H_s i.e.

$$f(T_m/H_s) \sim \Lambda(\mu_{T_m} + \rho\frac{\sigma_{T_m}}{\sigma_{H_s}}(\ln H_s - \mu_{H_s}), \sqrt{1-\rho^2}\,\sigma_{T_m})$$

(7)

6.4.2. Derivation of family of spectra

It was mentioned in the last subsection that the joint probability of significant wave height and modal period follows the bivariate log-normal distribution of equation (6) which carries five parameters. Ochi deduced values of these five parameters $\mu_{H_s}, \sigma_{H_s}, \mu_{T_m}, \sigma_{T_m}, \rho$ at each of the weather ships mentioned earlier. He found that the results of the statistical analysis indicated the sea severities at Stations A,B,C,D,I,J, and K were not significantly different but that the severities at Stations E and M are substantially low by comparision, Table 6.1. For this reason the results of the analysis obtained from data at Stations A,B,C,D,I,J and K are averaged and refered to as the "mean North Atlantic" data.

Weather Station		A	B	C	D	E	I	J	K	M
Significant Height	μ_H	0.946	0.910	1.024	0.968	0.671	1.112	1.053	0.748	0.605
	σ_H	0.619	0.588	0.571	0.578	0.577	0.562	0.565	0.680	0.571
Modal Period	μ_T	2.505	2.462	2.494	2.483	2.415	2.588	2.594	2.600	2.516
	σ_T	0.218	0.218	0.216	0.209	0.228	0.142	0.147	0.174	0.202
Correlation Coefficient	ρ	0.498	0.594	0.578	0.586	0.508	0.358	0.339	0.331	0.686

Table 6.1 Statistical Analysis - Wave Data North Atlantic

In order to generate a family of wave spectra through the probability density function of the modal frequency given in equation (7), the modal frequency which is most likely to occur (most probable value) and the upper and lower values of modal frequency for a specified confidence coefficient were obtained:

Most probable modal period, $T_m(m)$

$$T_m(m) = exp\{\mu_{T_m} + \rho \frac{\sigma_{T_m}}{\sigma_{H_s}} (ln H_s - \mu_{H_s}) - (1-\rho^2)(\sigma_{T_m})^2\}$$

(8)

Upper and lower values of the modal period, $T_m(\gamma)$ for a given confidence coefficient γ.

$$T_m(\gamma) = exp\{\mu_{T_m} + \rho \frac{\sigma_{T_m}}{\sigma_{H_s}} (ln H_s - \mu_{H_s}) \pm c\sqrt{1-\rho^2} \quad \sigma_{T_m}\}$$

(9)

where

$$\frac{1}{2\pi} \int_{-\infty}^{c} e^{-\frac{x^2}{2}} dx = \gamma$$

Specifically:

c = 1.96 for γ= 0.95

c = 1.44 for γ= 0.85

c = 1.15 for γ= 0.75

c = 0.67 for γ= 0.50

Thus by choosing confidence coefficients of 0.95, 0.85, 0.75 and 0.50 a total of nine modal periods (including the most probable value) is determined for a specified significant wave height (Table 6.2). This table also indicates the weighting factors for each modal period from the analysis, which are applicable irrespective of sea severity.

Confidence Coefficient γ	Modal Frequency	p(F/L)
0.95	0.048 (8.75 – ln Hs)	0.0500
0.85	0.054 (8.44 – ln Hs)	0.0500
0.75	0.06 1 (8.07 – ln Hs)	0.0875
0.50	0.069 (7.77 – ln Hs)	0.1875
Most Probable	0.079 (7.63 – ln Hs)	0.2500
0.50	0.099 (6.87 – ln Hs)	0.1875
0.75	0.1 1 1 (6.67 – ln Hs)	0.0875
0.85	0.1 1 9 (6.65 – ln Hs)	0.0500
0.95	0.1 34 (6.41 – ln Hs)	0.0500

Table 6.2 Modal frequencies and spectrum weightings for a given confidence coefficent for the (mean) North Atlantic as a function of significant wave height (ω_m in radians sec^{-1}, H_s in metres). Stations E and M are not included in the data.

An example of a Bretschneider 2-parameter wave spectral family (for a significant wave height of 3m) is given in Figure 6.2.

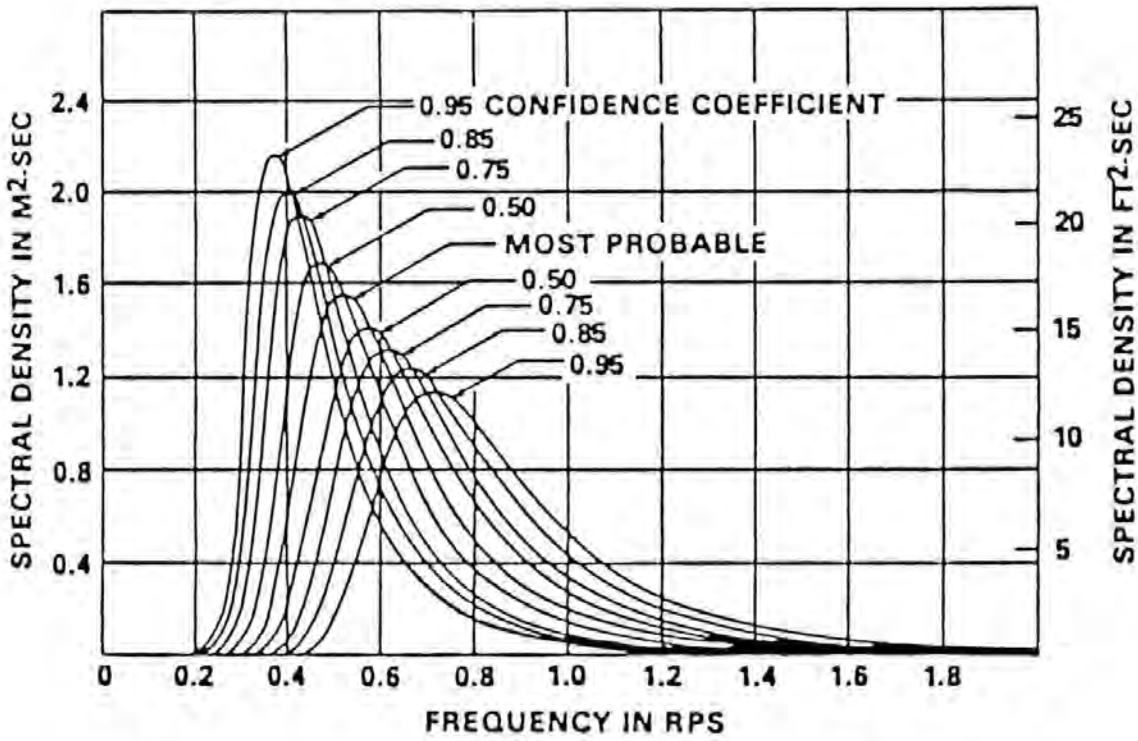


Figure 6.2 Bretschneider Spectral family, H_s = 3 metres

b) Six Parameter Wave Spectrum Family.

This family of wave spectra includes swell or (secondary peaks) in its formulation since it has been well illustrated by Hoffman et al (1976) that many measured open ocean spectra (moderate to high sea conditions) have at least two energy peaks corresponding to a local wind sea and one or more swells of distant origin. The omission of this second peak, near the natural period of some ship response mode, may cause a much larger response than that due to the primary peak to be missed. For example, in roll, a large ship will detect and respond to a long swell which may be virtually hidden to the observer's eye by a local wind sea of much larger amplitude.

In order to cover a variety of shapes of wave spectra associated with the growth and decay of a storm, including the existence of swell, a series of wave spectra involving six parameters was developed by Ochi et al (1976c).

Hoffman et al (1976) illustrated very well that many measured wave specta have a spectral shape similar to the one shown in Figure 6.3.

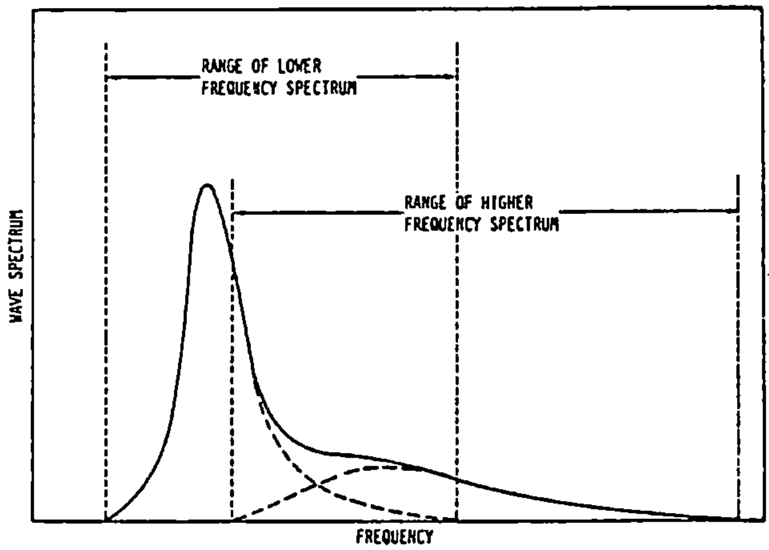


Figure 6.3 Decomposition of Wave Spectrum

Although the wave energy at the higher frequencies is usually much less than at the lower frequencies its contribution to responses of marine vehicles may be significant, thus it is highly desirable to follow the shape of the entire spectrum as closely as possible and this may be achieved by separating the spectra into two parts. Thus the wave spectrum is decomposed into components representing the lower and higher frequency contributions to the wave energy, figure 6.3.

Following Ochi et al (1976c) the spectrum of each part is expressed by a mathematical formula with three parameters - significant wave height H_s, modal frequency ω_m and shape parameter λ.

$$\Phi_\zeta(\omega) = \frac{1}{4} . ((\lambda + 0.25)\,\omega_m^4)^\lambda / \Gamma(\lambda) . \frac{H_s^2}{\omega^{4\lambda+1}} . e^{-(\lambda+0.25)\,(\omega_m/\omega)^4}$$

(10)

where $\Gamma(\lambda)$ is a gamma function.

The parameter λ controls the shape (sharpness) of the spectrum, when the other two parameters are held constant, and the spectral shape becomes sharper with increasing λ. In particular, by letting $\lambda = 1$ this equation reduces to the Bretschneider 2-parameter spectrum of equation (2). By combining 2 sets of 3-parameter spectra, one representing the low-frequency components and the other the high frequency components of the wave energy the following six-parameter spectral representation can be derived:

$$\Phi_\zeta(\omega) = \frac{1}{4} \sum_j ((\lambda + 0.25)\,\omega_{mj}^4)^{\lambda_j} / \Gamma(\lambda_j) . \frac{H_{s_j}^2}{\omega^{4\lambda_j+1}} . e^{-(\lambda_j+0.25)\,(\omega_{mj}/\omega)^4}$$

(11)

where j = 1,2 stands for the lower and higher frequency components respectively. The six parameters $H_{s1}, H_{s2}, \omega_{m1}, \omega_{m2}, \lambda_1$ and λ_2 are determined numerically such that the difference between theoretical and observed spectra is minimal.

A total of 800 available spectra observed in the North Atlantic (Bretschneider (1959) and Moskowitz et al (1962)) were classified into ten groups depending on severity and then for each group a statistical analysis was carried out on the parameters $H_{s1}, H_{s2}, \omega_{m1}, \omega_{m2}, \lambda_1, \lambda_2$ in equation (11).

Table 6.3 indicates the values of these parameters, for the family consisting of eleven members, expressed as functions of significant waveheight.

	H_{s1}	H_{s2}	ω_{m1}	ω_{m2}	λ_1	λ_2
Most Probable Spectrum	$0.84\ H_s$	$0.54\ H_s$	$0.70\ e^{-0.046\ H_s}$	$1.15\ e^{-0.039\ H_s}$	3.00	$1.54\ e^{-0.062\ H_s}$
	$0.95\ H_s$	$0.31\ H_s$	$0.70\ e^{-0.046\ H_s}$	$1.50\ e^{-0.046\ H_s}$	1.35	$2.48\ e^{-0.102\ H_s}$
	$0.65\ H_s$	$0.76\ H_s$	$0.61\ e^{-0.039\ H_s}$	$0.94\ e^{-0.036\ H_s}$	4.95	$2.48\ e^{-0.102\ H_s}$
	$0.84\ H_s$	$0.54\ H_s$	$0.93\ e^{-0.056\ H_s}$	$1.50\ e^{-0.046\ H_s}$	3.00	$2.77\ e^{-0.112\ H_s}$
	$0.84\ H_s$	$0.54\ H_s$	$0.41\ e^{-0.016\ H_s}$	$0.88\ e^{-0.026\ H_s}$	2.55	$1.82\ e^{-0.089\ H_s}$
0.95 Confidence Spectra	$0.90\ H_s$	$0.44\ H_s$	$0.81\ e^{-0.052\ H_s}$	$1.60\ e^{-0.033\ H_s}$	1.80	$2.95\ e^{-0.105\ H_s}$
	$0.77\ H_s$	$0.64\ H_s$	$0.54\ e^{-0.039\ H_s}$	0.61	4.50	$1.95\ e^{-0.082\ H_s}$
	$0.73\ H_s$	$0.68\ H_s$	$0.70\ e^{-0.046\ H_s}$	$0.99\ e^{-0.039\ H_s}$	6.40	$1.78\ e^{-0.069\ H_s}$
	$0.92\ H_s$	$0.39\ H_s$	$0.70\ e^{-0.046\ H_s}$	$1.37\ e^{-0.039\ H_s}$	0.70	$1.78\ e^{-0.069\ H_s}$
	$0.84\ H_s$	$0.54\ H_s$	$0.74\ e^{-0.052\ H_s}$	$1.30\ e^{-0.039\ H_s}$	2.65	$3.90\ e^{-0.085\ H_s}$
	$0.84\ H_s$	$0.54\ H_s$	$0.62\ e^{-0.039\ H_s}$	$1.03\ e^{-0.030\ H_s}$	2.60	$0.53\ e^{-0.069\ H_s}$

Table 6.3 Values of six parameters given as
f (significant wave height (m))

The weighting factor for each member of the family, the probability of the wave family member occuring given the location, is $p(F/L)=0.50$ for the most probable spectrum and 0.05 for all other spectra. These values arise from the derivation of the parameters which is detailed in Ochi et al (1976c). An example of a 6-parameter wave spectrum family is given in Figure 6.4. This family covers a wider variety of spectral shapes than other commonly used spectra and the co-existence of swell and sea waves is admitted by the presence of spectra with double peaks.

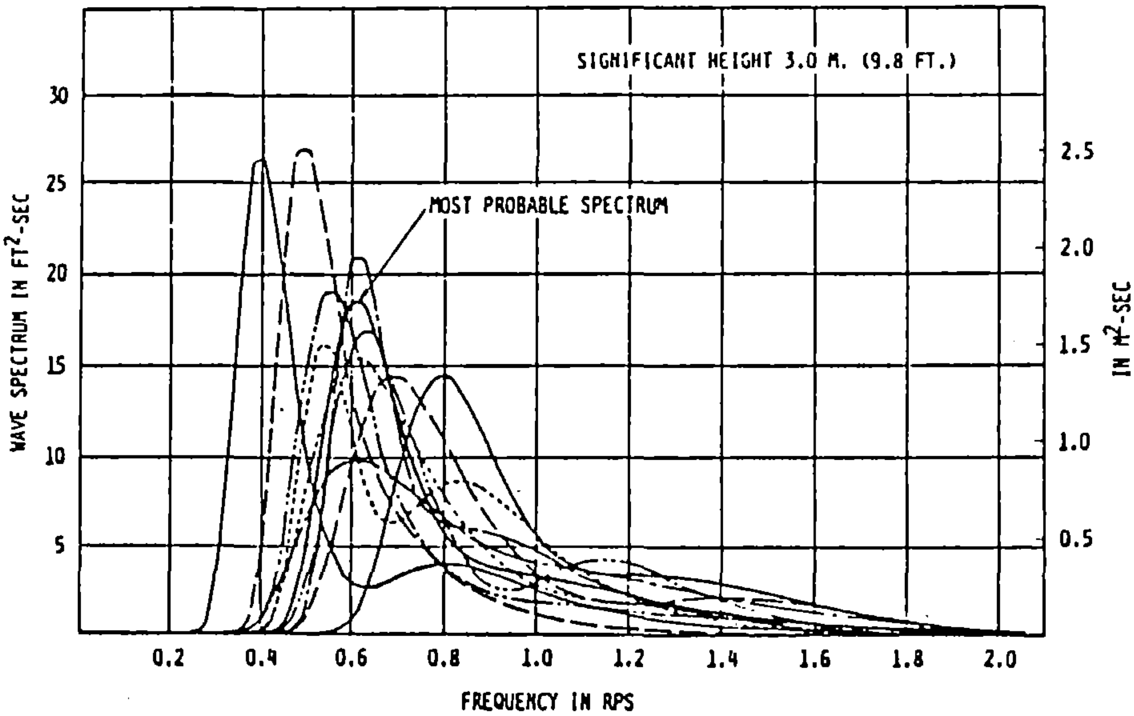


Figure 6.4 Ochi 6-Parameter Wave Spectrum Family, H_s=3m

c) JONSWAP Wave Spectrum Family.

A similar analysis has been performed for a family of JONSWAP wave spectra, which are suitable for fetch limited seas, to cover the variation in expected spectral shape.

The original JONSWAP spectrum was derived from the analysis of data observed in the North Sea and was given by:

$$\Phi_\zeta(\omega) = \alpha \cdot \frac{g^2}{\omega^5} \cdot e^{-1.25(\omega_m/\omega)^4} \cdot \gamma^{(\omega-\omega_m)^2/2\sigma^2\omega_m^2}$$

-Hasselman et al (1973)

where

γ is the peak shape parameter [3.30]

$\sigma = \sigma_a$ for $\omega \le \omega_m$ [0.07]

$\sigma = \sigma_b$ for $\omega > \omega_m$ [0.09]

α is the scale parameter [$0.076(X)^{-0.22}$]

ω_m is the modal frequency [$7\pi \frac{g}{U}(X)^{-0.33}$]

ω is the wave frequency (rad sec^{-1})

$$X = \frac{g \cdot FL}{U^2}$$

FL is the fetch length

U is the wind speed.

Values in brackets [-] are the average values for each parameter and the resulting spectrum is called the mean JONSWAP spectrum. The peak shape parameter was found to vary considerably in the JONSWAP measurements. Ochi (1979) showed that the histogram of the γ values follows the normal probability law and hence various γ values with appropriate weighting factor were determined, Table 6.4. The peak shape parameter is defined as the ratio of the maximum spectral energy to the maximum of the corresponding Pierson-Moskowitz spectrum (1964) for the same α and ω_m value, Figure 6.5. Figure 6.5 also shows an example of the resulting family of 5 JONSWAP wave spectra for the severest seastate expected at station N-2 in the North Sea. It can be seen that the range of modal frequencies is smaller and the peaks are much sharper for the JONSWAP family than for the open-sea spectral families.

γ -Value	Weighting Factor
1.75	0.081
2.64	0.256
3.30 (Mean JONSWAP)	0.326
3.96	0.256
4.85	0.081

Table 6.4 γ-Value and Weighting Factor for the Jonswap Family of Wave Spectra

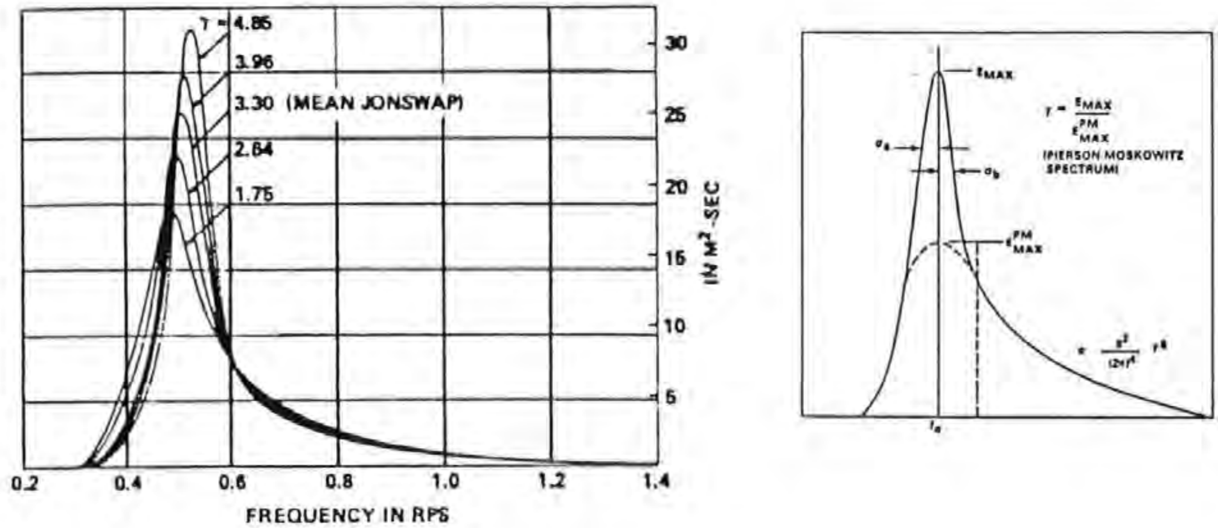


Figure 6.5 Family of JONSWAP Wave Spectra,
Severest Sea at Station N-2 in the North Sea

6.4.3. Notes on the adopted seastate definition

This study uses families of wave spectra which are appropriate for both open-sea and fetch-limited sea conditions. The ability to represent a variety of spectral shapes which would be expected to occur in nature, by a mathematical representation which is based upon statistical considerations of actual data, is held to be an important feature of the simulations.

In addition, by using the two-parameter, the six-parameter, or the Jonswap family of spectra for the short-term response prediction for each sea severity, one of the family members yields the largest response, while another yields the smallest response with a confidence coefficient of 0.95. Hence by connecting the points obtained in each sea severity the upper and lower bound responses can be established.

Ochi and Bales (1977) have shown that the upper and lower bounds (with a confidence coefficient of 0.95) of responses for the Bretschneider 2-parameter and Ochi 6-parameter spectral families reasonably well cover the variation of the magnitudes computed using the spectra measured at various oceanographic locations around the world, although in seas of great severity the 2-parameter family results in a wider range between upper and lower bounds. For this reason the use of Ochi 6-parameter spectra was favoured in the present study.

Figure 6.6 is a typical result presented by Ochi and Bales (1977). It shows probable-extreme values of the pitch motion of a conventional displacement ship in head seas using both measured and (bounds of) idealised spectra. The plus marks on the figure represent predicted pitch motions using the measured spectra reported by Hoffman et al (1977) for Station India in the North Atlantic. It can be seen that agreement with results for the measured spectra is generally good, though calculated results may be somewhat low for wave heights of 15 feet (4.6 metres) or less.

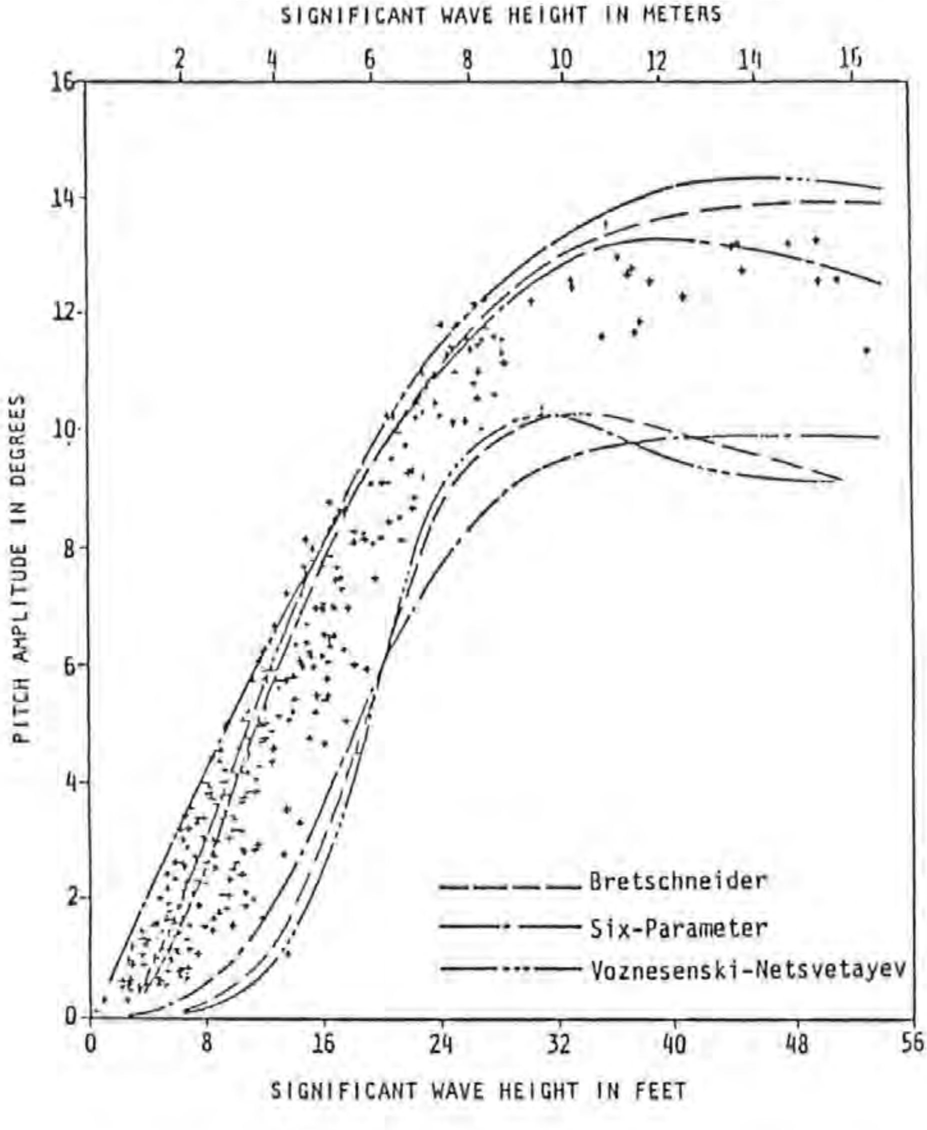


Figure 6.6 MARINER probable-extreme pitch amplitudes in head seas

6.4.4. Wave Energy Spreading

The directional nature of wave energy must be taken into account, since the use of uni-directional seas in performance prediction is known sometimes to bias design considerations e.g. Cox et al (1977). A complicating factor is the relatively wide directional distribution of wind seas and the usually narrower directional distribution of swells. In general for lower seastates there is a mix of directional components. As the seas intensify, usually a single primary direction is noted, though it is not generally as symmetric as that represented by the cosine-squared function, Bales (1984).

There is some evidence that storm seas are confused and short-crested, derived from a limited number of visual (aerial) observations and directional measurements of the sea, Forristall et al (1978). However it is unlikely that the seas are symmetrically defined and at a dispersion of ±90 degrees, since the effect of land mass to one side of the operating area or the presence of swell from a distant or locally decaying storm would perturb the symmetry of the cosine-squared model. Bales et al (1982) presented the analysis of the relative contributions of energy from each 30 degree band during a storm near Station India (59 deg. N,19 deg. W) in the North Atlantic. These contributions were computed from the 20 year hindcast climatology which is being developed by the U.S. Navy, Lazanoff (1975).

Bales concluded that the cosine-squared spreading function may be an adequate model for the North Atlantic near Station India, although the use of $\cos^2$ spreading with the Bretschneider 2-parameter spectrum generally gave over-predicted responses compared with the hindcast responses, Bales et al (1982). This over-prediction was heavily dependent on the type of vessel being considered. It was also suggested that the $\cos^2$ spreading function should be used with the JONSWAP wave spectrum for fetch-limited seaways until the data improves.

Roll motion is highly sensitive to wave direction. Figure 6.7 gives a comparison of roll motion for long and short-crested seas for the SULISKER. There is a distinct variation in roll motion over ship-to-wave relative headings in long-crested and short-crested seas. This has clear implications for the accurate assessment of extreme roll motion probability.

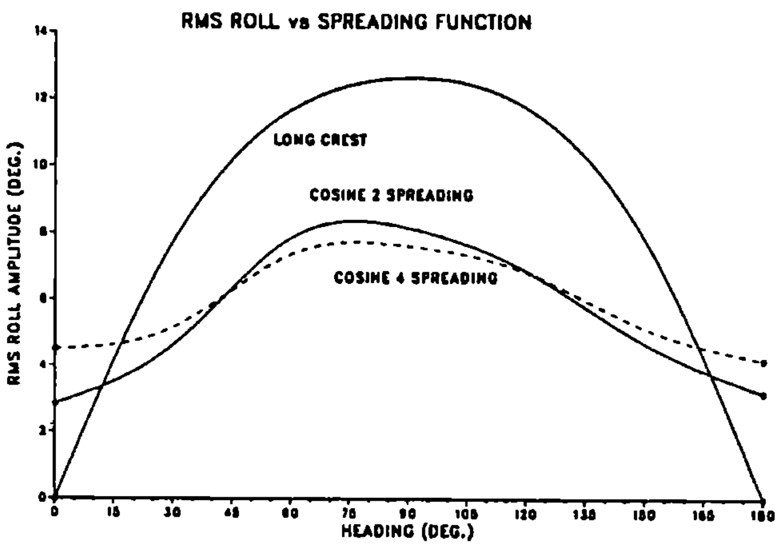


Figure 6.7 Comparison of Roll Motion For Long/Short-Crested Seas

6.4.5. Climatology Probability Aspects

It is required to determine the conditional probability of significant waveheight (H_s), modal period (T_m) and predominant wave direction (Φ) given a location (L) and season (S) i.e.

$$p(H_s T_m \Phi / LS) = p(H_s \Phi_m / LS) \,.\, p(T_m / H_s L)$$

However, because the spectral weighting for a wave spectrum family member (F) is a function of modal period, we may write:

$$p(H_s T_m \Phi / LS) = p(H_s \Phi / LS) \,.\, p(F / L)$$

The necessary climatological data $p(H_s \Phi / LS)$ are to be found in many sources e.g. Hogben et al (1967), Andrews et al (1983). An extensive database, which is convenient and contains climatological data for different geographical areas and seasons, is documented in Bales et al (1982), and this has been used in the present study:

6.4.6. Spectral Ocean Wave Model (SOWM)

The Spectral Ocean Wave Model (SOWM) is based on the work of Pierson et al (1964) who produced an empirical deepwater model providing a prediction of the directional wave spectrum for locations called grid points spread throughout the northern hemisphere. Numerical predictions are based upon the driving wind field, the prediction from the previous time step and the propagation of energy into the area from distant storms.

The open ocean spans the North Atlantic from the latitudes of the northeast Trade Winds (up to about 30 deg. N) through those of the prevailing westerlies (30 deg. - 60 deg. N) and into the Polar northeasterlies (above 60 deg. N), so that it is not surprising that the climatology of the operational area is strongly a function of latitude. Additionally the influence of land mass, currents, continental shelf, and local storm tracks each cause a similar climatology variation with longitude. Hence the open ocean area has been subdivided into sub-areas which are identified in Figure 6.8.

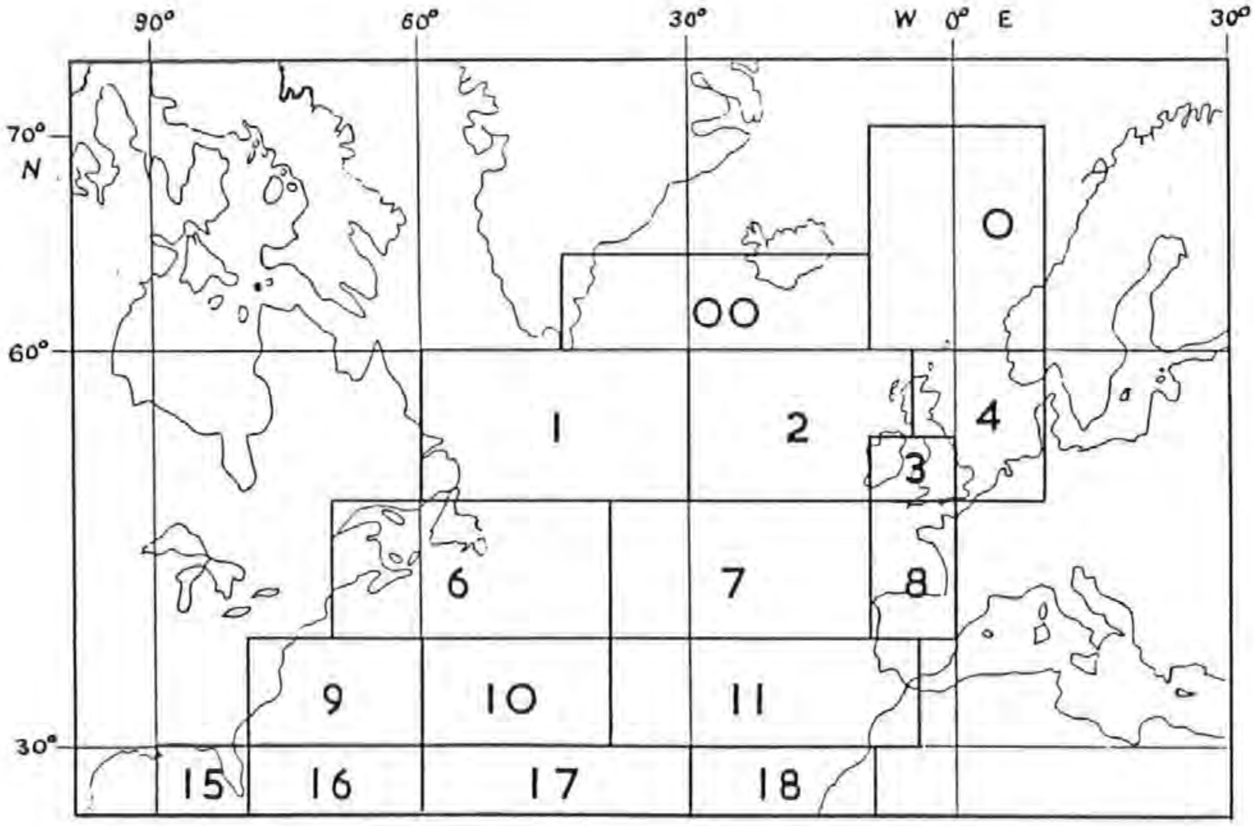


Figure 6.8 Definition of Representative Areas in the North Atlantic Basin

Because of the previous wide usage of the wave statistics provided by Hogben et al (1967) it was decided to adopt their definition of geographic zones where possible. Areas 1,2,3,4,6,7,8,9,10 and 11 are taken as defined by Hogben et al. Areas 15,16,17 and 18 are also taken as defined by Hogben et al but truncated at the Tropic of Capricorn (23 deg N). Areas 00 and 0 are new and have been added to span the more northerly operational regions.

The Spectral Ocean Wave Model (SOWM) utilizes archived wind fields from which directional wave spectra are hindcast at approximately 15000 locations at 6 hourly intervals for a continuous period of up to 18 years, Bales et al (1984). The propagation of wave energy from one location to another is reflected as well as the growth and decay of the seaway with local winds. A typical hindcast spectrum is given in Table 6.5. From the set of such spectra a series of parameters are derived which provide a simple summary of the character (height, period and direction) of the seaway and which can be used to define families of representative wave spectra. As the wind speed and direction is carried along with the data set, the joint probability of wind and wave parameters are also constructed.

WAVE FREQUENCY

DATETIME: 9Z 31 MAR 68

LOCATION: 58.292N 12.297W

WIND DIRECTION AND SPEED, WHITE CAP PERCENTAGE, FRICTIONAL WIND VELOCITY: WIND DIR 267.6 WIND SPD 22.6 WHITE CPS 0 USTR .89

FREQ IN HZ	.308	.208	.158	.133	.117	.103	.092	.081	.072	.067	.061	.056	.050	.044	.039		DIR (FROM)
	.00	.00	.01	.00	.00	.01	.00	.02	.06	.00	.00	.00	.00	.00	.00	.1	6.58
VARIANCE ENERGY	.03	.08	.15	.15	.17	.07	.00	.03	.00	.00	.00	.00	.00	.00	.00	.7	336.58
	.05	.15	.27	.25	.30	.22	.01	.04	.00	.00	.00	.00	.00	.00	.00	1.3	306.58
	.06	.21	.38	.38	.56	.42	.31	.00	.00	.00	.00	.00	.00	.00	.00	2.3	276.58
	.06	.19	.34	.30	.40	.06	.18	.11	.00	.00	.00	.00	.00	.00	.00	1.6	246.58
	.04	.12	.19	.14	.14	.00	.01	.03	.00	.00	.00	.00	.00	.00	.00	.7	216.58
POINT SPECTRUM	.24	.75	1.34	1.22	1.67	.78	.51	.23	.06	.00	.00	.00	.00	.00	.00	6.7	WAVE DIRECTIONS
																TOTAL ENERGY	

H1/3 10.35 FT — SIGNIFICANT WAVE HEIGHT

Table 6.5 A Typical SOWM Wave Spectrum

The parameter sets developed from the hindcast spectra are:

1. Significant wave height vs modal wave period.
2. Significant wave height vs wind speed.
3. Significant wave height vs primary wave direction**.
4. Wind speed vs wind direction.
5. Significant wave height vs wind speed (WMO).
6. Persistence of significant wave height.
7. Persistence of significant wind speed.

** Values used in this study.

Both annual and seasonal distributions are provided. Partial verification of SOWM has been carried out, Cummins et al (1980) and Chen (1979), which appears to indicate a reasonable standard of accuracy, although the hindcasting methods on which it is based have been criticised by oceanographers because they do not take account of the wave/wave interactions which play an important role in wave spectral development. It is difficult to develop a general conclusion regarding the validity of these results for all conditions and ocean regions. However, statistical comparisons with other data sets generally indicate good correlation and the U.S. navy has adopted SOWM data as a design standard since 1981, Bales (1986).

6.4.7. Frequency of Encounter with Extreme seas

Information of the frequency of encounter with seas for each sea severity is necessary in order to evaluate the extreme responses. This information on the frequency of occurence of each sea state may be obtained from hindcast (SOWM) data as previously described. Ochi (1978b) has shown that the occurence of sea severities can be obtained based on the log-normal distribution for the cumulative distribution up to about 0.99 and then the asymptotic extreme distribution is used for estimating the frequencies of extreme seas. On this basis the frequency of occurence of various sea states in the (mean) North Atlantic is presented in Table 6.6 for each one-metre interval of significant waveheight (H_s). Information from Ochi (1978b).

Significant Wave Height (in Meters)	Frequency of Occurrence	Significant Wave Height (in Meters)	Frequency of Occurrence
< 1	0.0503	9 - 10	0.0079
1 - 2	0.2665	10 - 11	0.0054
2 - 3	0.2603	11 - 12	0.0029
3 - 4	0.1757	12 - 13	0.0016
4 - 5	0.1014	13 - 14	0.00074
5 - 6	0.0589	14 - 15	0.00045
6 - 7	0.0346	15 - 16	0.00020
7 - 8	0.0209	16 - 17	0.00012
8 - 9	0.0120	17 <	0.00009

Table 6.6 Frequency of Occurrence of Seastates

6.5. Seamanship

This factor can have a large influence on both the motion probabilities obtained and the motions themselves once the severe seastates have been encountered. Firstly, by manoeuvring to avoid a storm area or (in the case of small vessels in particular) by not sailing at all until the storm has passed, the vessel is exercising avoidance seamanship. This is a function of the accuracy of weather forecasts and the skill of the ship's officers. Secondly, a vessel experiencing excessive motions and sea-loads may be manoeuvred to reduce these to perceived acceptable levels. The vessel is exercising what might be termed pacifying seamanship which is a function of the motion/sea-loads information available to the ship's officers and their skill in reducing these motions and sea loads.

Avoidance type seamanship can be represented by a Markov mapping, Hutchison (1981) i.e. $p(i/j)$ - the probability of encountering each seastate in the absence of avoidance seamanship to the probability of encounter with avoidance seamanship. An example transition matrix $p(H_s'/H_s)$ is given in Table 6.7 where H_s' is the seastate encountered after avoidance action and H_s the seastate which would have been obtained in the absence of avoidance action.

Encountered seastate after avoidance seamanship H_s'	Seastate which would have been encountered H_s: 1	2	3	4	5
1	1.0	0	0	0	0
2	0	1.0	0.2	0	0
3	0	0	0.8	0.5	0.1
4	0	0	0	0.5	0.6
5	0	0	0	0	0.3
	1.0	1.0	1.0	1.0	1.0

Table 6.7 Avoidance Seamanship Transition Matrix

Pacifying seamanship consists primarily in changes of speed and/or heading once a severe seastate has been encountered. These can be represented as conditional properties of speed V and relative heading to waves μ given the seastate actually encountered after appropriate avoidance $(H_s' T_m)$, unaltered speed V_0 and relative heading μ_0 i.e. $p(\mu V / \mu_0 V_0 H_s' T_m)$ where μ_0, μ are functions of the ship course C and wave direction Φ.

The achieved speed V and heading μ for each case of encountered seastate $(H_s' T_m)$ and initial speed V_0 and heading μ_0 may be assembled from a pair of transition matrices:

$(V / \mu_0 V_0 H_s' T_m)$ and $(\mu / \mu_0 V_0 H_s' T_m)$

i.e.

$$p(\mu V / \mu_0 V_0 H_s' T_m) = p(\mu / \mu_0 V_0 H_s' T_m) \cdot p(V / \mu_0 V_0 H_s' T_m)$$

Ship speed in a seaway comprises the involuntary speed reduction due to the added resistance and reduced propulsive efficiency in waves together with the voluntary speed reduction due to the master's action to reduce excessive motions and sea-loads. The present study is primarily concerned with higher seastates where the master's voluntary action overrides any consideration of natural speed reduction. Thus added resistance is not accounted for within the simulations. This is an area requiring further refinement.

The problem of voluntary change of speed/heading criteria to reduce motions and loads is no less difficult. It is inevitable that any proposed criteria will be subjective and based upon the master's previous experience. They will also depend upon how well the master perceives the motions and sealoads from his conning position, and will also be vessel dependent.

Once the criteria have been agreed, a more objective response from the master should be possible when suitable instrumentation is provided to indicate the motions and loads being imposed, together with suggested optimum courses of action to reduce these to acceptable levels, Chazal (1980).

In the meantime, and for the purposes of the present study, it has been necessary to assign a set of criteria which it will be assumed the master will adhere to in order that his vessel will be rendered more seakindly. The master is likely to take action to avoid damage to his vessel's structure, engines or cargo and to avoid undue discomfort to his passengers and crew. There have been several studies with both merchant and warships including Aertssen (1966), Kehoe (1973), Bledsoe et al(1960) and Conolly(1975) into limiting-motion criteria for different types of vessel. Several of the proposed criteria suffered from the drawback that they could not be readily assessed from the master's conning position and were also not relevant to the environment being experienced by the crew. For example Conolly (1975) proposed a criterion based upon slamming at 0.2 Lbp abaft the fore perpendicular and Aertssen (1966) used the amplitude of acceleration at the fore perpendicular. To address these deficiencies LLoyd et al (1977) proposed the following measures of ship behaviour in connection with predictions of voluntary speed loss in rough weather:

i) Slam-induced whipping vibration acceleration at bridge not to exceed 0.05 g in a 15 minute sampling period.

ii) Subjective motion magnitude (SM) weighted according to personnel location and averaged along the ship length not to exceed a value of 15.

iii) Average deck wetness interval at F.P. to be not less than 100 secs.

iv) Average propeller emergence interval to be not less than 30 secs.

The actual estimates for the limiting conditions were based on seakeeping trials with destroyers, Kehoe(1973), and the cargo ship "JORDAENS", Aertssen (1966).

The slamming criterion (i) has been subsequently amended because it is possible, by using the original criterion, to apparently improve the seakeeping performance by moving the bridge to the region of a node where there is no whipping response and thus no speed limitation. The amended slamming criterion refers to the "average whipping acceleration experienced over the entire ship" which should not exceed 0.18g and is based on full scale trials with 2 frigates, Andrew et al (1981). Aertssen meanwhile, in the discussion to this paper proposed a value of 0.20 g for the bridge whipping acceleration based on trials with the trawler "Belgian Lady", Aertssen (1965).

The Subjective Motion Magnitude (SM) concept attempts to quantify the motion environment within the ship experienced by the crew and to relate this to the human response to motion, Lloyd et al (1977). The original concept was proposed by Schoenberger (1975).

Subsequent full scale trials and results of questionaires have borne out the original proposed SM Value of 12-15 over a 12 hour period in head seas and it is therefore expected that higher values might be tolerable in the short term. It is generally agreed that a subjective magnitude criterion should not be based solely upon vertical accelerations in head seas but that rolling and lateral plane motions should also be accounted for in one single SM value if possible. It was reported by Lloyd et al (1985) that Hosoda et al (1983) have proposed a method based on reliability engineering techniques. By treating the human being as a series system an overall "human effectiveness"was obtained by multiplying individual effectiveness appropriate to each motion level being experienced. Baitis et al (1984) have also reported studies to determine criteria for limiting motions based on vertical-with-lateral forces though few details were available.

The average deck wetness interval has been changed to 40 seconds following full scale trials although this figure takes no account of sensitive equipment or men on deck, Lloyd (1981).

The above represents a great deal of ongoing work which, for the reasons outlined, are inconclusive except for some particular full scale trials results, which were obtained mostly with 2 frigates. For this reason the limiting motion criteria in Table 6.8 will be assumed in the present study.

Criterion	Fisheries Protection (64m)	Stern Trawler (58M)
No of slams	60 per hour	60 per hour
SM *	12	15
No of deck wetness +	90 per hour	90 per hour
No of propeller emergences	120 per hour	120 per hour

Table 6.8 Limiting Motion Criteria Used in the Study

(All of these values reflect the calculation assumptions and do not therefore necessarily reflect the physical situation observed).

N.B. For this length of vessel slamming whipping is not considered a problem. A slam is deemed to occur when the impact velocity exceeds 0.093 $(g/L)^2$, Ochi (1973a).

* Especially relevant in a survivability study when the master will tend to keep the seas on the bow if possible.

+ Method of calculation takes no account of distortion by hull of incident waves nor static/dynamic swell-up.

If the subject vessel exceeds one or more of these motion criteria it will be caused to alter heading/speed conducive to the continued "success" of the mission, which will reduce the motions to acceptable levels.

6.6. Responses

6.6.1. Introduction

In Chapter 5 the concept of a "potentially dangerous" roll motion was introduced. This was stated to be a pre-assigned roll angle (30 degrees in the present case) beyond which it can be assumed that the vessel will be considered potentially unsafe from a capsize point of view. Before the required probability of exceedance of the potentially dangerous roll motion ϕ_c can be ascertained, $p(\phi_c < \phi)$, an appropriate response statistic ϕ is required. For operability studies this ϕ-response is likely to be an average-type process such as the significant roll response, whereas when considering survivability some measure of the expected maximum is required.

The approach being advocated is now being more widely adopted in the design of offshore structures to take account of the whole range of sea conditions encountered by the structure, -rather than using a single severe wave which has been the procedure until now, Standing (1982). There are three design values which are considered to be most useful. These are the probability that a certain value will be exceeded (the "threshold value" which was discussed earlier); the 'probable-extreme value' which may be compared with experimental results since it is the most likely value expected in a series of experiments and the 'design-extreme value' which is the value which would not be exceeded with a preassigned probability. This last value is held to be particularly useful in design and rule formation work e.g. Morrall(1982).

6.6.2. Short-Term Prediction Method

It was discussed in Chapter 4 that it is appropriate to apply a short-term prediction method rather than a long-term method for the estimation of extreme values. Indeed Ochi (1978b) demonstrated that the estimation procedure for the extreme values is simpler and leads to more accurate results when using the short-term method provided that responses in seas up to the severest expected in the service area are considered.

In previous sections the severity and duration of sea states in the North Atlantic and sustained ship speed in each seaway have been discussed. Extreme values of ship responses may now be evaluated by applying order statistics to the probability function which represents the statistical properties of ship responses for a given speed/heading in a given sea.

6.6.3. Choice of Probability Function

In general, the Rayleigh probability distribution has been used for evaluating the statistical characteristics of the maxima (peak values) of ship responses in a seaway. This assumption is valid if the following conditions are satisfied:

(a) Random sea is a steady-state Gaussian (normal) process with zero mean.

(b) Ship response to waves is linear.

(c) Spectrum is narrow-banded.

Conditions (a) and (c) are usually satisfied. Seawaves, for example, are usually represented as a Gaussian random process, Longuet-Higgins (1952), and the bandwidth parameter ε of Cartwright et al (1956) allows the narrow banded assumption to be relaxed.

$$\varepsilon = \sqrt{1 - m_2^2 / m_0 m_4}$$

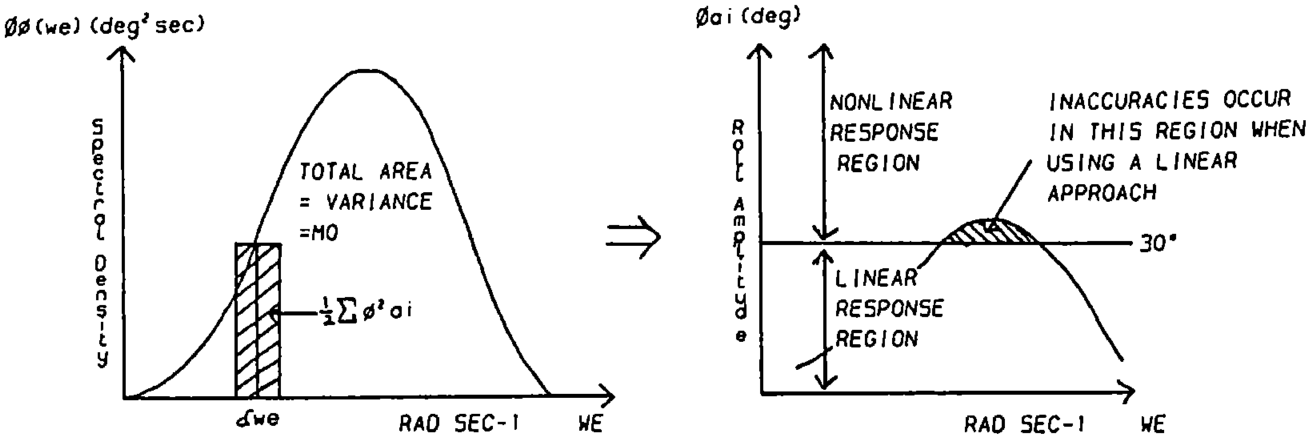
where m_n = moment of the spectral density function

For a narrow-banded spectrum ε is equal to zero and the p.d.f. is of Rayleigh form. For a wide-band spectrum ε is equal to one and the p.d.f. has a normal distribution.

However for estimating the extreme values of ship rolling in a seaway there may still remain a serious problem regarding the linearity assumption because, as was described earlier, rolling motion is distinctly non-linear by nature. This may not completely exclude a linear treatment and thus the use of conveniently assuming Rayleigh distributed peak responses. Rather it should be realised that (for any trial) as the probability of exceedance of 30 degrees of roll increases, the absolute values of the probability obtained reduces in accuracy[3].

To illustrate this, consider a typical roll response spectrum which may be transformed into an "amplitude" spectrum as shown in Figure 6.9.

[3]This argument assumes that roll angles up to 30 degrees can be computed with complete accuracy for the SULISKER.



$$\int_0^{\infty} \Phi_{\phi}(\omega_e)\,\delta\omega_e = \tfrac{1}{2}\sum \phi_{ai}^2$$

where $\Phi_{\phi}(\omega_e)$ is the response spectrum ordinate and ϕ_{ai}^2 is the amplitude spectrum ordinate.

Thus, as $\delta\omega_e \rightarrow 0$

$$\sqrt{2\,\Phi_{\phi}(\omega_e)\,d\omega_e} = \phi_{ai}$$

Figure 6.9 Amplitude Spectrum

It can be seen that certain of the contributions to the variance (variance denoted by m_0, the area under the response spectrum) cannot be predicted with accuracy by the linear superposition principle. Indeed the Rayleigh distribution over-predicts the probability of occurence of larger amplitude roll motions of the subject vessel, Roberts (1984), since the Rayleigh distribution is given by:

$$p(\phi) = \frac{\phi}{m_0}\, e^{-\phi^2/2m_0}$$

and

$$p(\phi > \phi_c) = e^{-\phi^2/2m_0}$$

In order that the degree of confidence in the predictions may be assessed the idea of a "confidence level" is introduced. This is simply a metric for describing the level of confidence in the probability obtained. As far as the author can ascertain, the partitioning of responses into regions of linear and non-linear behaviour for a marine vehicle has not been apportioned in quite this way. It is only applicable if the accuracy of the response prediction can be assured up to a certain response level.

Thus if $p(\phi > 30) = 0$ then consider that C.L.(confidence limit) = 1 i.e. one can be 100% sure that the probabilities obtained are accurate.

Similarly if $p(\phi > 30) = 1$ then consider C.L. = 0 i.e. one can be 0% sure that the probabilities are accurate.

Thus C.L. $= 1 - p(\phi > 30)$ as illustrated in Figure 6.10.

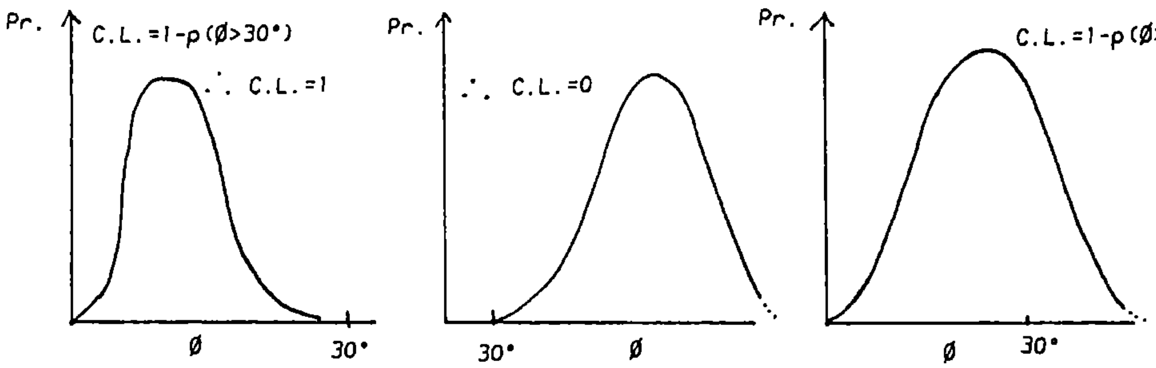


Figure 6.10 Definition of Confidence Limit

Thus if a Rayleigh distribution is assumed for the rolling response of a vessel it is suggested that this simple concept of "confidence limit" can be used to give a feel for the probabilities obtained since an indication of the proportion of the contributions to the variance, which are correctly predicted, can be obtained.

In the short-term prediction method used in this study, encounters with each seastate of a particular severity (characterised by significant waveheight, H_s) are considered and the peak values fitted to the Rayleigh distribution through the statistical variance (area under the response spectrum). The lifetime probability of response is not being calculated because of the use of the counting functional of section 4.6 to record only the occasions when 30 degrees of roll is exceeded.

The alternative, which will not be pursued here, is to carry out a series of experiments for the non-linear responses and to then fit a function to the histogram of the responses obtained. Many such functions have been proposed such as a generalisation of the Rayleigh or gamma probability function, Ochi (1978c). It should be noted that all the parameters for these distributions are obtained from the data observed and have no relationship with spectral analysis in the frequency domain. At present no theory exists for expressing the extreme values in a simple closed form, as for the Rayleigh distribution, hence the extreme values are evaluated only through numerical computations.

Various other researchers have proposed distributions fitted to observed data. For example Jasper(1956) fitted the measured data using the theory of extremes as developed by Gumbel(1954) to records of rolling under the assumption that the underlying distribution is of the log-normal type. In all of these fitting procedures the difficulty is in knowing where the underlying assumptions fail.

6.6.4. Prediction of Extremes

Figure 6.11 is an explanatory sketch of a random process $x(t)$ for which the maxima could be anywhere in the range ($-\infty$, $+\infty$) and several maxima could occur during one cycle as defined by zero crossings.

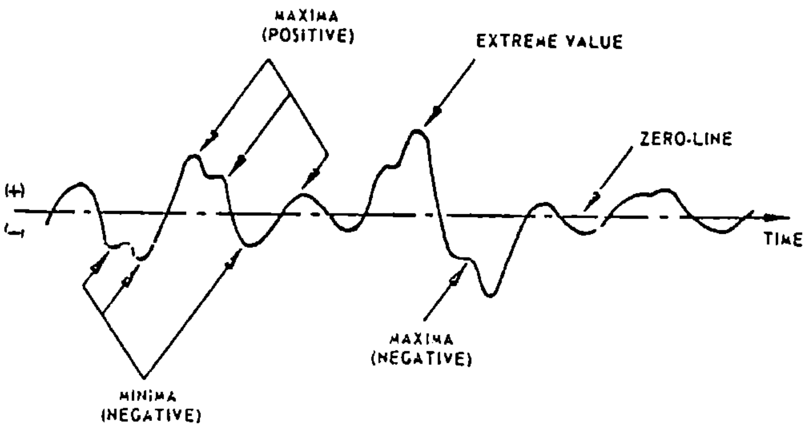


Figure 6.11 Random Process $x(t)$

The probability function of the maxima of a random process having an arbitrary bandwidth spectrum is given in Cartwright et al (1956), while the probability function of the positive maxima, defined as the peak value which will occur throughout the range of 0 to ∞ is discussed by Ochi (1973b). Let x be the motion response in a seaway and let Y_n be the extreme value of the response in n-encounters with waves. By applying order statistics the probability density function for the extreme value, Y_n, denoted by $g(y_n)$ becomes:

$$g(y_n)=n[f(x).(F(x))^{n-1}]_{x=y_n}$$

-Ochi(1973b)

where $f(x)$ is the p.d.f. of the response and $F(x)$ is the cumulative distribution function of x.

From the above equation the extreme value which is likely to occur (the probable-extreme value denoted by $\bar{y}_n$) is the modal value of the p.d.f. of $g(y_n)$ and is obtained (Figure 6.12) by letting the derivative of $g(y_n)$ with respect to y_n be zero, thus:

$$\frac{d}{dy_n}(g(y_n)) = \left\{ \frac{d}{dx}f(x) \, . \, F(x) + (n-1)(f(x))^2 \right\}_{x=y_n} = 0$$

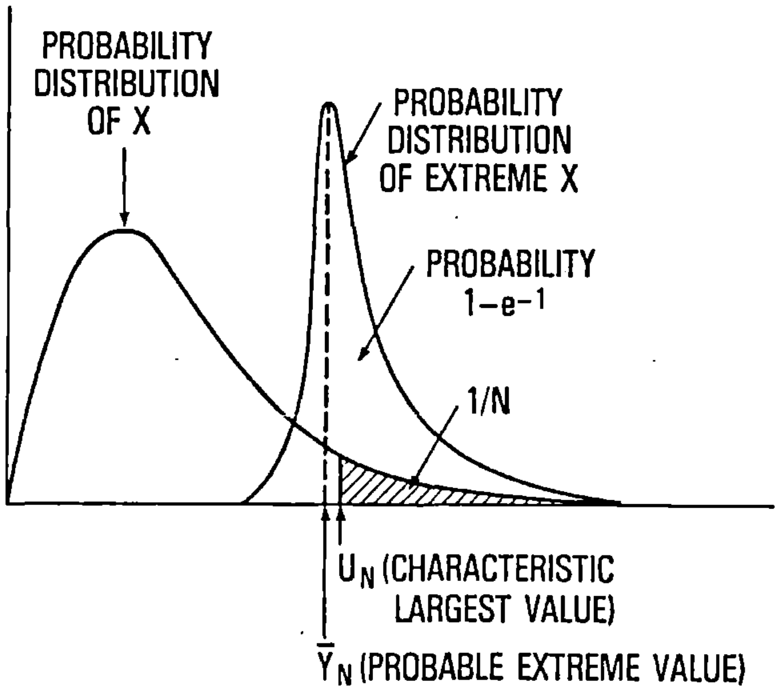


Figure 6.12 Explanation of Probable-Extreme value

On the other hand the expected number of positive maxima in the observed data which are greater in extreme value than the most probable is rather higher. Indeed, it can be proved that if the number of wave encounters is large then the probability that the extreme value will exceed $\bar{y}_n$ is theoretically $1\text{-}e^{-1}$ = 0.632, regardless of the spectrum bandwidth, Ochi(1973b). It appears therefore that the most probable-extreme value $\bar{y}_n$ is too low to be considered for engineering design consideration. A certain margin above the expected largest value is required, and this can be obtained by estimating the extreme value, $\hat{y}_n$, which is unlikely to be exceeded with a preassigned probability α, i.e. $\hat{y}_n$ can be found by obtaining the solution (Figure 6.13) of:

$$\int_{y_n}^{\infty} g(y_n)\, dy_n = \alpha$$

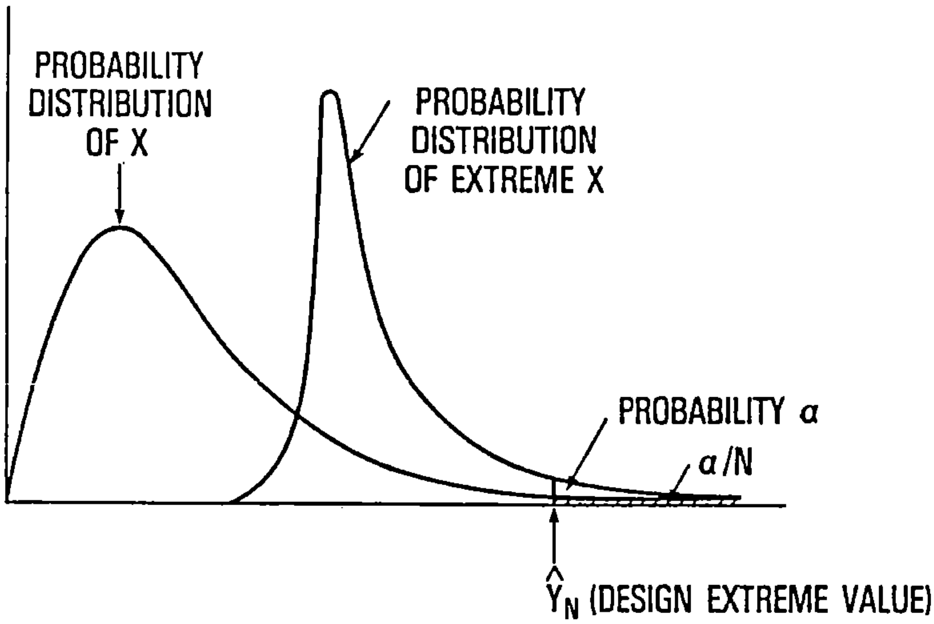


Figure 6.13 Explanation of Design-Extreme Value

Under the assumption that n is large and that the peak values of responses follow the Rayleigh probability law, as previously discussed, the amplitudes of extreme values are as follows, Ochi (1973b).

Most Probable-Extreme value:

$$\bar{y}_n = \sqrt{2\, ln((2\sqrt{1-\varepsilon^2})/(1+\sqrt{1-\varepsilon^2}))\, n} \;.\; \sqrt{m_0}$$

Design-Extreme value:

$$\hat{y}_n = \sqrt{2\, ln((2\sqrt{1-\varepsilon^2})/(1+\sqrt{1-\varepsilon^2}))\, n/\alpha} \;.\; \sqrt{m_0}$$

where ε = bandwidth parameter and m_0, m_2, m_4 are the zero'th, 2nd and 4th moments of the response spectrum respectively.

For the present purpose it is more convenient if the number of observations is expressed in terms of time hence:

Most Probable-Extreme Value:

$$\bar{y}_n = \sqrt{2\, ln((60)^2 T/(2\pi)\, \sqrt{m_2/m_0})} \;.\; \sqrt{m_0}$$

Design-Extreme Value:

$$\hat{y}_n = \sqrt{2\, ln((60)^2 T/(2\pi\alpha)\, \sqrt{m_2/m_0})} \;.\; \sqrt{m_0}$$

Where T is the time in hours. These formulae include the effect of the bandwidth of the response spectrum ε on extreme values.

The risk parameter, α, represents the probability that the extreme response in a given sea will exceed the predicted value. If α is chosen by the designer to be 0.01 it implies that the extreme value experienced in a certain specified time will exceed the predicted value once in 100 occurences of a storm of the same severity.

In general the storm duration and frequency of its occurrence have to be considered in determining the α value. If a ship may encounter seas of the same severity k times in her lifetime then it is necessary to divide α by k to maintain the percentage assurance in the calculation. Hence the Design-Extreme value becomes:

$$\hat{y}_n = \sqrt{2\, ln((60)^2 T/(2\pi(\alpha/k))\, \sqrt{m_2/m_0})}\ .\ \sqrt{m_0}$$

These aspects require individual attention in the actual calculations.

6.6.5. Operation (or exposure) time

The extreme values of responses are a function of the number of encounters with waves and hence the persistence of each sea state has to be considered in the estimation.

Figure 6.14 taken from Ochi et al (1974) shows the persistence of every 1.52m (5ft) interval of significant wave height estimated from an analysis of North Atlantic data given in Moskowitz et al (1965). For example a sea of significant wave height 10m would not last more than 20 hours during one storm: hence it is sufficient to evaluate the extreme responses for 20 hours of ship operation in this sea severity.

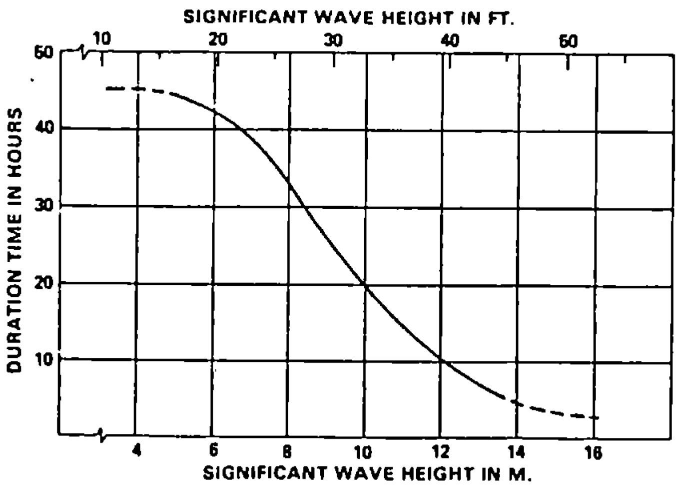


Figure 6.14 Significant Waveheight and its Persistence

The effect on the extreme roll angles of seastate duration is shown in Figure 6.15 for the Bretschneider 2-parameter wave spectrum (H_s = 5m). The (SULISKER) extreme values increase significantly during the first 10 hours approximately and thereafter at a slower rate.

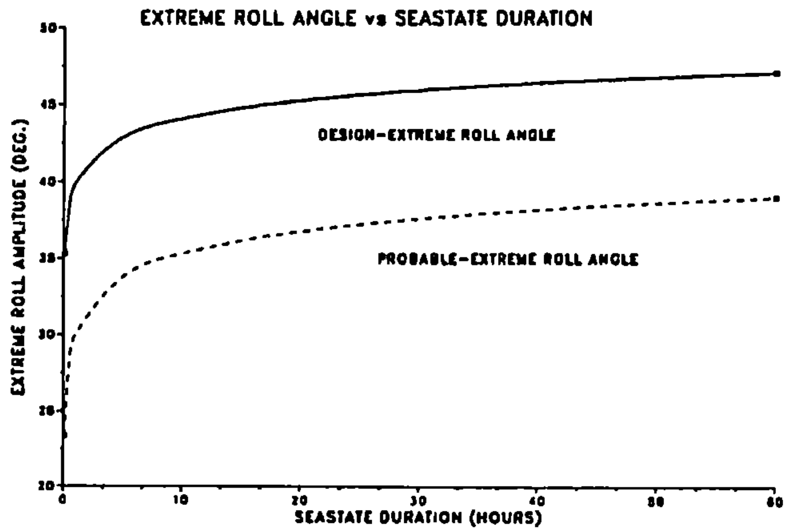


Figure 6.15 Effect of Seastate Duration on Extreme Roll

6.7. Chapter Summary

The treatment of the important factors described in this chapter which are considered in this study may be summarised as shown in Table 6.8. Any short-comings are also highlighted.

Table 6.8 Treatment of Important Simulation Factors

Factor	Treatment	Comments
Hull Design Features	Strip theory & empirical formulae using measured values	No modelling of above–water features occurs
Displacement Conditon	Range of values taken from stability booklet	No values used outside of operating norm
Cargo	–	No cargo carried
Route	Domain segments chosen to give worst expected responses	Method is iterative and seeks worst cases
Climate (Waves)	Statistically derived open–sea and fetch limited families of wave spectra used Cosine squared wave energy spreading	Covers a great range of spectral shapes Extreme values of wave height and probabilities of occurence used
Climate (Wind)	–	Wind effects and gusting are not considered
Seamanship	Avoidance and Pacifying–type seamanship are considered Empirical values of critical motion are assumed	This area is somewhat subjective with reasonable values used based on correspondence
Responses	Based on Statistics of extremes Rayleigh distributed process assumed (Corrected for bandwidth)	Upper and lower bound responses obtained with 95 percent confidence Assumes that roll response is accurately predicted up to 30 degrees

Chapter 7

Description of the Simulation Computer Program

7.1. Introduction

In chapter 4 it was described how the probability of exceeding a potentially dangerous roll motion can be estimated by making use of independent (Bernoulli) trial concepts. It was proposed that every new vessel design be subjected to a set of analytical test-tracks. These, taken together, comprise the proving ground appropriate in nature to the particular vessel's likely operating cycle. This chapter is concerned with the practical application of such concepts. It brings together the motion prediction aspects of chapter 5 and highlights the treatment of the important factors -climatology, seamanship and resulting response which were previously described in chapter 6. Any limitations and assumptions are given particular attention.

A computer program RISK.F77 has been written in Fortran 77 for the analysis. Structurally it comprises a main program which may further access up to eleven subroutines depending on:

- user requirements set externally to the program;
- decisions taken within the program (for example simulation of the the master's likely courses of action)

The complete program logic is presented in Appendix A3 as a set of flowcharts. Reference will be made to these throughout the chapter but Figure 7.1 is reproduced here to show the overall logic flow of the main program.

It can be observed that the main program of figure 7.1 may be conveniently divided into two parts. The first and major part is concerned with the realistic prediction of vessel motions when subject to various factors including climate and master's action (which when taken together comprise a scenario). The second part is concerned with calculating the associated probability of occurrence of these factors in order to calculate the scenario probabilities which gave rise to the motions.

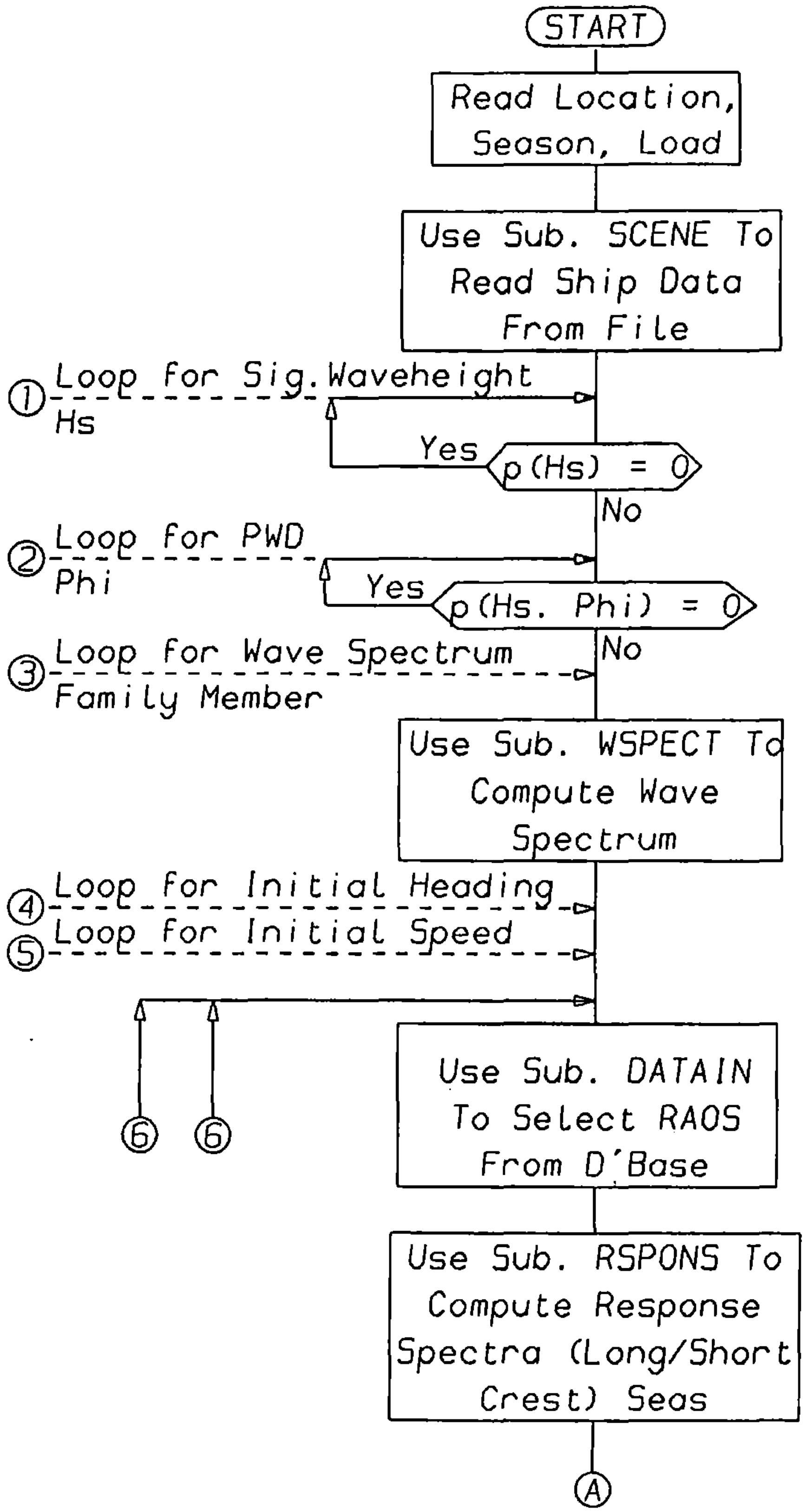
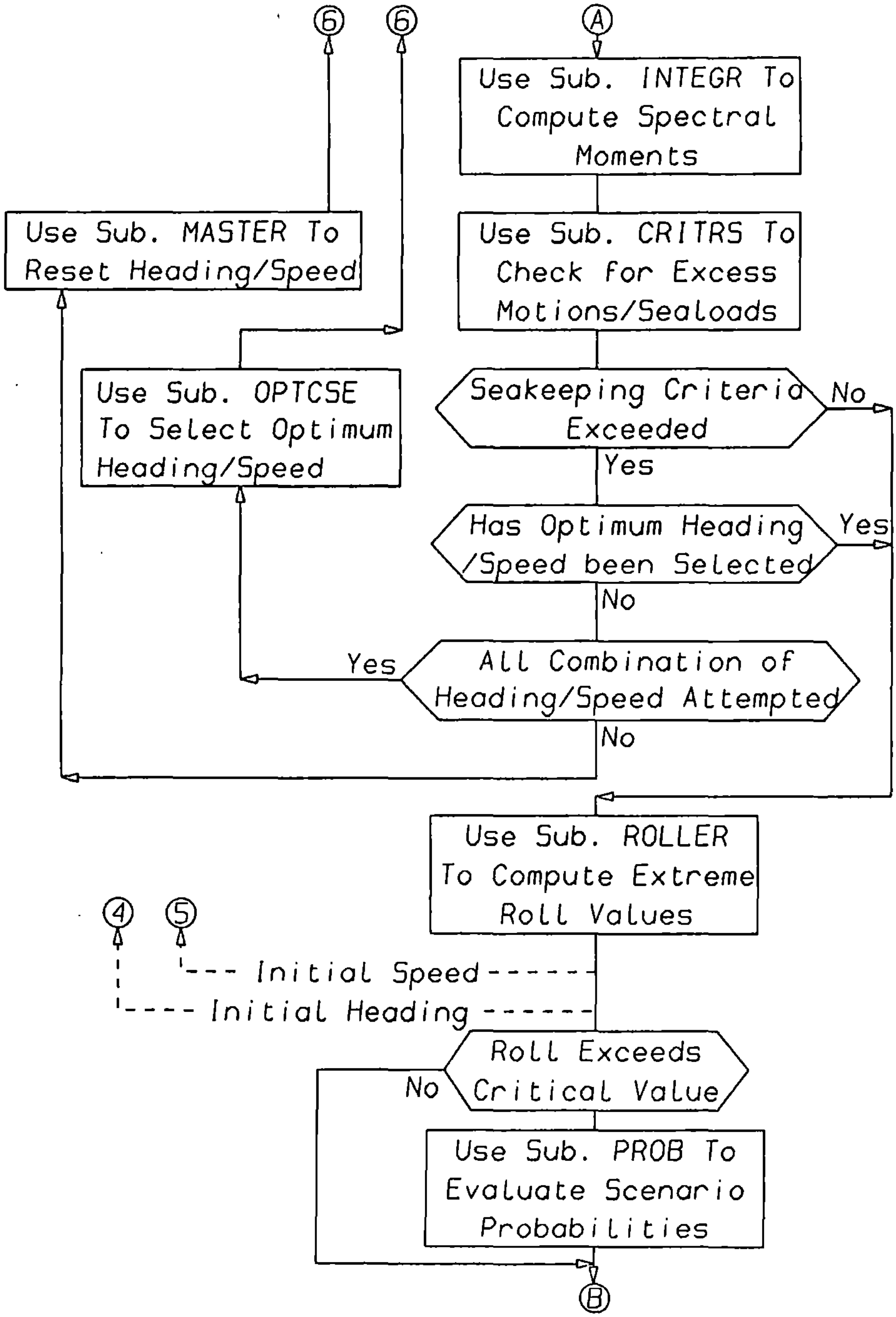
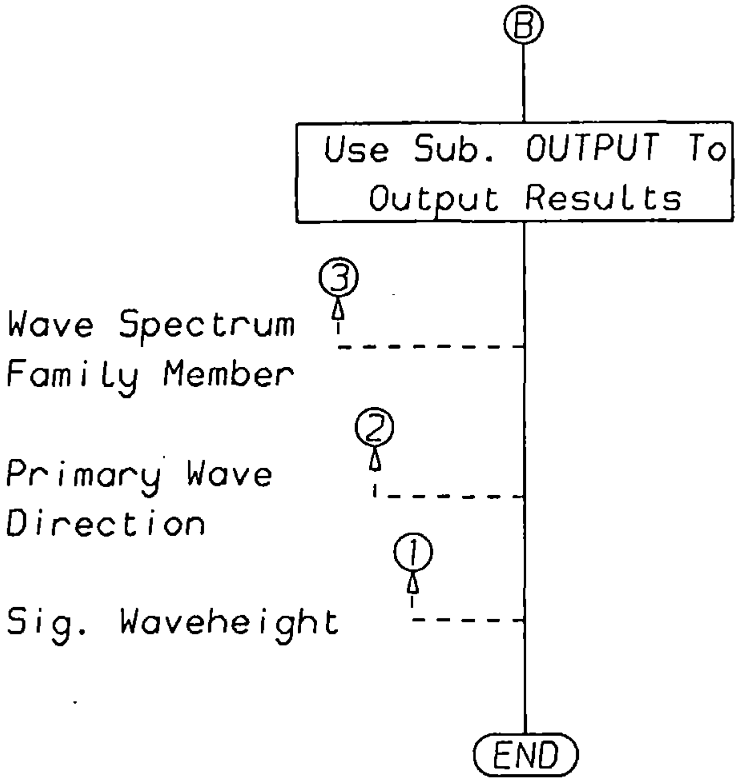


Figure 7.1 Main Program RISK.F77 for a given Domain, Season and Load condition


6
6
A
Use Sub. INTEGR To Compute Spectral Moments
Use Sub. MASTER To Reset Heading/Speed
Use Sub. CRITRS To Check for Excess Motions/Sealoads
Use Sub. OPTCSE To Select Optimum Heading/Speed
Seakeeping Criteria Exceeded
No
Yes
Has Optimum Heading /Speed been Selected
Yes
No
Yes
All Combination of Heading/Speed Attempted
No
Use Sub. ROLLER To Compute Extreme Roll Values
4
5
Initial Speed
Initial Heading
Roll Exceeds Critical Value
No
Use Sub. PROB To Evaluate Scenario Probabilities
B


B
Use Sub. OUTPUT To
Output Results
3
Wave Spectrum
Family Member
2
Primary Wave
Direction
1
Sig. Waveheight
END

7.2. Motion Prediction

7.2.1. Wave Spectra

Responses to the following wave spectra are available within the program (numbers in brackets [-] indicate the number of wave spectra in the family):

- Pierson-Moskowitz (ISSC formulation) [1]
- Bretschneider 2-parameter (with optional Ochi North Atlantic data) [9]
- JONSWAP (North Sea data by Ochi) [5]
- Ochi 6-parameter (North Atlantic data) [11]

For the present study the last two spectra are predominantly used, with families of spectra being considered for the reasons discussed in chapter 6. A difficulty which is associated with using the response amplitude operators (RAO's) derived from Britsea is that they are only available for the range of frequency (ω) of between 0.3 rad sec^{-1} and 1.3 rad sec^{-1} (0.04 rad sec^{-1} increment). This truncated frequency range was judged by the original 'author' of Britsea to contain most of the wave energy for the Pierson-Moskowitz point spectrum (the only spectrum available to users of Britsea). However, for the present purposes this may lead to the truncation of the wave spectrum from which the extreme responses are eventually calculated. Figure 7.2 illustrates this for an ISSC spectrum. The effect of this truncation on computed responses will vary depending on the shape of the wave spectrum as well as on the shape of the RAO curve with respect to frequency, Figure 7.3 and Figure 7.4.

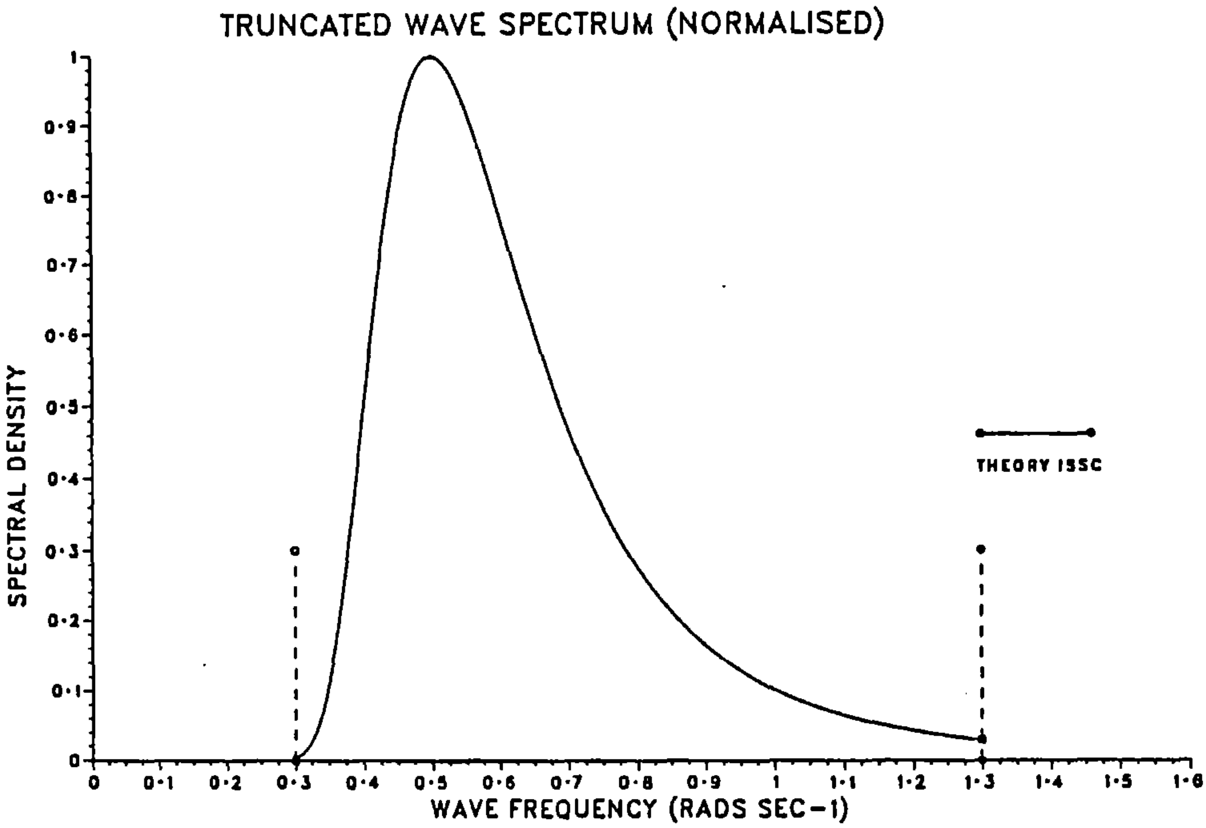


Figure 7.2 Truncated ISSC Wave Spectrum

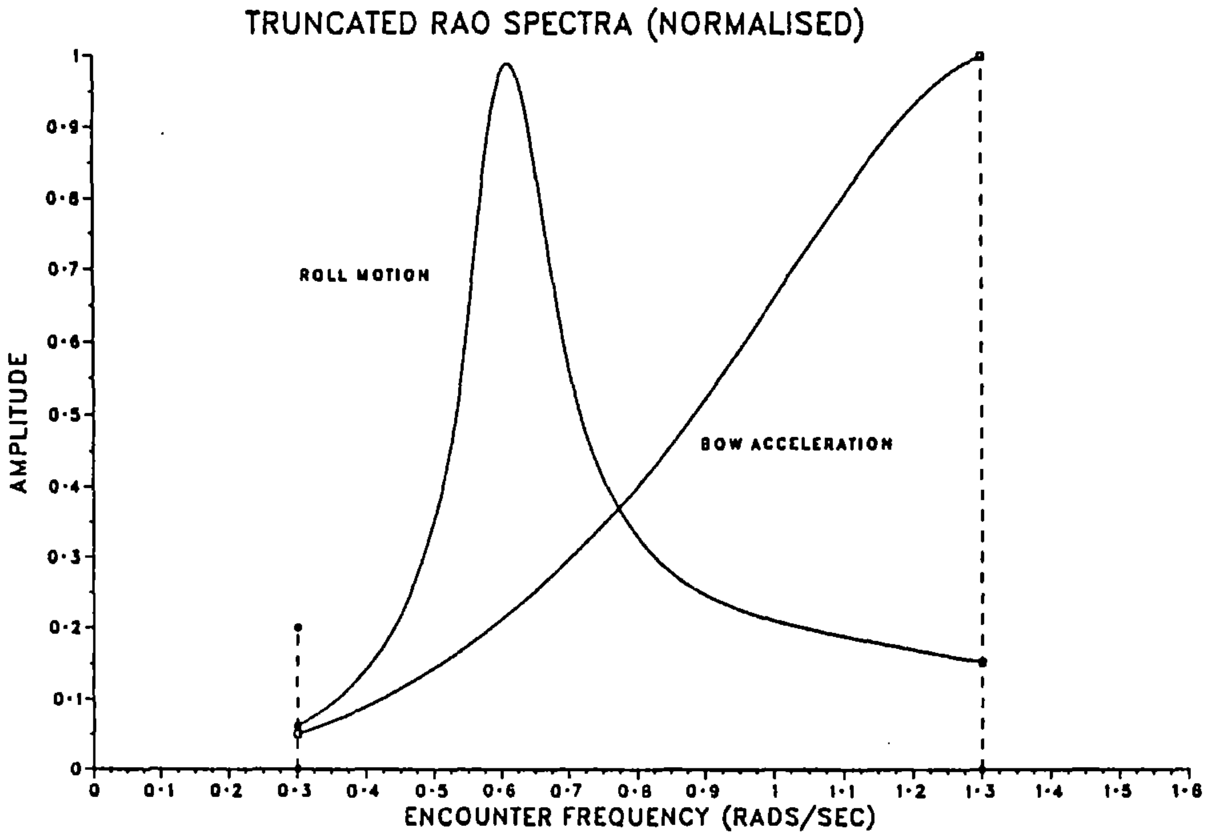


Figure 7.3 Truncated RAO Spectra

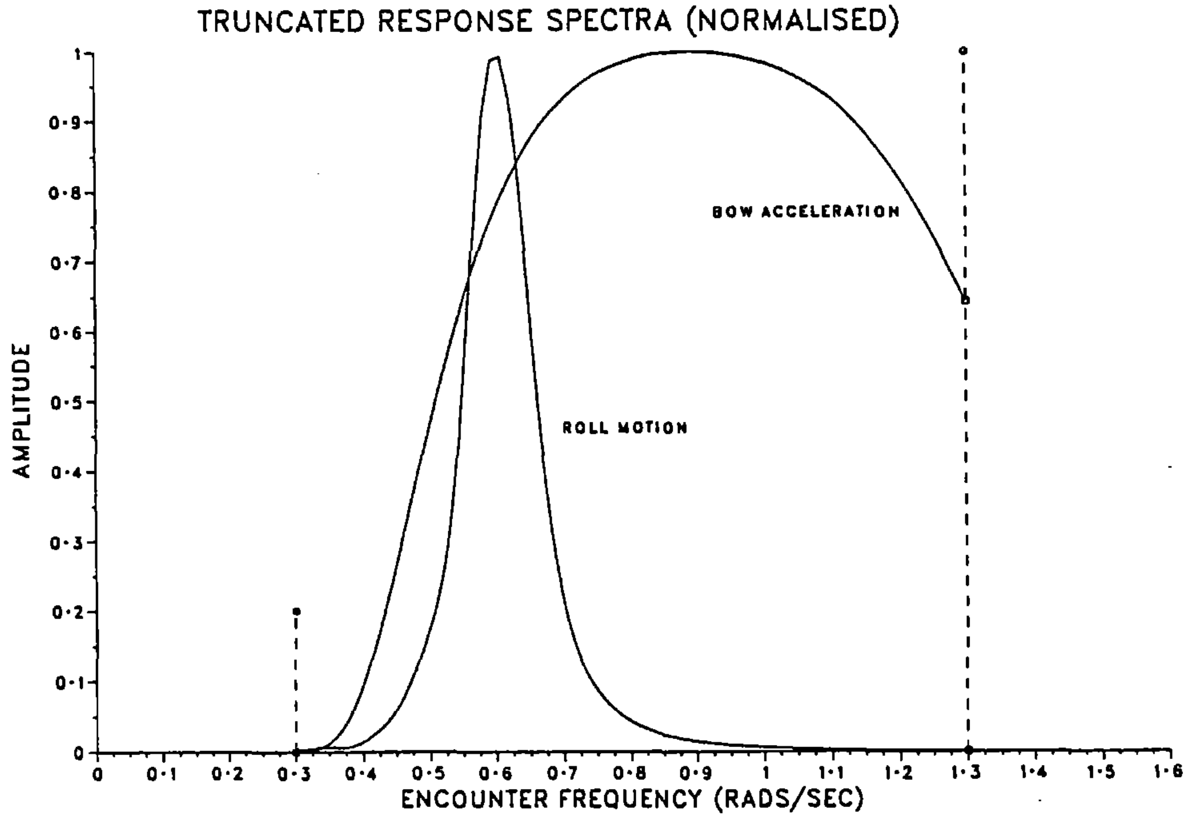


Figure 7.4 Truncated Response Spectra

Since the roll response amplitude operator curve tends to be very highly peaked, figure 7.3, at a frequency value close to the ship natural roll frequency (0.6 rad sec^{-1} for the SULISKER) and falls away sharply on either side, this is not judged too much of a problem for roll, provided that values of roll velocity or acceleration are not considered. These values are proportional to ω^2 and ω^4 respectively.

The effect is likely to be more pronounced for pitch, heave and the associated vertical responses, figure 7.4, but it is extremely difficult to quantify this given the large number of runs through the program, thus a systematic error is assumed in the present study.

7.2.2. Response Amplitude Operators

These are pre-computed using Britsea and held in a database for access by the main program (using subroutine DATAIN). The database contains both transverse and longitudinal response amplitude operators (amplitudes and phases) for different frequencies and headings to waves. A typical entry for roll is outlined in Table 7.1. There is a separate entry relating to each displacement condition and speed.

	Heading to Waves
Wave Frequency ω	0 30 60 90 120 150 180
Amplitude	
0.30	
0.34	
	Roll Amplitude
1.30	
Phase	
0.30	
0.34	
	Roll Phase
1.30	

Table 7.1 RAO Database for a given Speed V_0 and Displacement condition Δ

The computer interpolation of the RAO values, with respect to heading, uses a Lagrange technique based on Everett's formula, Froberg (1969), with a finite difference error estimation. The net result of this is that motions may be computed to within a 3 knot speed resolution and a 15 degree heading resolution. This was felt to be a reasonable tradeoff between practical 'real-life' accuracy and the potentially enormous increase in computing time and storage that would result if the speed/heading resolution were made any finer.

7.2.3. Response Spectra

The superposition principle of St Denis and Pierson (1953) is used throughout i.e. the responses are assumed linearly related to wave amplitude or wave slope. This may not be the case (even for vertical responses) when the seaway is very severe but this was felt to be not too great a problem as the actual capsize roll angles themselves are not being predicted. Only the exceedance of the threshold value of potentially dangerous roll motion is being monitored in this study.

The following responses are available in subroutine RSPONS:

- Roll motion, velocity and acceleration
- Sway motion, velocity and acceleration
- Yaw motion, velocity and acceleration
- Pitch motion, velocity and acceleration
- Heave motion, velocity and acceleration
- Pitch/Heave coupled absolute motion, velocity and acceleration *
- Pitch/Heave coupled relative motion and velocity *
- Pitch/Heave/Roll coupled absolute motion, velocity and acceleration *
- Pitch/Heave/Roll coupled relative motion and velocity *
- Added resistance

*Vertical responses are available for up to 5 positions of interest on the hull, measured from the centreline and amidships. These are the bow, bridge and propeller positions at which vertical motion values are required for subsequent evaluation of critical motion/sea-load values.

Responses to both long and short-crested seas are available. In the latter case, which is the case usually considered for realism, cosine squared or $\cos^4$ spreading of wave energy is generally used.

Subroutine INTEGR performs the necessary integrations of the long and short-crested response spectra to obtain RMS values and broadness correction factors. A third order difference technique, with error estimates according to a method by Gill and Miller (1972), is used for this purpose. Again it is noted that the response spectra are necessarily truncated.

7.2.4. Responses Critical to Master's Action

(a) Deck wetness (subroutine CRITRS)

It was stressed in chapter 6 that the maximum number of deck wetnesses of 90 per hour is assumed to be acceptable to the master of the SULISKER.

(i) The actual number of deck immersions/hour (N_w) is obtained, Bhattacharrya (1978), from:

$$N_w = \frac{\text{Probability of Deck Wetness}}{\text{Average Rel.Motion Period at } F_{PP}} \,.\, 3600$$

$$= \frac{P_w}{T_f} \,.\, 3600$$

$$= \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}} \,.\, P_w \,.\, 3600$$

$$= \frac{3600}{2\pi} \,.\, \sqrt{\frac{m_2}{m_0}} \,.\, exp^{-(f_e^2/(2m_0 \,.\, CF^2))}$$

where f_e' is the effective freeboard at the bow accounting for static and dynamic swell-up

$CF=(1-\varepsilon^2)^{0.5}$ is the spectrum bandwidth correction factor

$$\varepsilon^2 = 1 - \frac{m_2^2}{m_0\, m_4}$$

$m_0\ m_2\ m_4$ are moments of the relative motion spectrum.

(ii) Effective Freeboard (f_e)

Shipping of green water is caused primarily by deck motion relative to the wave surface. It is therefore a function of the freeboard of the ship. The actual freeboard of the ship is modified by both static and dynamic swell-up to give the effective freeboard (f_e).

(iii) Statical Swell-up at the bow.

This is caused by 2 phenomena; bow waves generated by the vessel while moving in still water and sinkage of the bow while running at speed. The effect is a reduction of the freeboard i.e:

$$f_e' = f - h$$

where

f_e' is the freeboard corrected for statical swell-up

f is the actual freeboard in still water (bowheight - forward draught)

h is the statical swell-up

$h = \zeta_B + \zeta_S$

ζ_B is the elevation due to the bow wave

ζ_S is the sinkage due to speed

An approximate formula for statical swell-up is given by:

$$h=0.75\,B\,\frac{L}{L_e}\,F_n^2$$

-Tasai(1969)

where

B is the ship breadth

L is the length between perpendiculars

L_e is the length of entrance

F_n is the Froude number

thus

$$f_e=f-0.229\,B\,\frac{L}{L_e}\,F_n^2\ (m)$$

(iv) Dynamic Swell-up of Water at the bow

This phenomenon is not considered because of a lack of reliable data pertinent to the subject vessel.

(b) Slamming

The maximum number of slams that the master will accept is assumed to be 60 per hour for the subject vessel.

Slamming is the impact experienced when the forefoot hits the water surface during a severe pitching motion. This most sudden change in the acceleration takes place at the bow and stern where both acceleration and motion are greatest. Slamming causes excessive pressure on the bottom plating with the possibility of stress-whipping in the main structure.

Although it may occur without forefoot emergence, there is a greater probability of slamming with emergence of the forefoot. Thus there are three kinetic conditions to be investigated in the study of slamming:

- Does forefoot emergence occur in a given seaway?
- Value of phase difference between wave motion and bow motion
- Magnitude of relative bow velocity. Is it greater than a threshold value necessary to cause a slam to occur?

(i) Probability of Slamming

The probability of forefoot emergence is the probability that the relative bow displacement exceeds the forward draught i.e.

$$p(\text{Forefoot Emergence}) = e^{-(T^2/2m_0 CF_1^2)}$$

where

T is the draught at the bow

m_0 is the zero'th moment of the (relative) bow motion spectrum

CF_1 is the motion spectrum bandwidth correction factor

Similarly the probability that the relative bow velocity exceeds the threshold velocity is given by:

$$p(\text{Rel.Vely} > V_c) = e^{-(V_c^2/2m_2 CF_2^2)}$$

where

V_c is the threshold velocity

m_2 is the second moment of the relative bow (vertical) motion spectrum

CF_2 is the vertical velocity spectrum bandwidth correction factor

If it is assumed that bow emergence and relative bow velocity are statistically independent then:

$$p(\text{Slam}) = e^{-(T^2/2m_0 CF_1^2 + V_c^2/2m_2 CF_2^2)}$$

(ii) Number of Slams

The number of slams per hour, N_s is given by:

$$N_s = \frac{\text{Probability of a Slam}}{\text{Average Rel.Motion period at } F_{pp}} \,.\, 3600$$

$$= \frac{3600}{2\pi} \,.\, \sqrt{\frac{m_2}{m_0}} \,.\, e^{-(T^2/2m_0 CF_1^2 + V_c^2/2m_2 CF_2^2)}$$

where, for the SULISKER, it is assumed in the absence of available data:

$V_c = 0.093\ \sqrt{gL} = \sqrt{9.81\,.\,64} = 2.33$ m sec^{-1}, Ochi(1964)

It is noted that this formula does not hold for all full scale trials results e.g. Aertssen (1966).

(c) Subjective Motion Magnitude

In order to predict voluntary speed loss in rough weather it is important that the captain's perception of the ill-effects on his ship and crew are considered. Thus it is important to relate criteria to the way in which the captain detects the occurrence and severity of slamming, ship motions, deck wetness and propeller emergence. The subjective motion (SM) magnitude is given by:

$$SM = \{3.087 + 1.392(\ln(1/2\pi)\sqrt{\frac{m_6}{m_4}})^2\} . m_4^{0.715}$$

-Lloyd et al (1977)

where

m_4, m_6 are absolute (vertical) motion variances

SM is calculated at the bridge position. If $SM > 12$ it is assumed that the master will choose to alter speed and/or heading.

N.B. Involuntary speed loss is not covered in this work since it is assumed that, in the main, severe seas cause the largest responses and the master will have over-ridden added resistance effects in these circumstances.

(d) Propeller Emergence

Assuming that the propeller has emerged when one quarter of its diameter is exposed above the water surface the number of emergences per hour N_E is given by:

$$N_E = \frac{P_E}{T_R} . 3600$$

$$= \frac{3600}{2\pi} . \sqrt{\frac{m_2}{m_0}} . e^{-((T_P - D/4)^2)/2 m_0 CF^2}$$

where

P_E is the probability of propeller emergence

T_R is the average relative (vertical) motion period at the propeller

T_P is depth of propeller shaft below still water level

m_0 is the variance of the relative motion at the propeller

m_2 is the variance of the relative velocity at the propeller, Figure 7.5.

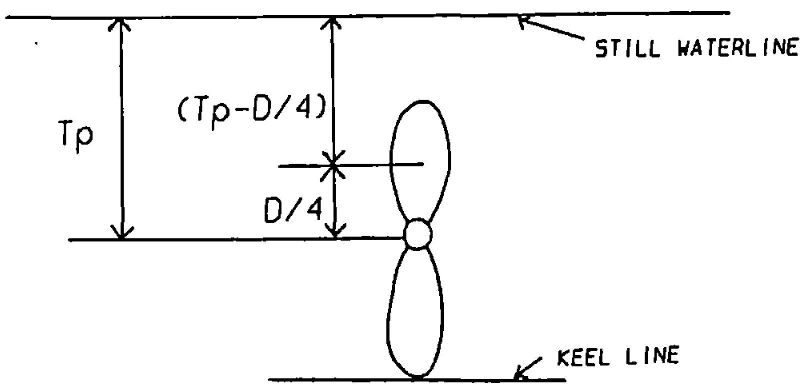


Figure 7.5 Propeller Emergence Definitions

If the number of propeller emergences exceeds 120 per hour it is assumed that the master will alter speed and/or heading.

(e) Roll Motion

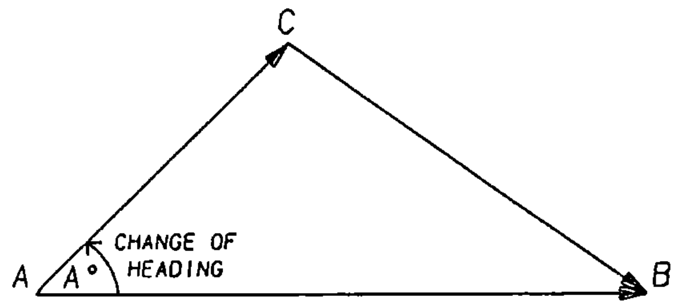
It is assumed that if the average roll motion exceeds 15 degrees the master will alter speed and/or heading - although this is a secondary effect for the subject vessel because there is no cargo which might break loose. It is a figure based on consideration of crew comfort only, which is generally not exercised on the SULISKER, Dickson (1984).

7.2.5. Master's Action

When one or more of the motion or seaload criteria of section 7.2.4 are exceeded the master will adjust ship speed and/or heading to try and bring levels to within acceptable limits.

The principle adopted within subroutine MASTER is that speed/heading will be adjusted in an attempt to bring motions and sea-loads to just within acceptable limits while simultaneously maintaining 'best progress' in the desired direction. Thus the assumption being made is that 'least time on passage' is a primary concern of the master. While this is certainly true of certain vessel types, such as container ships, it may be questionable for other vessels such as naval ships or fishing vessels. In fact it is apparent that in a true survivability situation the reduction of motions and sealoads is paramount and the actual choice of heading/speed to attain this is largely irrelevant provided that the vessel does not stand into further danger, - from risk of running aground for example.

'Best progress' may be adjudged by simple geometric considerations, Figure 7.6.



where

AB is the unaltered heading/speed vector

AC is the heading/speed vector after alteration

CB is the "Residual" heading/speed vector

Figure 7.6 Best Progress

The magnitude of the residual vector is found from:

$$CB=\sqrt{AC^2+AB^2-2.AC.AB\cos A^\circ}$$

where A° is the change in ship heading.

In order to reduce the amount of computation while still achieving a reasonable degree of realism the vessel is allowed to alter heading in 30 degree increments (0°, $\pm 30, 60, 90, 120, 150$, and 180°) and speed in 6 knot increments (0,6, 12 and 18 knots). This gives 48 different heading/speed combinations, and leads to the mapping given in Figure 7.7. This shows the order of the heading/speed changes in order to maintain best progress. It is assumed that these are the attained values of speed (after added resistance has been considered).

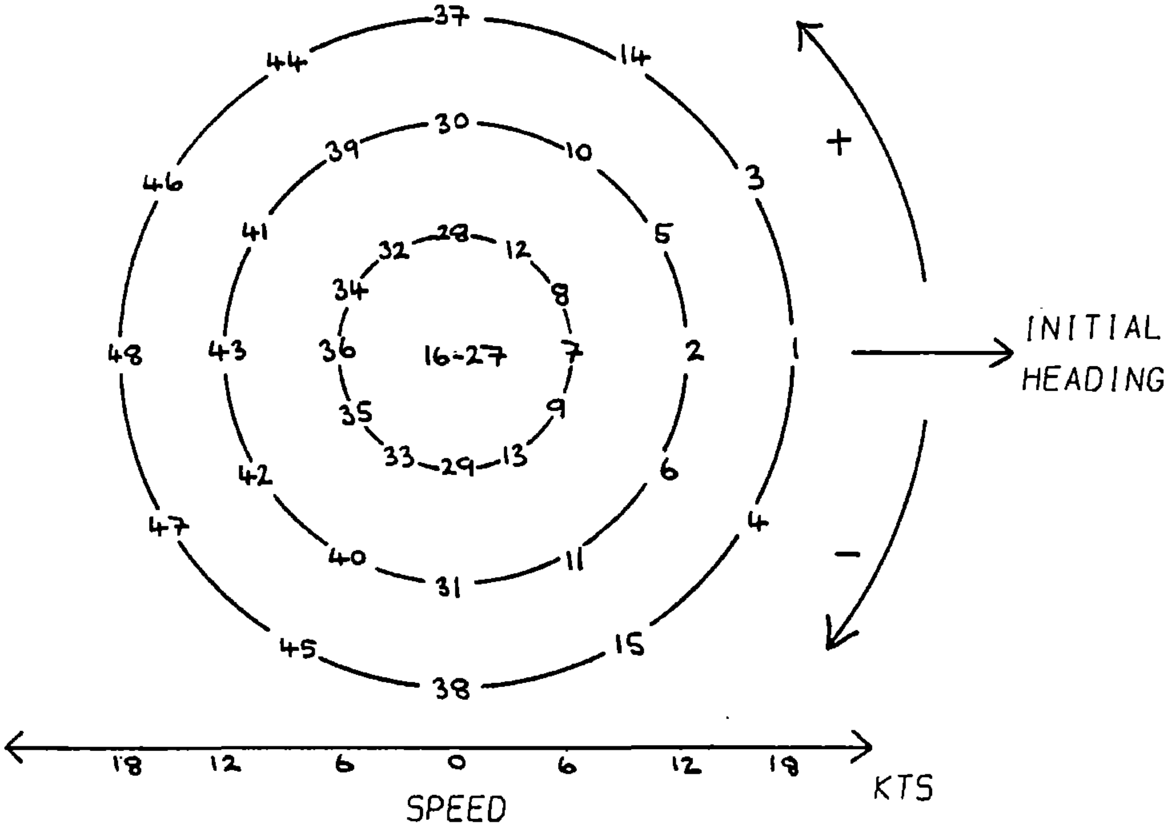


Figure 7.7 Order of Speed/Heading Changes Attempted by the Master

It should be noted that the order of computation shown in the mapping of figure 7.7 does not infer that the master will slavishly follow this pattern order. The program will consider all of the speeds and deviations from the initial speed and heading, if necessary, in order to reduce motions and sealoads to within acceptable levels. On the first occasion that this occurs the extreme roll values are evaluated using order statistics (section 6.6.4) and the loop ends.

If all of the 48 combinations of heading and speed have been tried and the motions and sealoads are still too large then the 'best' combination of heading/speed is sought:

Subroutine OPTCSE uses the response mapping obtained from the 48 combinations in order to ascertain which critical-response profile most closely matches the maxima allowed. The mean value of normalised response level is calculated for each of the 48 cases and the heading/speed combination which gave the minimum mean value is chosen to be the 'best' case. To illustrate this consider Table 7.2 with Figure 7.8.

These indicate just two critical response profiles which have been designated (A) and (B). In this case (B) is preferred. For the SULISKER an equal weighting of the critical responses has been assumed (Wt = 1.0) in the absence of relevant information. Nevertheless the eventual inclusion of such a weighting of obtained critical response levels is desirable to reflect how the vessel's master may "view" his vessel for a particular condition of load displacement. For example a master may be more concerned to reduce rolling and will be willing to accept more deck wetnesses or slams if his cargo is liable to shift due to severe roll levels being experienced.

Once the 'best' value for heading and speed has been selected the corresponding probable-extreme and design-extreme roll angles are evaluated in subroutine ROLLER. Using order-statistics, full account is taken of the duration of exposure to the seastate severity.

Critical Response Criterion (maximum value allowed)	Response Levels Obtained A 1	2	B 1	2
Deck Wetnesses/hour (90)	95	0.056	75	−0.167
Slams/hour (60)	62	0.033	47	−0.217
Subjective Motion (12)	10	−0.167	13	0.083
Prop.Emergences/hour (120)	140	0.167	160	0.333
Average roll (15)	17	0.134	12	−0.200
Mean		0.045		−0.034

Key:

(1) Response Level Obtained

(2)

$$\text{Normalised Response Level} = \frac{(\text{Response Obtained - Criteron})}{\text{Criterion}} . \text{Weight}$$

Table 7.2 Response Profile

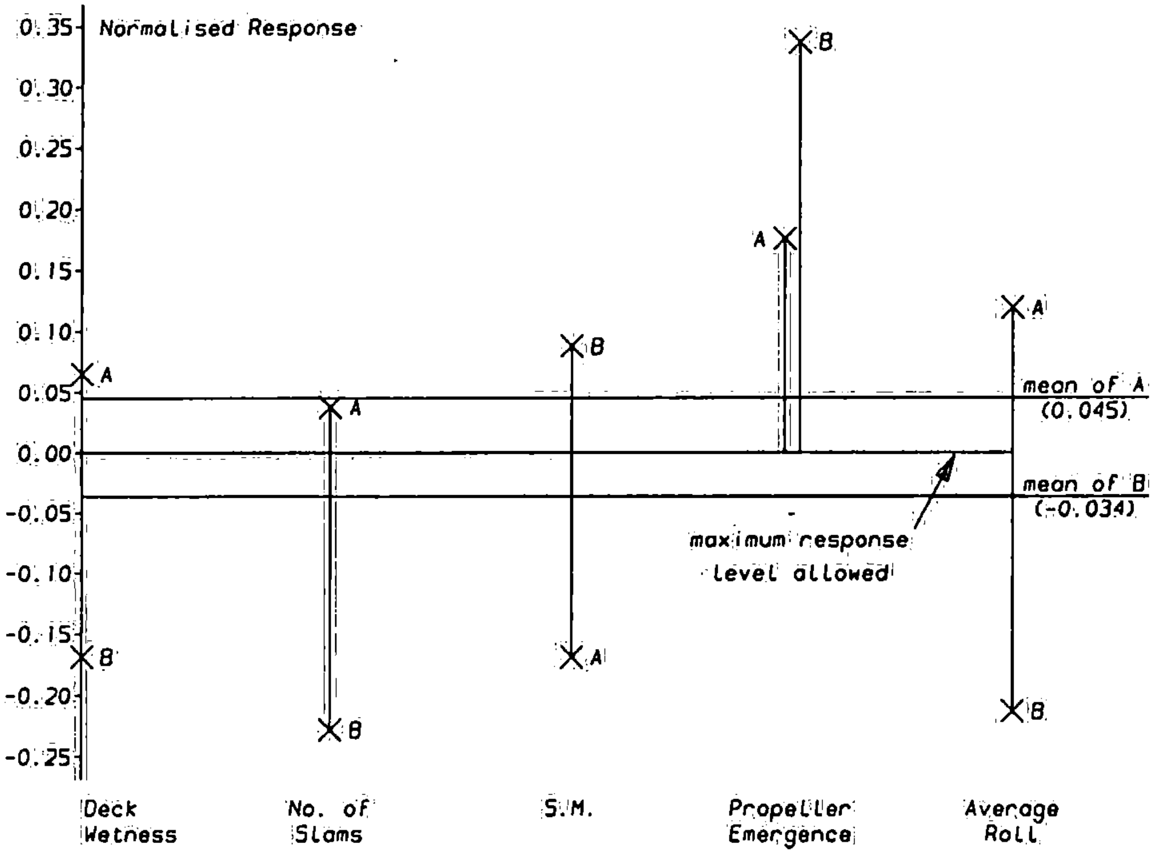


Figure 7.8 Normalised Response Levels

7.3. Prediction of the Scenario Probability

If the design-extreme roll angle exceeds the critical value of potentially dangerous roll motion (30 degrees in this study), subroutine PROB is used to calculate the single independent trial probability that the potentially dangerous roll motion was exceeded. This is equal to the single independent scenario probability which gave rise to this large response.

The scenario probability is the basic building block for the probability calculation. Essentially, program Risk.F77 is used many times to calculate appropriate scenario probabilities and to construct the test-track response probabilities from them. Ultimately the proving ground probability of critical roll-motion exceedence is calculated according to the method presented in chapter 4. This proving ground probability is obtained according to the following order of computation in program RISK.F77:

1. Loop for different domain Locations L, 1 to M
2. Loop for different Seasons S, 1 to 4
3. Loop for different Domain segments i.e load conditions Δ, 1 to N
4. Loop for different significant waveheights H_s
5. Loop for different primary wave directions Φ
6. Loop for different wave modal periods T_m
7. Loop for different initial headings μ_0
8. Loop for different initial speeds V_0
9. Calculate the design-extreme roll angle experienced (ϕ) as a function of seastate duration
10. Calculate the single independent trial probability of obtaining the predicted roll response (ϕ). This is the same as the single independent scenario probability $p^1(H_s T_m \mu V / L S \Delta)$

    In fact this step actually occurs between steps (12) and (13) for each ($\mu_0 V_0$) combination, since knowledge of final relative heading and speed given the initial heading and speed ($\mu V / \mu_0 V_0$) in a given encountered seastate ($H_s T_m \Phi$) is required
11. Initial speeds continue V_0
12. Initial headings continue μ_0
13. Wave periods continue T_m
14. Primary wave directions continue Φ
15. Significant waveheights continue H_s
16. Calculate the cumulative single trial probability that Φ will exceed Φ_c at least once given the location, season and displacement, $p^1(\phi_c < \Phi / L S \Delta)$
17. Calculate the number of independent trials, $N = R / T_* V$ where R is the distance along the course track for which the load condition Δ is assumed constant. T_* is the independence period, V is the attained ship speed
18. Calculate the cumulative multiple independent trial probability of critical motion exceedance:

$$p^N(\phi_c < \phi / L S \Delta) = 1 - \{1 - p^1(\phi_c < \phi / L S \Delta)\}^N$$

19. Load Conditions (domain segments) Δ continue

20. Seasons S continue

21. Domain locations L continue

22. Calculate the cumulative single test track probability of exceeding ϕ_c at least once:

$$p_T^1(\phi_c < \phi / L S \Delta) = 1 - \{\prod_L \prod_S \prod_\Delta (1 - p^N(\phi_c < \phi / L S \Delta))\}$$

23. Repeat all and calculate the proving ground probability of exceeding ϕ_c at least once in Q different test regions:

$$p^{\sum_P Q_i}(\phi_c < \phi) = 1 - \prod (1 - p^1(\phi_c < \phi)^{Q_i}$$

Thus if it is assumed initially that all combinations of M significant waveheights, L primary wave directions, K wave spectrum family members, J initial headings and I initial speeds are considered; the order of calculation for any particular combination of sea area, season and load condition will be as shown in Table 7.3.

It should be noted that the order of sea severity H_s is from the most severe expected in the operating area to the least severe expected. This continues until the value of obtained design-extreme roll angle ϕ is less than ϕ_c for <u>all</u> values of heading, speed, family member and wave direction encountered $(\mu_0 V_0 F \Phi)$ when the simulation skips lower seastates in favour of the next load condition value (Δ). In addition, simulation will only occur if the sea severity H_s can exist i.e. if $p(H_s \Phi) > 0$ and a test is made for this at the start.

The simulation pauses at position "A" indicated in table 7.3 i.e. at every increment of wave spectrum family member F, (a function of modal wave period T_m), in order to calculate the probabilities of attained heading and speed for the given initial heading, initial speed and encountered seastate $p(\mu / \mu_0 V_0 H_s' F)$ and $p(V / \mu_0 V_0 H_s' F)$. The significance of this step is explained in the next section.

The remainder of this chapter describes fully, with the aid of a worked example, the procedure for calculating the <u>scenario probability</u> within subroutine PROB.

Domain = L_1	Season = S_1	Load = Δ_1	$Hs = Hs_1$	$\Phi = \Phi_1$	$F = F_1$	$\mu_0 = \mu_{01}$	$V_0 = V_{01}$
–	–	–	–	–	–	–	$V_0 = V_{02}$
–	–	–	–	–	–	–	
–	–	–	–	–	–	–	$V_0 = V_{0I}$
–	–	–	–	–	–	$\mu_0 = \mu_{02}$	$V_0 = V_{01}$
–	–	–	–	–	–		
–	–	–	–	–	–		$V_0 = V_{0I}$
–	–	–	A	–	–	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–		–	$F = F_2$	$\mu_0 = \mu_{01}$	$V_0 = V_{01}$
–	–	–	–	–			
–	–	–	–	–			$V_0 = V_{0I}$
–	–	–	–	–		$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	–	–	$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	–	$\Phi = \Phi_2$	$F = F_1$	$\mu_0 = \mu_{01}$	$V_0 = V_{01}$
–	–	–	–				
–	–	–	–				$V_0 = V_{0I}$
–	–	–	–			$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	–		$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	–	$\Phi = \Phi_L$	$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	$Hs = Hs_2$	$\Phi = \Phi_1$	$F = F_1$	$\mu_0 = \mu_{01}$	$V_0 = V_{01}$
–	–	–					
–	–	–					$V_0 = V_{0I}$
–	–	–				$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–			$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–		$\Phi = \Phi_L$	$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
–	–	–	$Hs = Hs_M$	$\Phi = \Phi_L$	$F = F_K$	$\mu_0 = \mu_{0j}$	$V_0 = V_{0I}$
Domain = L_1	Season = S_1	Load = Δ_2	ETC	ETC	ETC	ETC	ETC
ETC	ETC	ETC					

Table 7.3 Order of Simulation

7.3.1. Worked Example Using Subroutine PROB.

Consider the following Scenario:

The F.P.V. SULISKER operating fully laden in the N. Atlantic in winter encounters a severe storm. This forces a change in course C and speed V_0 from 150 degrees (T) and 15 knots to 120 degrees (T) and 12 knots in order to reduce motions and sealoads, due to vertical motion, to within acceptable limits. This 'best' course and speed still yields a design-extreme roll angle of 35 degrees, taking account of seastate duration. Calculate the single independent trial probability of obtaining this roll response.

Additional data:

Location code L $=2$
Season code S $=4$
Load index Δ $=1$
Significant waveheight H_s $=15\,m$
Primary wave direction Φ $=270°$
Ochi 6 - parameter family member F $=1$
Initial relative heading μ_0 $=60°$
Initial speed V_0 $=15$ knots
Final relative heading μ $=30°$
Final speed V $=12$ knots
Design-extreme roll angle ϕ $=35°$

N.B. this data has been chosen for convenience and ease of calculation in order to avoid protracted iteration steps.

(Additional probability tables will be introduced where appropriate in the calculation)

According to the notation of chapter 4 it is required to calculate $p^1(\mu V H_s' T_m / LS)$ for a given (Δ) i.e. the probability of encountering the scenario which gave rise to the response.

• Calculation Summary

The order of computation in subroutine PROB for calculating the single independent trial probability of obtaining the predicted roll response is:

Step(a) Calculate the two transition matrices:

$T(\mu / \mu_0 V_0 H_s' F)$ - the probability of final attained heading given the initial heading, initial speed and encountered seastate.

$T(V / \mu_0 V_0 H_s' F)$ - the probability of final attained speed given the initial heading, initial speed and encountered seastate.

Step (b) Calculate the climate probability:

$p(H_s T_m \Phi / L S)$ - the probability of seastate given the location and season.

Step (c) Calculate the encountered climate probability following avoidance seamanship by the master:

$p(H_s' T_m \Phi / L S)$

Step (d) Calculate the probability of initial course and initial speed for a given location and season:

$p(C V_0 / L S)$

Step (e) Calculate the probability of initial course, initial speed and encountered seastate given the location and season:

$p(C V_0 H_s' T_m \Phi / L S)$

Step (f) Calculate the probability of the initial heading, initial speed and encountered seastate given the location and season:

$p(\mu_0 V_0 H_s' T_m \Phi / L S)$

Step (g) Calculate the required single trial probability of final heading, final speed and encountered seastate incorporating pacifying seamanship given the location and season (the scenario probability):

$p^1(\mu V H_s' F / L S)$

Calculation

Step (a) Calculate the transition matrices:

$$T(\mu / \mu_0 V_0 H_s' F) \equiv T(\mu = 30° / \mu_0 = 60° V_0 = 15\,kts\, H_s' = 15\,m\, F = 1)$$

- the probability of final heading given the initial heading, initial speed and encountered seastate (from knowledge of the attained final speeds and headings from the simulations)

Similarly calculate the probability of final speed given the initial conditions:

$$T(V / \mu_0 V_0 H_s' F) \equiv T(V = 12\,kts / \mu_0 = 60° V_0 = 15\,kts\, H_s' = 15\,m\, F = 1)$$

For each wave spectrum family member (F - a function of modal wave period) for a given seastate severity the program runs through all the available combinations of initial heading μ_0 and initial speed V_0, according to the order given previously in table 7.3. For each of these (49) heading/speed combinations, values of final attained heading μ, final speed V and design-extreme roll angle ϕ are calculated by the main program, Table 7.4.

This information is stored in compact matrix form in Table 7.5 and Table 7.6 to show values of final heading given initial heading and final speed given initial speed. For example the tables indicate how an initial heading μ_0 of 60 degrees and an initial speed V_0 of 15 knots gave a final heading μ of 30 degrees and final speed V of 12 knots.

μ_0	V_0	μ	V	φ	μ_0	V_0	μ	V	φ
0	0	0	3	12	90	12	30	6	17
0	3	30	6	14	90	15	90	12	16
0	6	60	12	17	90	18	120	3	13
0	9	90	15	14	120	0	60	9	18
0	12	90	18	15	120	3	0	0	15
0	15	30	15	12	120	6	0	3	22
0	18	90	18	9	120	9	60	15	24
30	0	60	9	17	120	12	0	0	22
30	3	30	0	17	120	15	150	6	19
30	6	90	0	21	120	18	90	6	20
30	9	60	6	25	150	0	30	3	20
30	12	30	6	21	150	3	60	0	15
30	15	60	18	22	150	6	90	18	17
30	18	30	3	19	150	9	90	6	12
60	0	60	0	18	150	12	30	18	15
60	3	90	3	22	150	15	30	12	17
60	6	60	12	27	150	18	60	3	15
60	9	30	12	27	180	0	30	3	5
60	12	30	18	25	180	3	30	3	5
60	15	30	12	35	180	6	30	6	8
60	18	150	9	29	180	9	60	15	9
90	0	30	3	28	180	12	30	3	12
90	3	60	9	28	180	15	0	15	7
90	6	90	15	17	180	18	30	3	5
90	9	90	9	18					

Table 7.4 Example Response Mapping

Enter Initial Heading

1

μ_0						μ	
0	0	30	60	90	90	30	90
30	60	30	90	60	30	60	30
60	60	90	60	30	30	30	150
90	30	60	90	90	30	90	120
120	60	0	0	60	0	150	90
150	30	60	90	90	30	30	60
180	30	30	30	60	30	0	30

Table 7.5 (μ / μ_0)

Enter Initial Speed

V_0

0	3	6	9	12	15	18
3	6	12	15	18	15	18
9	0	0	6	6	18	3
0	3	12	12	18	12	9
3	9	15	9	6	12	3
9	0	3	15	0	6	6
3	0	18	6	18	12	3
3	3	6	15	3	15	3

V

Go To 1

Table 7.6 (V / V_0)

It is required that all of the initial heading/speed $(\mu_0 V_0)$ combinations which resulted in the final attained heading/speed values of $\mu = 30°$ and $V = 12\ kts$ be identified

i.e.

$$\mu_0 = 60 \ \ V_0 = 9$$

$$\mu_0 = 60 \ \ V_0 = 15$$

$$\mu_0 = 150 \ \ V_0 = 15$$

This was achieved by considering the corresponding matrix positions with final heading μ of 30° and final speed V of 12 kts (indicated by the circled positions in table 7.5 and 7.6)

Step(b) - Calculate the required climatology probability (before avoidance seamanship)

$$p(H_s T_m \Phi / LS) = p(F / L) \ . \ p(H_s \Phi / LS)$$

Table 7.7 contains values of the probability of the wave spectrum family member given the location $p(F / L)$. The Ochi 6-parameter spectrum family with 11 members, rather than the JONSWAP spectrum family, is used in this example.

Family Member (F)	Most Probable Spectrum	All Other Spectra
p(F/L)	0.50	0.05

Table 7.7 Wave Spectrum Family Weighting $p(F / L)$
Ochi 6-parameter spectra, Ochi(1978)

Table 7.8 contains values of the joint probability of significant waveheight and primary wave direction for the relevant location L and season S, $p(H_s \Phi / L S)$.

	N.Atlantic (Winter) Area 2 :Sample Size 3526								
Hs	N	NE	E	SE	S	SW	W	NW	Tot.
16							0.1		0.1
15					0.0	0.1	0.1		0.2
13						0.2	0.3	0.0	0.6
11				0.0	0.0	0.7	0.8	0.1	1.6
9.5				0.1	0.1	0.5	1.1	0.1	1.9
8.5	0.1			0.3	0.1	1.4	1.9	0.2	4.0
7.5	0.3	0.1		0.6	0.7	2.0	1.9	0.2	5.8
6.5	0.7	0.2	0.0	0.7	1.1	2.9	1.9	0.3	7.8
5.5	0.8	0.7	0.4	0.9	1.3	4.2	3.5	0.5	12.4
4.5	1.9	1.1	0.4	1.7	2.0	5.7	3.0	0.9	16.6
3.5	3.0	1.5	0.3	1.4	2.5	4.3	2.0	0.9	15.9
2.5	3.4	2.6	0.5	1.7	1.7	4.0	2.7	0.4	17.1
1.5	3.5	1.5	0.3	1.4	1.7	2.6	1.5	0.3	12.7
0.5	0.6	0.6	0.0	0.2	0.8	0.5	0.6	0.0	3.4
Tot.	14.1	8.4	2.0	9.6	12.2	29.3	21.2	3.8	100.0

Table 7.8 Joint Probability of Significant Waveheight and Primary Wave Direction: $p(H_s \Phi) x\, 10^2$

The required climate probability:

$$p(H_s = 15\, F = 1\, \Phi = 270 / L = 2\, S = 4) = p(F = 1 / L = 2) \,.\, p(H_s = 15\, \Phi = 270 / L = 2\, S = 4)$$

$$= 0.50 x\, 0.10 x\, 10^{-2}$$

$$= 5 x\, 10^{-4}$$

Step (c) Encountered climate after avoidance seamanship:

Correspondence with the masters of SULISKER and the sister ship VIGILANT, Dickson (1984) and Rattray (1984), indicated that no avoidance seamanship is attempted for winds less than Beaufort force 8. For winds in excess of force 8 the ships proceed to or remain in sheltered waters until the weather improves.

The example transition matrix of Table 7.9 states that on 10% of the occasions when a significant waveheight H_s of 15m would have been encountered, in the absence of avoidance seamanship, the master's action will result in exposure to a significant waveheight H_s' of 11 m (reading the 15 m column in table 7.9).

Seastate After Avoidance (Hs')	Seastate Before Avoidance (Hs)													
0	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	11	13	15	18+
0.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2
1.5	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.5	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
5.5	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0
6.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0
7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.1	0.0	0.1	0.0	0.2
8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.1	0.0	0.1	0.0
9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1	0.0	0.1
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
18+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4

Table 7.9 Seastate Transition Matrix: $p(H_s'/H_s)$

Similarly on 10% of the occasions when H_s = 15 m would have been encountered a seastate of H_s' = 8.5 m is encountered and again on 20% of occasions a 6.5 m waveheight is encountered. On 40% of the occasions when H_s = 15 m would have been encountered the master either takes no action or takes action which is not effective. On the remaining 20% of occasions when a significant waveheight H_s = 15 m would have been encountered the master opts to proceed to or remain in port. A similar pattern is reflected in the choice of master's action for other seastates when winds greater than force 8 are experienced.

Now, the probability of encountered seastate:

$p(H_s' T_m \Phi / LS)$

$= p(H_s' = 15\, F = 1\, \Phi = 270 / L = 2\, S = 4)$

$$= \int_0^{\infty} p(H_s' / H_s) . p(H_s F \Phi / L S) \quad dH_s$$

$$= \int_0^{\infty} p(H_s' = 15 / H_s) . p(H_s F = 1\, \Phi = 270 / L = 2\, S = 4) \quad dH_s$$

$= 0.40 . 5 x\, 10^{-4}$ (when H_s = 15m) + 0.0 (for all other H_s values - table 7.9)

hence

$$p(H_s' = 15\, F = 1\, \Phi = 270 / L = 2\, S = 4) = 2.0 x\, 10^{-4}.$$

Step (d) Initial Course and speed for a given Location $p(C\, V_0 / L\, S)$

Table 7.10 illustrates an example of an initial course/speed probability matrix for the North Atlantic in winter.

	Initial Speed V_0						
Initial Course C.	0	3	6	9	12	15	18
0	1	0	1	0	1	0	1
15	1	0	1	0	1	0	1
30	1	0	1	0	1	0	1
45	1	0	1	0	0	1	1
60	1	0	1	0	0	1	1
75	1	0	1	0	0	1	1
90	1	0	1	0	1	0	1
105	1	0	1	0	1	0	1
120	1	0	1	0	1	0	1
135	1	0	1	0	1	0	1
150	1	0	1	0	1	0	1
165	1	0	1	0	1	1	1
180	1	0	1	0	1	1	1
195	1	0	1	0	1	1	1
210	1	0	1	0	1	0	1
225	1	0	1	0	1	0	1
240	1	0	1	0	1	1	1
255	1	0	1	0	1	0	1
270	1	0	1	0	1	1	1
285	1	0	1	0	1	0	1
300	1	0	1	0	1	0	1
315	1	0	1	0	1	0	1
330	1	0	1	0	1	0	1
345	1	0	1	0	0	0	1

Table 7.10 Initial Course and Speed Probability $p(C\, V_0 / L\, S) x\, 10^2$

For this example it is assumed that initial speeds of 3 knots and 9 knots are not possible and that all initial courses are equally possible for the initial speeds of 0, 6 and 18 knots. For initial speeds of 12 and 15 knots the situation is more involved.

Step (e) Calculation of the probability of Initial Course and Speed in the Encountered Seastate.

This 7 x 24 matrix of speed/course combinations will combine with the 8 primary wave directions Φ, in some instances to yield the same initial heading to waves (μ_0). Certain of these are not of interest in the light of the data pairs that were identified in step (a).

It is necessary to consider all of the relevant combinations of initial heading (μ_0) and speed (V_0) which gave rise to $\mu = 30°$ and $V = 12$ knots, in the seastate in order to calculate $p(\mu V / \mu_0 V_0 H_s' F)$

i.e. from step (a)

$\mu_0 = 60°, V_0 = 9$ knots
$\mu_0 = 60°, V_0 = 15$ knots
$\mu_0 = 150°, V_0 = 15$ knots

Each of these data pairs has associated with it 2 courses. Recalling that the primary wave direction Φ was 270 degrees then, as example, for the last data pair ($\mu_0 = 150°\ V_0 = 15$ knots) the associated courses will be 240 degrees (T) and 300 degrees (T), Figure 7.9, since $\mu = \Phi - C$.

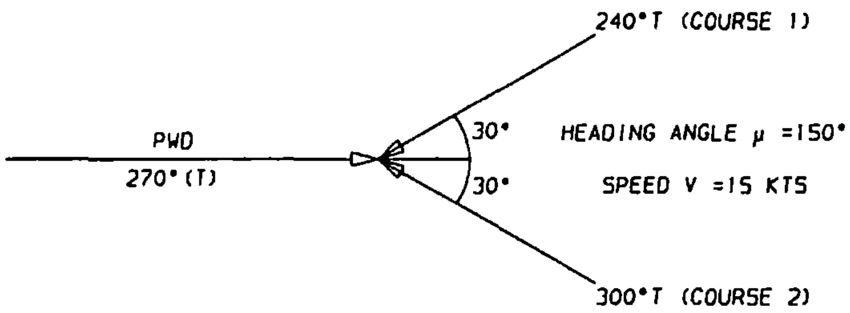


Figure 7.9 Two Courses for a Single Relative Heading to Waves

Hence, $C = 240°$ (T), $V_0 = 15$ kts and $p(C\,V_0) = 1\,x\,10^{-2}$ from table 7.10.

Also $C = 300°$ (T), $V_0 = 15$ kts and $p(C\,V_0) = 0$ from table 7.10.

This process is repeated and the values are given in Table 7.11.

Initial Heading/Speed	Courses	$p(C, V_0)$
μ_0= 60°, V_0= 9 kts	C_1= 030° T	p(30, 9) = 0.00
μ_0= 60°, V_0= 9 kts	C_2= 150° T	p(150, 9) = 0.00
μ_0= 60°, V_0= 15 kts	C_1= 030° T	p(30, 15) = 0.00
μ_0= 60°, V_0= 15 kts	C_2= 150° T	p(150, 15) = 0.00
μ_0= 150°, V_0= 15 kts	C_1= 240° T	p(240, 15) = 0.01
μ_0= 150°, V_0= 15 kts	C_2= 300° T	p(300, 15) = 0.00

Table 7.11 Values of $p(C\,V_0/L\,S)$

Step (f) Calculate the probability of the initial heading, initial speed and encountered seastate given the location and season.

As example consider the case when $\mu_0 = 150°$ and $V_0 = 15\,kts$ in table 7.11.

$$p(\mu_0 V_0 H_s' F/LS) \equiv p(\mu_0 = 150\, V_0 = 15\, H_s' = 15\, F = 1/L = 2\, S = 4)$$
$$= \int_0^{2\pi} p(C\,V_0 = 15/L = 2\,S = 4).p(H_s' = 15\,F = 1\,\Phi = 270/L = 2\,S = 4) \quad dC$$
$$= 0.01\,.\,2x\,10^{-4} + 0.00\,.\,2x\,10^{-4}$$
$$= 2x\,10^{-6}$$

This process is repeated for each of the (μ_0, V_0) values of table 7.11. In this contrived case the resulting values are all zero.

Step (g) Finally, incorporating the pacifying seamanship:

$$p(\mu V H_s' F/LS) = \int_0^{\infty}\int_0^{2\pi} p(\mu V/\mu_0 V_0 H_s' F).p(\mu_0 V_0 H_s' F/LS) \quad d\mu_0\, dV_0$$
$$= \int_0^{\infty}\int_0^{2\pi} p(\mu/\mu_0 V_0 H_s' F).p(V/\mu_0 V_0 H_s' F).p(\mu_0 V_0 H_s' F/LS) \quad d\mu_0\, dV_0$$

(section 6.5)

Thus

$$p(\mu = 30\, V = 12\, H_s' = 15\, F = 1/L = 2\, S = 4)$$
$$= p(\mu = 30/\mu_0 = 150\, V_0 = 15\, H_s' = 15\, F = 1).p(V = 12/\mu_0 = 150\, V_0 = 15\, H_s' = 15\, F = 1).$$
$$p(\mu_0 = 150\, V_0 = 15\, H_s' = 15\, F = 1/L = 2\, S = 4)$$

$= (1/7) x (1/4) x 2 x 10^{-6} = 7.14 x 10^{-8}$

Hence the scenario probability = 7.14×10^{-8}

Thus for this special example this figure is the independent single trial probability of the scenario occuring, in the specified location and season, which gave rise to the design-extreme value of 35 degrees.

Chapter 8

Simulation of the Capsize Probability

8.1. Sensitivity of Roll Motion to Parametric Variation

8.1.1. Introduction

In this section the factors with primary influence on vessel rolling are studied for an operationally meaningful range of speed and sea conditions. This is necessary because the idealised "long-term" calculation of motion probabilities described in Chapter 4, which uses apparently continuous probability distributions, is not possible in practice. This arises because certain of the variables used in the calculation are conceptually discrete (e.g. spatial domain, season) while for others there is insufficient data to provide continuously variable probabilities. One example of this is the vessel's load condition which displays continuous changes over a voyage as well as longer term variation of the lightship weight. This long term variation is largely due to the accumulation of equipment items, corrosion and paint as the vessel ages. The sensitivity study is intended to demonstrate how such variations affect the roll motion so that the complete variation of the motions for each parameter is revealed. It is important that the resulting discretisation scheme for each of the parameters reflects this sensitivity so that the final long-term motion distributions may be accurately assessed from the "integrations" of the (well chosen) discrete probability distributions.

8.1.2. Scope of the Sensitivity Study

The parent vessel used in the study is the F.P.V. SULISKER at the full design displacement condition. Leading particulars are given in Table 8.1. Results were derived from the main simulation program RISK.F77 using transfer functions obtained from the Britsea seakeeping computer programs.

Parameter	Value
Displacement	1532 tonnes
Length Overall	71.03 metres
Length perps.	64.00 metres
Beam mld.	11.60 metres
Draft mld.	4.595 metres
Metacentric Height	0.778 metres
Roll Gyradius	3.90 metres
Yaw Gyradius	16.0 metres
Length/Displacement Ratio M	5.60
Block Coefficient Cb	0.4574
Midship Area Coefficient Cm	0.8464
Waterplane Coefficient Cw	0.7052
Bilge Keel Length	8.68 metres
Bilge Keel Width	0.38 metres

Table 8.1 Parent Vessel, Leading Particulars

Variation of the main hull design parameters was not attempted in this study since a vessel already built was used. A comprehensive study of the seakeeping characteristics of a new design would have included the effect of the variation of hull form parameters on roll. One example of such a study is by Schmitke (1980) for frigate rolling.

The parameters which were varied in this study may be grouped into 2 categories:

a) Internal Parameters Affecting Roll Response:

1. Displacement;
2. Weight distribution (roll gyradius and metacentric height);
3. Trim.

b) External Parameters Affecting Roll Response:

1. Significant Waveheight;
2. Wave period;
3. Wave energy spreading;
4. Wave spectra;
5. Duration;
6. Vessel speed and heading.

A further important consideration is the standard of seamanship demonstrated by the master. This aspect is discussed within the main simulation section.

a) Internal Parameter Variation.

The general philosophy in varying parameters from the parent values is to achieve a reasonably large variation whilst keeping within practical limits. The overall scheme of internal parametric variations is summarised in Table 8.2 and these may be compared against the likely range of vessel load conditions taken from the stability booklet, DTI (1981) - Table 8.3.

Parameter	Low Value	Parent Value	High Value
Δ	1380 (−10%)	1532	1685 (+10%)
GM	0.500 (−36%)	0.778	0.810 (+4%)
Kxx	4.060 (−4%)	4.234	4.408 (+4%)
Trim	0.038 (−31%)	0.055	0.318 (+478%)

Table 8.2 Summary of Internal Parametric Variations used

Parameter	Low Value	Parent Value	High Value
Δ	1229 (−20%)*	1532	1546 (+1%)
GM	0.500 (−36%)*	0.778	0.778 (+0%)
Kxx	no information	4.234	no information
Trim	0.038 (−31%)	0.055	0.318 (+478%)**
	* Light Condition		** Ice Condition

Table 8.3 Range of Actual Parameter Values
(F.P.V. SULISKER Stability Booklet)

It can be seen that the range of internal parameter values used in the sensitivity study (table 8.2) generally encompasses the actual range of parameter values taken from the stability booklet. Exceptions to this rule are the 'low value' of displacement which was the non-seagoing lightship displacement condition and the value of roll gyradius, Kxx, the likely range of values for which has been taken from measured model data, Freeman (1986).

The basis ship condition for all of the realistic variations was given in table 8.1. A ship speed of 10 knots at a heading of 90 degrees to longcrested waves is assumed. The ISSC wave spectrum with significant waveheight of 5 metres and modal period 10 seconds was used in all cases.

b) External Parameter Variation.

External parameter variation was according to Table 8.4. The parent hull was used in all cases for a speed of 10 knots at a heading of 90 degrees to waves. Again, unless otherwise stated, longcrested waves of the ISSC spectrum with significant waveheight 5 metres and modal period of 10 seconds were used throughout.

Parameter	Value Range	Comments
Significant Waveheight (m)	4 – 12	-
Wave Modal Period (sec.)	4 –14	Natural roll period 8.5 sec.
Initial Heading (deg.)	0 – 180	Head Sea 180 deg.
Initial Speed (kts.)	0 – 15	-
Wave Spectrum	Bretschneider Ochi 6-Parameter Jonswap	Longcrest
Wave Energy Spreading	Long/Shortcrest	$\cos^2$ $\cos^4$ 180 deg. spread
Independence Period (hours)	1–60	-

Table 8.4 Summary of External Parametric Variations

The implications of the results of the sensitivity study for the simulation are discussed within the following sections.

8.2. Parameter Values Used in the Main Simulation

8.2.1. Introduction

Figure 8.1 shows the proving ground divided into two distinct climatology domains (labelled 2 and 4) for the simulation. Each domain has associated with it two sub-domains which reflect the different wave conditions (open-sea/fetch-limited) likely to be encountered within the same climate domain:

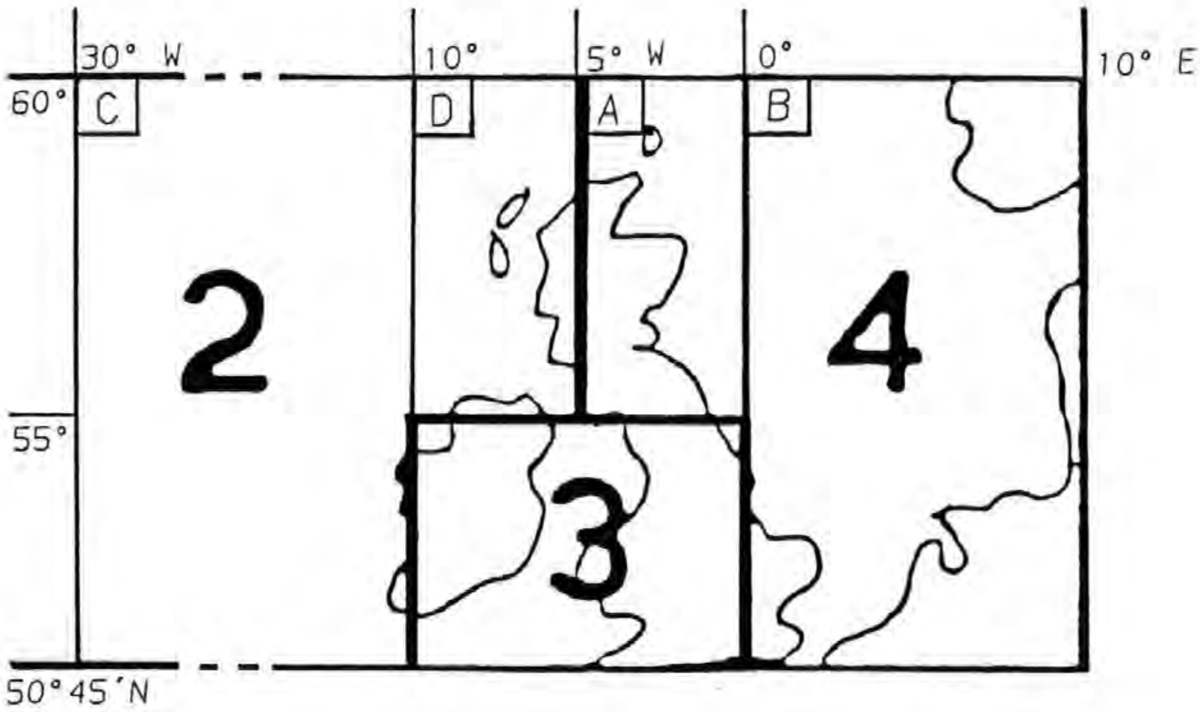


Figure 8.1 Spatial Domains and Sub-Domains

Sub-Domain A

An area along the north-east coast of Scotland, sheltered from the west and with a limited fetch from the south. This is mainly a transit area for the vessel to/from the patrol areas;

Sub-Domain B

An open sea area (mainly) in the northern North Sea (patrol area);

Sub-Domain C

An open sea area in the eastern North Atlantic (patrol area);

Sub-Domain D

An area along the north-west coast of Scotland with limited fetch from the south and east (patrol area).

Sub-domains A and B lie wholly within the spatial domain "4" given in the long-term climatology used in this study, Bales et al (1981). Sub-domains C and D similarly lie within spatial domain "2".

It was assumed that of the total time spent at sea, 10 percent was spent in sub-domain A, 20 percent in sub-domain B with 70 percent being spent in sub-domains C and D combined. This was confirmed by a single voyage analysis of the SULISKER by Spouge (1985).

8.2.2. Displacement Condition

Figure 8.2 shows that the ship internal parameters of displacement, roll gyradius and trim have only a small effect on roll response over the realistic range of parameter values used. Also, that the roll response varies in a linear manner with change in each parameter. Corresponding values for heave and pitch (not shown) indicate virtually no change in response level for each of the above parameters.

Correspondence with the commanding officer of SULISKER, Dickson (1984), and the sister ship VIGILANT, Rattray (1984), confirmed that the operating values of displacement and trim alter very little during a patrol because, as fuel and freshwater is consumed, the ship condition is adjusted by appropriate ballasting. In addition, the stability booklet indicates that the metacentric height will only take values between 0.6 - 0.7 metres for which range of values the resulting roll response may reasonably be assumed constant, figure 8.2.

Thus only one (constant) condition of ship displacement was used in the main simulation and it was not necessary to divide the sea area sub-domains into domain segments each of distinct (different) displacement condition. In this respect the treatment of the SULISKER was unusual. Most merchant and fishing vessels display relatively large variation of displacement, trim and metacentric height particularly between the ballast and fully-laden conditions. Indeed the SULISKER displays small variation of load condition more reminiscent of a naval vessel. The ship condition used was the same full-scale trial condition (designated 4SK) for which good correlation with full scale measured sea trials was obtained in chapter 5.

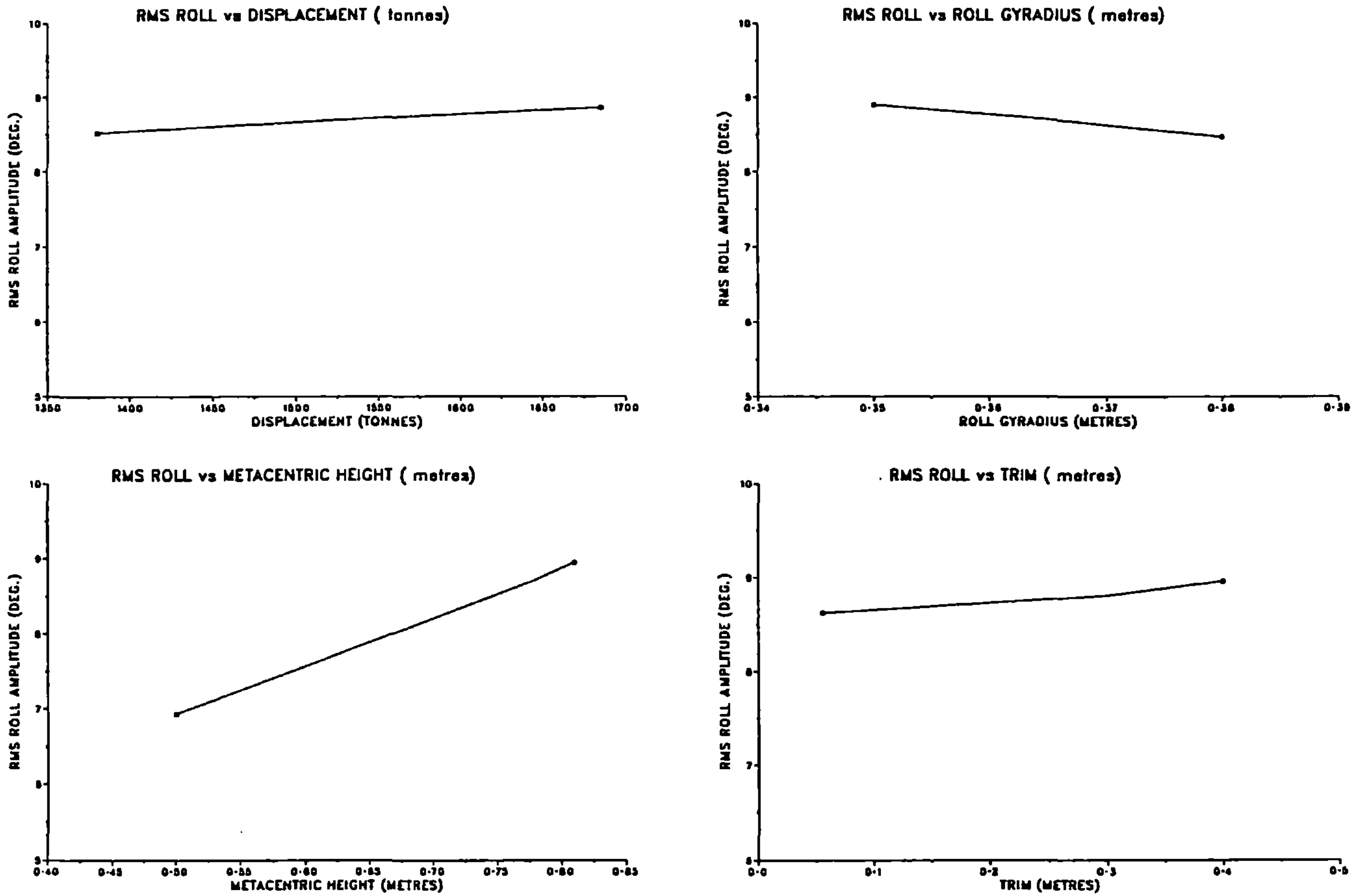


Figure 8.2 Sensitivity Study, Internal Parameters

8.2.3. Wave Climate

• Wave Spectrum

Figure 8.3 shows that RMS roll response effectively varies linearly with significant waveheight. The effect is distinctly non-linear with regard to modal wave period (figure 8.3) since the response is highly tuned to waves with frequency close to the natural roll frequency. For this reason it is important to ensure that values of wave frequency close to the resonant value are not left out of the analysis. For subdomain C, the open-sea area of the North Atlantic, it is appropriate to use the Ochi 6-parameter family of wave spectra to cover the likely range of spectral shapes which occur in practice. This comprises eleven family members i.e. eleven modal periods for any given significant waveheight.

In subdomain D the fetch is limited for winds from the east and southeast. Analysis of the North Atlantic wave climate (later table 8.6) revealed relatively small probabilities of occurence of severe seastates for these wind directions, compared with the probabilities of the (prevailing) winds from the south and west which have the fetch of the whole of the North Atlantic. This was confirmed by correspondence with the ships' masters. It was for this reason that the Ochi 6-parameter (open-sea) family of wave spectra was also used for sub-domain D to predict the severest responses. For subdomains A and B in the North Sea the JONSWAP family of (5) wave spectra was used with the fetch length set as a function of location and primary wave direction.

Figure 8.3 shows that a greater spread of roll response is obtained (for the same sea severity) using the Ochi 6-parameter and Bretschneider 2-parameter families of wave spectra compared with the family of Jonswap spectra.

• Wave Energy Spreading

Figure 8.4 illustrates the effect of different wave energy spreading on RMS roll. Cosine-squared wave energy spreading at ±90 degrees about the primary wave direction was assumed throughout the simulations in all of the sea areas.

The reasons for this were:

a) unidirectional seas are rare;

b) spreading about a predominant wave direction as narrow as ±60 degrees and as broad as ±120 degrees is not rare with ±90 degrees probably representing the most frequent case, Bales et al (1981);

c) the severest seastates generally have a single predominant wave direction, Bales (1984);

d) the 16th International Towing Tank Conference (ITTC) recommended its use in 1981.

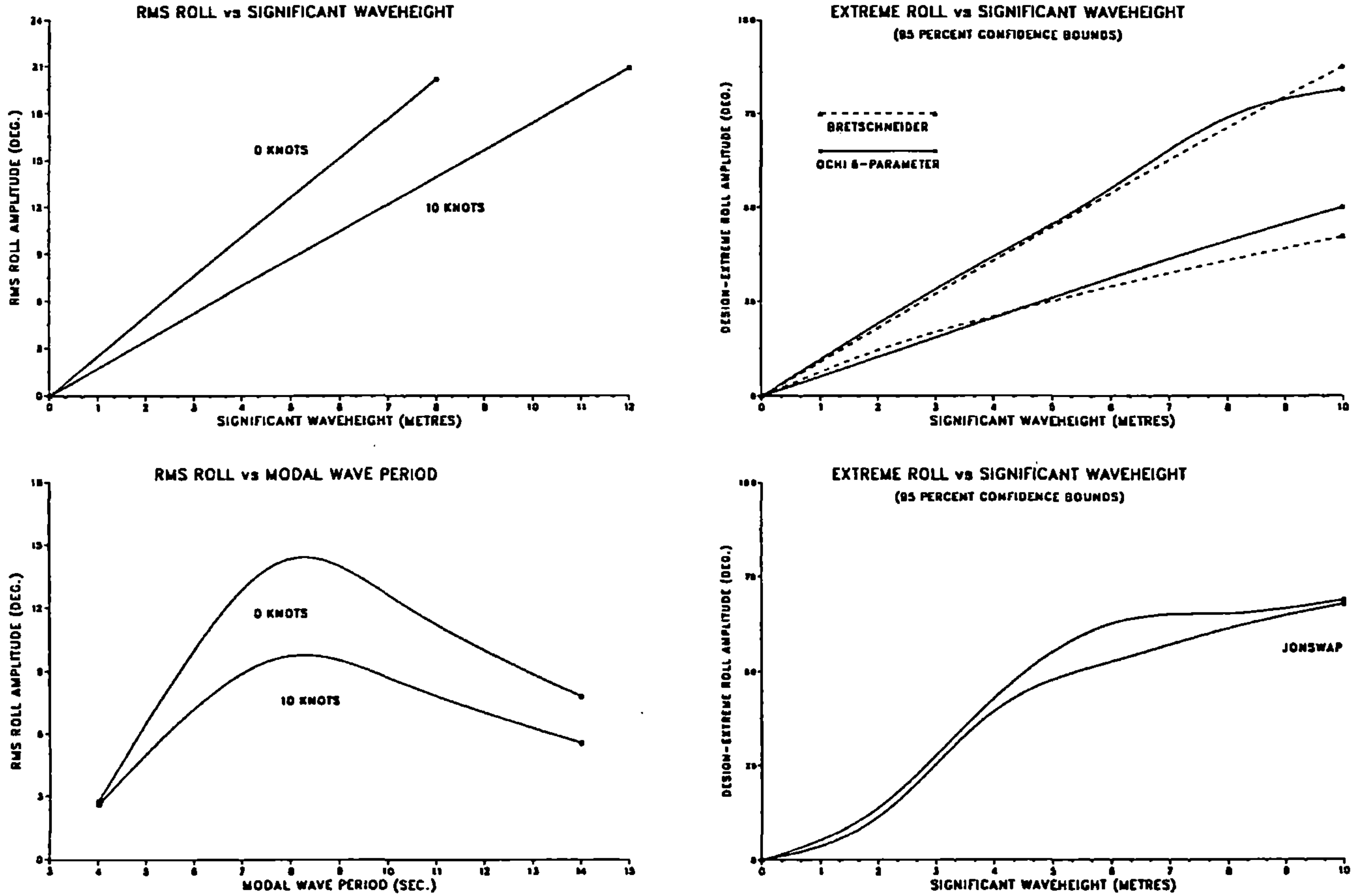


Figure 8.3 Results of Sensitivity Study, External Parameter variation

Further work is required in this area and it is likely that a future refinement would be to use a variable model of directionality for particular operational scenarios in specific geographic areas once they have been verified.

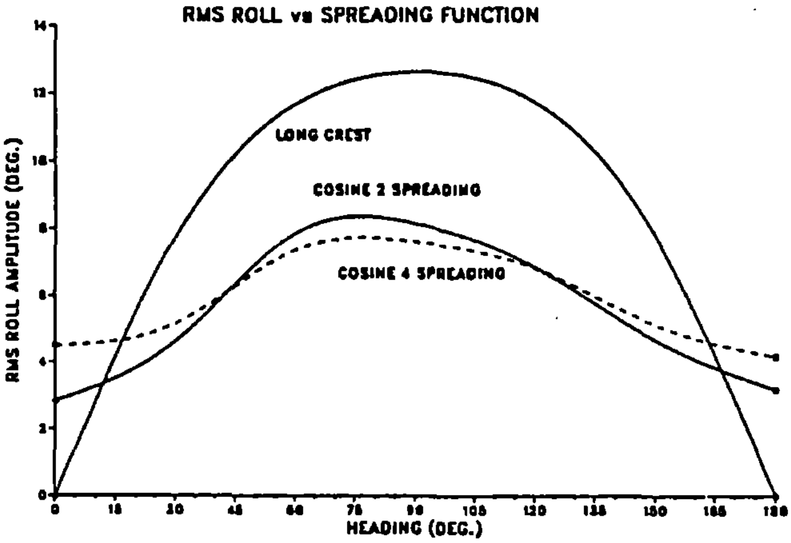


Figure 8.4 Effect of Wave Energy Spreading on Roll

- Probability Aspects

The required joint probability of significant waveheight, modal period and primary wave direction before avoidance seamanship is, as before:

$$p(H_s T_m \Phi) = p(F/L).p(H_s \Phi/LS)$$

where $p(F/L)$ is the probability of the wave family member (Table 8.5) for a given location and $p(H_s \Phi/LS)$ is the joint probability of significant waveheight and primary wave direction for a given location and season.

Location	Family Member										
	1	2	3	4	5	6	7	8	9	10	11
N. Atlantic	0.500	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
N. Sea	0.081	0.26	0.33	0.26	0.081						

Table 8.5. Wave Spectrum Family Weighting

Values of the joint probability of significant waveheight and primary wave direction, $p(H_s \Phi/LS)$, for the North Atlantic and North Sea climate domains are given in Table 8.6. and Table 8.7 respectively.

Hs	N.Atlantic (Spring) Area 2 :Sample Size 3371								
	N	NE	E	SE	S	SW	W	NW	Tot.
18						0.1			0.1
15						0.1			0.1
13						0.2	0.1		0.3
11						0.3	0.5		0.7
9.5						0.4	0.3	0.0	0.7
8.5				0.1	0.1	0.5	0.6	0.1	1.3
7.5			0.0	0.4	0.1	0.7	1.2	0.1	2.5
6.5	0.2	0.1	0.1	0.4	0.3	1.1	1.7	0.4	4.4
5.5	0.4	0.3	0.1	0.9	0.7	2.1	2.4	0.4	7.2
4.5	0.8	0.8	0.3	1.5	1.3	3.9	2.4	0.7	11.6
3.5	1.6	1.3	0.4	2.6	1.4	6.0	3.5	0.9	17.7
2.5	2.9	2.5	0.7	1.6	2.3	6.0	2.9	1.1	20.3
1.5	3.6	4.0	1.1	1.8	2.3	5.4	2.9	0.8	21.8
0.5	1.9	2.6	0.4	0.3	2.2	2.0	1.3	0.5	11.2
Tot.	11.5	11.7	3.1	9.6	10.8	28.5	18.7	5.1	100.0

Hs	N.Atlantic (Summer) Area 2 :Sample Size 3180								
	N	NE	E	SE	S	SW	W	NW	Tot.
18									
15									
13									
11									
9.5						0.0			0.0
8.5						0.1	0.1		0.2
7.5						0.1	0.1		0.2
6.5						0.0	0.3	0.1	0.4
5.5	0.0			0.1	0.1	0.4	1.0	0.1	1.8
4.5	0.1	0.1		0.2	0.4	1.5	1.8	0.1	4.2
3.5	0.1	0.1		0.8	0.9	4.2	3.1	0.3	9.5
2.5	0.7	0.5	0.2	1.7	2.2	10.2	5.4	1.3	22.0
1.5	3.6	3.6	0.5	1.9	1.8	11.7	8.5	2.1	33.5
0.5	3.2	5.5	0.8	0.8	1.9	7.3	4.5	2.6	28.4
Tot.	8.7	9.5	1.5	5.7	7.5	35.5	24.6	6.7	100.0

Hs	N.Atlantic (Autumn) Area 2 :Sample Size 3180								
	N	NE	E	SE	S	SW	W	NW	Tot.
18									
15						0.1			0.1
13						0.0	0.1		0.1
11						0.3	0.3	0.1	0.8
9.5					0.1	0.3	0.3	0.0	0.9
8.5				0.1	0.1	0.4	0.6	0.1	1.3
7.5	0.1			0.1	0.0	0.8	1.3	0.5	2.7
6.5	0.2	0.1		0.1	0.2	1.7	2.1	0.3	4.8
5.5	0.3	0.7	0.1	0.8	0.7	2.8	2.9	0.6	8.8
4.5	1.1	1.0	0.1	1.3	1.1	4.0	4.9	0.6	14.2
3.5	1.8	1.9	0.1	1.1	1.6	5.1	4.9	1.2	17.8
2.5	1.9	2.3	0.5	2.8	2.7	8.5	3.7	0.8	23.0
1.5	2.7	3.1	0.4	1.5	1.6	4.0	4.4	0.5	18.2
0.5	1.3	1.3	0.0	0.7	0.8	1.7	1.8	0.2	7.6
Tot.	9.4	1.5	1.3	8.8	8.9	28.4	28.1	9.0	100.0

Hs	N.Atlantic (Winter) Area 2 :Sample Size 3528								
	N	NE	E	SE	S	SW	W	NW	Tot.
18							0.1		0.1
15					0.0	0.1	0.1		0.3
13						0.2	0.3	0.0	0.6
11				0.0	0.0	0.7	0.8	0.1	1.6
9.5				0.1	0.1	0.8	1.1	0.1	1.9
8.5	0.1			0.3	0.1	1.4	1.9	0.2	4.0
7.5	0.3	0.1		0.6	0.7	2.0	1.8	0.2	5.8
6.5	0.7	0.2	0.0	0.7	1.1	2.9	1.9	0.3	7.8
5.5	0.8	0.7	0.4	0.9	1.5	4.2	3.5	0.5	12.4
4.5	1.9	1.1	0.4	1.7	2.0	5.7	3.0	0.9	16.6
3.5	3.0	1.5	0.3	1.4	2.5	4.3	2.0	0.9	15.9
2.5	3.4	2.6	0.5	1.7	1.7	4.0	2.7	0.4	17.1
1.5	3.6	1.5	0.3	1.4	1.7	2.8	1.5	0.3	12.7
0.5	0.8	0.6	0.0	0.2	0.6	0.5	0.8	0.0	3.4
Tot.	14.1	8.4	2.0	9.6	12.2	29.3	21.2	3.8	100.0

Table 8.6 $p(H_s\,\Phi)$: North Atlantic

Hs	North Sea (Spring) Area 4 :Sample Size 3548								
	N	NE	E	SE	S	SW	W	NW	Tot.
18									
15									
13									
11	0.0							0.0	0.1
9.5							0.1	0.3	0.4
8.5	0.0						0.2	0.2	0.5
7.5	0.0						0.7	0.3	1.1
6.5	0.0					0.2	0.8	0.4	1.4
5.5	0.1		0.1			0.3	1.5	0.8	2.8
4.5	0.3		0.3	0.1	0.2	0.6	1.5	1.3	4.5
3.5	0.2	0.0	0.4	0.4	0.9	0.9	3.2	1.4	7.4
2.5	2.7	0.4	1.9	1.4	2.3	2.4	7.0	3.1	21.2
1.5	4.3	1.4	5.2	2.9	4.2	2.3	8.2	7.5	35.9
0.5	4.7	0.9	3.4	0.7	1.7	1.3	4.2	9.5	26.4
Tot.	12.4	2.8		5.5	9.3	8.2	25.4	24.9	100.0

Hs	North Sea (Summer) Area 4 :Sample Size 3548								
	N	NE	E	SE	S	SW	W	NW	Tot.
18									
15									
13									
11									
9.5									
8.5									
7.5	0.1								0.1
6.5	0.1							0.0	0.1
5.5	0.0							0.3	0.4
4.5	0.6					0.2	0.5	0.8	2.3
3.5	0.6				0.0	0.4	1.7	1.5	4.2
2.5	0.8			0.0	0.8	3.1	6.4	4.5	15.6
1.5	2.6	0.4	2.4	1.0	3.7	4.8	10.9	7.1	33.1
0.5	6.2	1.7	3.4	1.0	3.4	2.3	12.8	13.4	44.3
Tot.	11.4	2.1	5.8	2.0	7.8	10.8	32.3	27.8	100.0

Hs	North Sea (Autumn) Area 2 :Sample Size 3180								
	N	NE	E	SE	S	SW	W	NW	Tot.
18									
15									
13									
11									
9.5							0.3		0.3
8.5							0.0		0.0
7.5							0.3	0.1	0.4
6.5	0.1					0.2	0.5	0.2	1.0
5.5	0.2				0.1	0.5	0.9	0.7	2.4
4.5	0.5			0.0	0.1	0.9	1.8	0.6	3.9
3.5	0.8	0.9	0.3	0.3	2.4	3.0	3.2	1.9	12.8
2.5	1.2	0.6	1.4	1.4	2.9	4.4	7.4	3.1	22.4
1.5	3.3	0.3	4.4	3.8	4.2	3.5	7.4	5.3	32.2
0.5	5.8	0.3	2.4	1.7	2.3	0.4	4.1	7.9	24.7
Tot.	11.7	1.9	8.5	7.2	12.0	12.8	25.9	19.8	100.0

Hs	North Sea (Winter) Area 4 :Sample Size 3528								
	N	NE	E	SE	S	SW	W	NW	Tot.
18							0.0		0.0
15							0.1		0.1
13							0.1		0.1
11	0.1							0.1	0.2
9.5							0.2	0.2	0.4
8.5	0.1						0.5	0.3	1.0
7.5	0.1						0.4	0.4	1.0
6.5	0.3	0.0			0.1	0.2	1.8	0.4	2.8
5.5	0.4		0.1	0.1	0.1	1.2	1.6	1.2	4.7
4.5	0.3		0.2	0.2	0.4	1.8	2.5	2.4	7.8
3.5	2.9		0.4	0.4	2.4	2.5	4.9	2.5	16.0
2.5	2.7	0.0	2.4	1.4	3.0	2.6	5.4	5.8	23.0
1.5	4.2	1.7	4.3	1.8	3.5	1.8	5.4	5.4	27.9
0.5	3.2	0.5	1.5	0.6	0.4	0.3	4.1	4.6	15.2
Tot.	14.3	2.3	8.9	4.4	9.9	10.3	28.6	23.4	100.0

Table 8.7 $p(H_s\,\Phi)$: North Sea

This represents a 10 year (long-term) average of the wave conditions in each area and season, Bales et al (1981). In the medium-term (on a voyage by voyage basis) it is inevitable that the vessel will experience seastates which are more severe than the long-term average conditions. The medium-term climate is simply a sample drawn from the long-term climate and will display variability above (and below) the mean. The results of the sensitivity study confirmed that the greatest effect on vessel motions is likely to be due to the variability in the encountered wave climate and thus, ideally, this variability should be taken into full account. One approach would be to compute individual motion results for each of (in this case) 10x12 monthly hindcast periods and this would demonstrate the complete climate variability as far as is possible. Equally, it is important when predicting long-term (average) performance to use reliable long-term wave climate statistics and not the wave data from any individual voyage, month or season which may be quite untypical of the climate.

The proposed method falls somewhere between these two extremes. On the one hand it is desirable that the method should predict every conceivable instance when capsize could occur (with the associated probability of occurence) for each individual vessel. On the other hand it is desirable that the method should be capable of incorporation as a stability assessment procedure which requires that typical plausible and consistent values be used.

Thus in this preliminary study the 10 year average hindcast climatology was used. The necessary refinement of the method to account for medium-term climate variability between different medium-terms may require an unacceptable 30 fold increase in the number of runs through the program. Indeed further work is required to assess how best to incorporate climate variability in order that the framework might be used for correlation purposes. An alternative likely way forward is to use, say, a 95 or 99 percentile sea severity to give expected bounds of extreme motion.

8.2.4. Avoidance Seamanship

Correspondence with the Fleet Support Unit of the Department of Agriculture and Fisheries for Scotland, Corse (1984), revealed typical values of the sea areas by season in which the fisheries protection vessels SULISKER and VIGILANT may be expected to operate.

It was reported that typically 254 days are spent at sea and 111 days in port. In addition the master of VIGILANT indicated that "There are many occasions in winter when winds are in excess of force 9, the ship proceeds to or remains in sheltered waters until weather conditions improve", Rattray (1984). Assuming that no avoidance seamanship is attempted for wind strengths less than force 9 gave the following avoidance seamanship transition matrix of Table 8.8.

Seastate After Avoidance (Hs')	Seastate Before Avoidance (Hs)													
0	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	11	13	15	18+
0.5	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.20	0.20
1.5	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.5	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.5	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.5	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.5	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00
6.5	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00
7.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.15	0.00
8.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.25	0.00	0.00	0.15
9.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.25	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.25	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.25
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00
18+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40

Table 8.8 Seastate Transition Matrix $p(H_s'/H_s)$

This shows that no avoidance seamanship would be attempted for seastates of less than 11 metres significant waveheight (Beaufort wind force 8/9). There is a uniform treatment of all seastate severities of 11 metres and above which is summarised in Table 8.9.

Percentage Reduction in Seastate Severity	p(Hs'/Hs)
0% (no change)	0.4
25%	0.25
50%	0.15
100% (proceeds to or remains in port)	0.2

Table 8.9 Summary of Avoidance Seamanship

It is assumed that on 40 percent of occasions the master either takes no action or takes avoidance seamanship which is not effective. On 25 percent of occasions avoidance seamanship enables the vessel to obtain some degree of shelter resulting in a 25% reduction in waveheight. On 15 percent of occasions a corresponding reduction of 50% is assumed. Finally (for seastates of 11m and above) it is assumed that on 20 percent of occasions the vessel remains in or returns to port.

This is a somewhat subjective area of the analysis which is dependent on the individual master. Assumed values must be used in the absence of a statistical analysis of previous avoidance seamanship.

As the result of the avoidance seamanship the seastate actually encountered is given by:

$$p(H_s^{'} F \Phi / LS) = p(H_s^{'} / H_s) . p(H_s F \Phi / L S)$$

8.2.5. Initial Course and Speed

The main problem to be addressed is how to define a typical operating pattern in order to determine the likely combinations of intended heading and speed.

Figure 8.5 shows that response in roll is very sensitive to the vessel speed and heading to waves. Roll response is particularly non-linear with respect to heading and the figure emphasises the need for a fine discretisation mesh of headings to be used in order that severe responses are not overlooked. This is achieved within the risk model by enabling the simulated vessel to achieve any desired course between 0° (T) and 345° (T) in 15 degree increments. In addition, the vessel was able to achieve any intended speed between 0 and 18 knots in 3 knot increments.

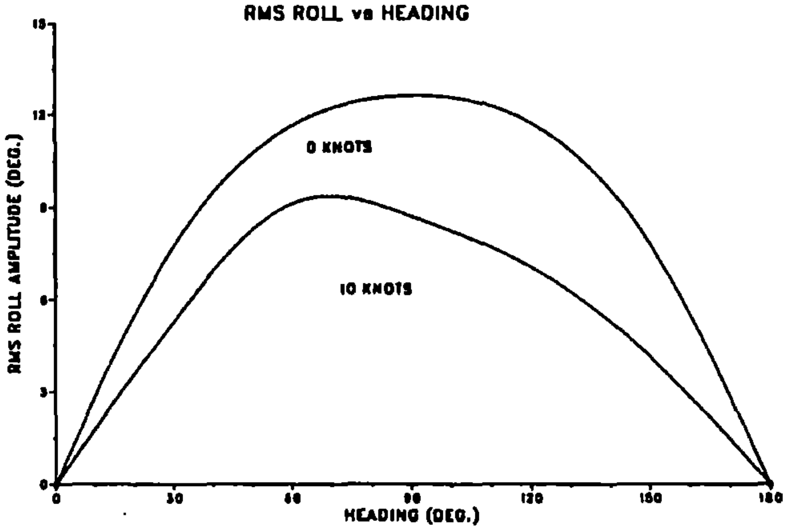
The SULISKER is based at Leith. Her patrol area extends out to the median line with Norwegian waters in the east, and to the 200 mile limit north and west of Rockall and the Shetlands, although she usually patrols around the Scottish islands and westwards out to the 100 fathom line. The patrol area is reached from the Firth of Forth by the east coast thence to westward mainly through Pentland Firth. At times the route is varied by using the westward leg via the Fairisle Passage or a more northerly route is taken about Shetland.

The SULISKER displays operating profile characteristics which are a combination of a merchant vessel, having a well defined transit route to the patrol areas, as well as those of a small warship or fishing vessel which is required to hunt prey on an opportune basis. Her routine task is to patrol the Scottish fishing grounds, gathering information for the Department of Agriculture and Fisheries for Scotland (DAFS), and checking that the fishing vessels are operating within the law. In calm weather the fishing vessels may be boarded, otherwise they are questioned by radio. The SULISKER may also be used for cleaning up oil spillages and to undertake a firefighting role if necessary. At times the patrol area is the northern North Sea. The patrol frequency is not influenced by the time of year since it is reported that "there are numerous occasions in the summer when severe gales can be experienced, but these generally do not last more than a couple of days, and patrols are not restricted unduly at this time of year", Rattray (1984).

Values of the joint probability of initial (intended) course C and speed V_0 are obtained from:

$$p(C\,V_0) = p(C) . p(V_0)$$

Values of the course probability, $p(C)$ are given in Table 8.10 for each subdomain location in figure 8.1.



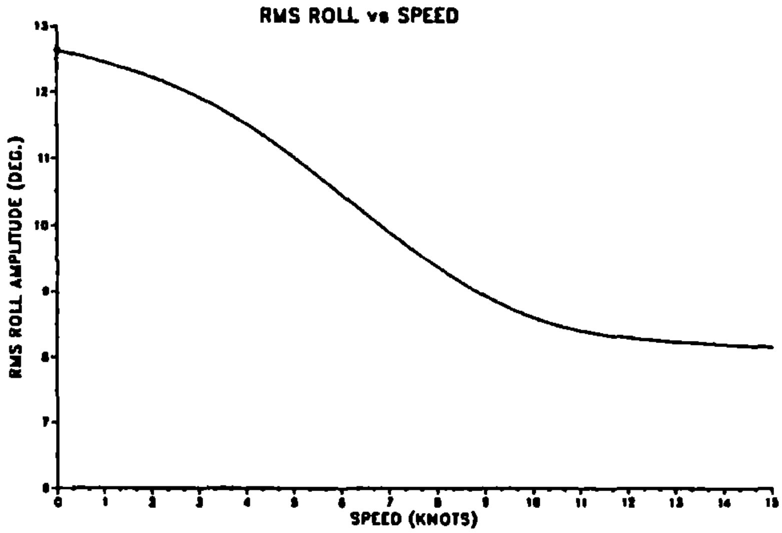


Figure 8.5 Roll Response to Vessel Heading and Speed

Course	p(C)	Course	p(C)	Course	p(C)	Course	p(C)
0	0.01	90	0.01	180	0.01	270	0.01
15	0.01	105	0.01	195	0.01	285	0.01
30	0.39	120	0.01	210	0.39	300	0.01
45	0.01	135	0.01	225	0.01	315	0.01
60	0.01	150	0.01	240	0.01	330	0.01
75	0.01	165	0.01	255	0.01	345	0.01

$p(C)$ Subdomain A

Course	p(C)
0	0.04167
15	0.04167
30	0.04167
|	|
345	0.04167

$p(C)$ Subdomains B, C, D.

Table 8.10 Values of $p(C)$: All Areas

Subdomain "A" is strictly a transit area to and from the patrol areas. A medium-term voyage analysis would reflect these constraints on the initial courses in detail. However, since the aim of the present study is to "license" the vessel for operation anywhere within the subdomain "A", thus other course probabilities are admitted while still maintaining a strong bias towards transit course values of 030°T and 210°T.

In subdomains B,C,D it is assumed that (while on patrol) there is a uniform probability of intended course value.

Values of the probability of initial (intended) speed are given in Table 8.11.

V_0	$p(V_0)$
0	0.05
3	0.00
6	0.00
9	0.05
12	0.00
15	0.90
18	0.00

$p(V_0)$ Subdomain A

V_0	$p(V_0)$
0	0.05
3	0.00
6	0.00
9	0.30
12	0.00
15	0.60
18	0.05

$p(V_0)$ Subdomains B, C, D.

Table 8.11 Values of $p(V_0)$ All Areas

It is assumed that while on transit in subdomain A the vessel will tend to cruise at an intended speed of 15 knots, which is close to the two-engine cruising speed value. Some occasions of 0 knots and the single engine cruising speed of 9 knots are also admitted. These are attained speeds i.e. no allowance is made for added resistance in waves within the simulation.

For subdomains B,C and D values are used which are based on a single voyage monitoring of the SULISKER by Spouge (1985). It can be observed that the ship spent most time near its two engine cruising speed but also reduced to the single engine cruising speed of 9 knots on occasion. In addition to the monitored values some occurences of 0 knots (station keeping) and 18 knots (full speed) are admitted. Thus values of $p(C\,V_0)$ are given in Table 8.12 for all subdomains. The table for the transit subdomain "A" reflects the strong bias towards the reciprocal course values of 030°T/210°T and speeds close to the two engine cruising speed. It is inevitable that there will be a certain degree of subjectivity with the values used but, provided comparative assessments of survivability between vessels (or for the same vessel) are intended over the same proving ground, this is not considered a problem. Correlation exercises would require that actual values be used whenever possible.

Initial Course C.	Initial Speed V_0						
	0	3	6	9	12	15	18
0	5	0	0	5	0	90	0
15	5	0	0	5	0	90	0
30	195	0	0	195	0	3,510	0
45	5	0	0	5	0	90	0
60	5	0	0	5	0	90	0
75	5	0	0	5	0	90	0
90	5	0	0	5	0	90	0
105	5	0	0	5	0	90	0
120	5	0	0	5	0	90	0
135	5	0	0	5	0	90	0
150	5	0	0	5	0	90	0
165	5	0	0	5	0	90	0
180	5	0	0	5	0	90	0
195	5	0	0	5	0	90	0
210	195	0	0	195	0	3,510	0
225	5	0	0	5	0	90	0
240	5	0	0	5	0	90	0
255	5	0	0	5	0	90	0
270	5	0	0	5	0	90	0
285	5	0	0	5	0	90	0
300	5	0	0	5	0	90	0
315	5	0	0	5	0	90	0
330	5	0	0	5	0	90	0
345	5	0	0	5	0	90	0

$p(C\,V_0)$ Subdomain A

Initial Course C.	Initial Speed V_0						
	0	3	6	9	12	15	18
0	20.833	0	0	125	0	250	20.833
15	20.833	0	0	125	0	250	20.833
30	20.833	0	0	125	0	250	20.833
45							
60							
75							
90							
105							
120							
135							
150							
165							
180							
195							
210							
225							
240							
255							
270							
285							
300							
315							
330							
345	20.833	0	0	125	0	250	20.833

$p(C\,V_0)$ Subdomains B, C, D.

Table 8.12 Values of $p(C\,V_0)x10^4$, All Areas

8.2.6. Independent Trials Cycles

In order to use the Bernoulli trials procedures for combining the scenario probabilities (Appendix A4) it is necessary to ensure scenario independence. In chapter 4 it was explained how this is achieved by using the concept of an independence period T_* - the time that must elapse between two scenarios for them to be considered independent.

Thus the expected number of independent trial samples for each sub-domain location (L) and season (S) for this long-term calculation is found from:

$$N=\frac{R}{VT_*}$$

where

R is taken as the average (maximum) course-track distance

V is the average vessel speed relative to the advancing weather

T_* is the average independence period

The value of the average independence period T_* was based on heuristic arguments by Hutchison (1981) given an absence of firm calculated values. Thus a value of 24 hours was used for the North Atlantic domain and 20 hours was used for the more enclosed domain of the North Sea. This is a reasonable assumption for the present long-term comparative study but a medium-term study or a correlation study would require that the degree of correlation of adjacent seastates be correctly ascertained.

The average distance/speed in each sub-domain R should strictly be given as a function of attained course/speed - after both avoidance and pacifying seamanship have taken place. If the assumption is made that on most occasions of mild/moderate sea conditions no alteration of course or speed from the intended values would be necessary, and that only a small deviation is necessary for the remainder, then it is reasonable to use intended values rather than attained values of distances and speeds.

The required average course track distance in each sub-domain was obtained as the weighted sum of all possible course track distances multiplied by their respective probabilities of occurence. The distances were taken to be the maximum traversible distance on each intended course in each sub-domain in order that the vessel might be licensed to operate anywhere within the proving ground, Table 8.13.

The required average speed relative to the advancing weather conditions is more difficult to obtain, being a function of both the location and the predominant wind direction in each season. Again, given the long-term nature of the calculation it is considered reasonable to use the average intended vessel speed in each sub-domain location. On a roughly equal number of occasions the vessel will be travellling with/against the prevailing weather conditions. The weighted sum of all intended speeds multiplied by their respective probabilities of occurence were used. Table 8.14 summarises the calculations.

Course Attained (T)	Subdomain A	B	C	D
0	300	555	555	300
15	200	574	574	310
30	160	616	641	308
45	145	435	785	218
60	135	356	794	178
75	140	318	712	159
90	154	308	688	154
105	159	318	712	150
120	178	356	794	178
135	218	435	785	218
150	308	616	641	309
165	310	574	574	310
180	300	555	555	300
195	200	574	574	310
210	160	616	641	308
225	145	435	785	218
240	135	356	794	178
255	140	318	712	159
270	154	308	688	154
285	159	318	712	159
300	178	356	794	178
315	218	435	785	218
330	308	616	641	308
345	310	574	574	310

Table 8.13 Maximum Course Track Distances (N.Miles), All Sub-domains

	Sub–domain A	B	C	D
Average Distance R (N.miles)	225	455	688	233
Average Speed V (knots)	13.95	12.60	12.60	12.60
Independence Period T_* (hours)	20	20	24	24
Number of Bernoulli Cycles N	0.81	1.80	2.28	0.77

Table 8.14 Summary of Independent Trials Calculation

8.3. Main Simulation Results

8.3.1. Computation

The motion simulation and probability calculations were performed by a PRIME 6350 super-mini computer. The results for each sub-domain and season were processed separately and the probability information combined using the principles of chapter 4.

The maximum possible number of computer program iterations, for one displacement condition, was given by:

- North Atlantic

$L \times S \times \Delta \times H_s \times \Phi \times F \times \mu_0 \times V_0$

$2 \times 4 \times 1 \times 14 \times 8 \times 11 \times 7 \times 7 = 482,944$

- North Sea

$L \times S \times \Delta \times H_s \times \Phi \times F \times \mu_0 \times V_0$

$2 \times 4 \times 1 \times 14 \times 8 \times 5 \times 7 \times 7 = 219,520$

Total = 702,464

In addition, the master may try up to 48 combinations of heading and speed during his attempt to reduce excessive motions and sea-loads. Thus potentially there were approximately 34 million program iterations during the simulation.

Certain simplifications were made in order to reduce this number of calculations:

1. Sub-domains C and D were treated as one large area and the average maximum traversible distances "R", in the independence cycle calculation, adjusted accordingly.
2. A test was made at the start to ensure that only physically realiseable values of significant waveheight and primary wave direction were used.
3. It was assumed that the master, for the same seastate severity (characterised by its spectrum, significant waveheight, wave direction and family member) will always choose the same optimum heading/speed combination regardless of the original intended heading/speed combination.

These savings reduced the total number of program iterations from around 34 million to approximately 256,000. This is still a considerable number when it is considered that four-dimensional matrices of 27,000 data elements occur frequently within the program although this does include short-crested seaways.

No attempt was made to use the linearity of vessel motions with respect to significant waveheight or to interpolate for the smooth variation of roll motion with ship speed, in order to reduce the calculations. This would have increased the file handling complexity considerably.

In using a JONSWAP wave spectrum family, a 5 fold increase of the number of computations over the more usual single wave spectrum formulation was experienced, with an 11 fold increase when using the Ochi 6-parameter wave spectrum family. It was observed that for many of the severest seastates all of the family members produced motions in excess of the maximum seakeeping criteria allowed. This at least suggests that, when calculating the probability of a critical roll motion being exceeded, certain of the severest seastates may be represented by an appropriately weighted single wave spectrum. Only when the seastate, characterised by significant waveheight, was reduced did certain of the family members disappear from the extreme roll response results.

8.3.2. Results

The single independent trial probability of critical motion exceedance was obtained for each sub-domain and season in order to locate the particularly hazardous segments of the test-track, Table 8.15.

	$p'(\phi>\phi_c)\times10^3$			
Sea Area	Spring	Summer	Autumn	Winter
North Sea				
Transit Subdomain "A"	8.182	2.974	6.475	19.481
Patrol Subdomain "B"	11.118	2.502	8.054	21.580
North Atlantic				
Patrol Subdomain "C&D"	41.140	10.293	42.353	70.411

Table 8.15 Values of the Single Independent Trial Probability

It may be observed that operations in the North Atlantic (subdomains "C&D") are particularly hazardous. They account for almost 60.5% of the cumulative probability value before any account is taken of location probability and number of independent trial cycles. This value may be largely attributed to the more severe seastates encountered in all seasons. Corresponding values for the (transit) subdomain "A" and (patrol) subdomain "B" are 23.5% and 16.0% of the total probability respectively, with the larger value for "A" reflecting the severely fetch-limited wave conditions in this sea area. Operations in the North Atlantic in the winter months are particularly hazardous -yielding the largest single contribution to the total probability.

Final probabilities were obtained by the principles of chapter 4 using parameter values described in earlier sections. Table 8.16 shows values of the multiple independent trial probabilities after the vehicle location, season and number of independent trial samples was incorporated. As was previously noted, no allowance was necessary for the location being constrained by operating season.

	$p^N(\phi>\phi_c)\times10^4$			
Sea Area	Spring	Summer	Autumn	Winter
North Sea				
Transit Subdomain "A"	2.046	0.744	1.619	4.870
Patrol Subdomain "B"	5.591	1.251	4.027	10.790
North Atlantic				
Patrol Subdomain "C&D"	71.994	18.012	74.117	123.219

Table 8.16 Values of the Multiple Independent Trial Probabilities

When these factors are taken into account, operations in the North Atlantic account for almost 94 percent of the total Proving Ground value of 4.951×10^{-2}. This represents the probability that the potentially dangerous roll angle of 30 degrees would be exceeded at least once on the passage through the proving ground, which represents a lifetime of operation.

Major factors which may have influenced this result include:

1. the assumption that no fin stabilisers were used. This was a failing of Britsea to account for roll damping due to active fins. This will tend to increase the probability of critical roll motion exceedance obtained from the simulations.
2. the assumption that the master will infallibly select the "best" heading/speed combination. In the first case, for the severest seastates when it is necessary to choose an optimum combination of heading and speed, this will always tend to reduce the probability by definition.

   In the second case the master selects the heading/speed combination which simultaneously gives least deviation from the intended track and satisfies the vertical motion seakeeping criteria. The effect of this on the motion probabilities will vary depending upon the values of extreme roll which are experienced. However, this is a secondary influence on the overall probability of critical motion exceedance.
3. certain of the capsize phenomena have not been modelled i.e. only a single "general ship rolling" test-track has been used. This will have two effects. The most obvious is that the attained final probability value will be smaller than actual due to the exclusion of capsize phenomena. Secondly, the vessel will tend to favour headings and speeds which would normally be avoided in practice. Thus there is a tendency for the vessel to assume high speed in following or quartering seas when broaching and parametric resonance is likely to be a problem.
4. steady wind-heel and wind gusting effects were not considered.

These factors are future refinements to the existing program. In order to investigate (2) the program was amended so that the master was further constrained in his choice of an optimum heading/speed combination in the severest seas. Correspondence with the officers commanding SULISKER and the sister vessel VIGILANT indicated that in severe weather conditions there is a tendency to reduce speed and to keep the seas on either bow. Adjustment of the master's action was made so that an optimum heading/speed combination was chosen only from among the motion results obtained for seas forward of the beam. Although larger roll angles were experienced than without these additional constraints, the original assumption of a uniform distribution of initial desired courses when the vessel is on patrol, tended to yield very similar scenario probabilities. The situation for lower seastates was unchanged when no decision regarding an optimum was required. Thus for the hazardous North Atlantic, which accounts for 94% of the Proving Ground probability little change was experienced and it may be concluded that, for the SULISKER, the probability of critical motion exceedance is of the order of 5×10^{-2}.

The value of 5.0×10^{-2} that was obtained from the simulation is not the same as the actual risk of vessel capsize. Rather, it represents the probability that a roll angle of 30 degrees will be exceeded at least once during the lifetime of the vessel. Thus it may be argued that it is more representative of the probability of being overwhelmed by the seaway which could eventually lead to a capsize. Unfortunately, the corresponding actual probability of loss is difficult to determine from casualty data because the vessel used in this study has a highly specialised role and there are relatively few of this type in service. However, as a rough guide, close examination of fishing vessel casualty statistics presented in chapter 1 indicates a value of 2.3×10^{-3} for the probability of being overwhelmed by the seaway (vessels capsized, foundered and missing). The value obtained from the simulation for the SULISKER, which is reported to have good seakeeping characteristics, represents the larger probability of exceedance of a potentially dangerous roll motion. The inadequacy of present knowledge of the basic physical processes immediately prior to capsize and lack of the required prediction methods necessarily leads to this compromise evaluation. The result should have meaningful comparative significance between different vessels provided that the 30 degree threshold value described by seagoing personnel and used in this study has significance as a potentially dangerous motion.

The inclusion of further test-tracks (capsize phenomena) to improve the prediction is also simple in principle. It is suggested that, in order to utilise the results of these other specialist techniques, it is probably simplest if a heading/speed specific database of vessel responses is appended to the motion response amplitude operators used in this study and accessed in the same way.

In principle the method may also be used to pinpoint operating scenarios which are of particular concern. This is especially relevant for a vessel which, because of the nature of its operational profile, displays large variation in displacement condition with consequent affect on motions. For the SULISKER this was not the case; the vessel had a very fixed displacement condition. Thus it is only possible to highlight the fact that operations in the North Atlantic in winter are particularly hazardous since these gave the largest contribution to the final attained Proving Ground probability.

The SULISKER has a large metacentric height (0.778m) and is reported to have good seakeeping characteristics, especially when the active fin stabilisers are used. In order to assess how the stability of the SULISKER compares with other vessels it is necessary to repeat the procedure for a wide range of vessels including those that have capsized or nearly capsized. In this way the relative stability of different types of vessel may be obtained based upon a rational stability assessment procedure which correctly accounts for the probability of the governing parameters.

The complete calculation occupied typically 3300 minutes of CPU time and 127 minutes of disk input/output time. Over two-thirds was attributed to the "North Atlantic" calculation with the remainder almost equally divided between the two North Sea subdomains. The PRIME 6350 (32 bit) processor was operating at 11.4 MIPS (millions of instructions per second). This computing time requirement could be reduced by incorporating sophisticated file handling techniques as noted above. In addition, by taking advantage of the single wave spectrum in the severest seastates, it is estimated that an eight-fold reduction in computing time could realistically be achieved. This would enable the complete calculation to run overnight.

It should be emphasised that this is a once-only survivability calculation which it is being proposed should be performed in the design stages before a vessel is even built. No further assessment would be required unless the vessel is subsequently required to extend its operating domain or it undergoes alterations which materially affect its motion response.

Chapter 9

Conclusions and Further Work

9.1. Overall Approach

For as long as man has ventured onto the sea there has always been present the possibility that his craft might capsize and be lost. This is still the situation today. The problem remains how to model the complex, irregular, six degrees of freedom vessel motion with sufficient accuracy to predict when a "dangerous" roll motion may be experienced, which could lead to the loss of the vessel, in order that a sufficient margin of stability may be provided.

The current I.M.O. Resolution A.167(ES.IV) "Recommendation on Intact Stability for Passenger and Cargo Ships under 100 metres in Length", which recommendations have been adopted by many countries, embodies the current deterministic approach to assessing ship stability. While criteria of this kind have the main advantage of being simple to apply, they involve no explicit use of external forces or motion characteristics. They cannot give any indication of safety margins or of likely motion behaviour in any seastate except still water. Also, when some significant departure from established design practice occurs, no recourse can be made to previous experience.

The lack of a necessary rational framework for assessing ship stability was the main concern of this research. The aim was to develop a rational philosophy and a logical procedure of assessing intact stability in order to ensure a consistent approach to design. This would show clearly where the uncertainties lie and where further research is most needed.

The method uniquely brings together a linearised analysis for assessing a "potentially dangerous" roll motion with a probabilistic assessment of ship performance on a standard test-track. A realistic modelling of total system behaviour included the effects of likely human behaviour on the performance. This represents a significant advancement on previous research work which has tended to ignore safety and vessel performance in rough seas in favour of an apparently intractable problem to predict large angle roll motion very accurately in idealised wave conditions.

It was demonstrated that retrospective reliability analyses, such as a fault-tree analysis, require information on the sequences of events giving rise to capsize as well as on the probability of each of the causal events occurring. Structural reliability methods also require greater detail (means and variances of demand and capability) than is currently available in the casualty records before the safety indices or partial safety factors may be used with confidence. In this respect the requirement for motion/accident recorders, similar to those which are fitted to aircraft, to be routinely provided on seagoing vessels would appear to have particular merit.

The probability approach to stability assessment that was developed at Plymouth comprised three distinct and interacting parts:

1. Modelling of total system behaviour comprising primarily vessel response but also containing aspects of human behaviour.
2. Indentification, selection and treatment of the potentially critical (capsize causing) operating scenarios.
3. Evaluation and combination of the probabilities of the critical scenarios in order to predict the cumulative probability of critical roll motion exceedence.

9.1.1. Potentially Dangerous Roll Motion

A great deal of work is still necessary before large amplitude roll motion may be routinely and accurately predicted. The development of more advanced theory for fluid active and reactive forces that vary with amplitude, together with mathematical models describing the coupled roll-sway-yaw motions is required.

Thus a further important and novel feature of the analysis was that the prediction of the actual large-angle capsize was not attempted per se. Instead, a lesser roll angle termed the "potentially dangerous" roll angle was selected, beyond which there was evidence that loss of the vessel is likely by being overwhelmed by the seaway. Thus the potential for disaster was being predicted rather than the disaster itself. This distinction is extremely important. In predicting a potentially dangerous motion there is no longer the necessity to describe the nonlinear extreme roll motion and the use of a linear theory may be defensible in certain circumstances. In essence it was proposed that linear theory be stretched to its prediction limits in order to estimate the probability of a roll motion judged to be potentially dangerous.

This novel approach to intact stability assessment can be justified for the following reasons:

1. The nature of the roll motion equation/s at large angles is uncertain since large nonlinear changes in the hydrodynamic coefficients occur as the deck edge is immersed. Further changes occur as the superstructure becomes immersed.
2. Long before the vessel reaches its capsize angle there is often great likelihood of cargo shifting.
3. Simultaneously there is great likelihood of water downflooding into the hull as well as water trapped on deck.

The requirement simultaneously to predict large angle damage stability, including the effects of cargo shifting and water on deck, is particularly daunting given the current state of the art for the intact case.

Following discussions with seagoing personnel a roll angle of 30 degrees from the upright was judged to be appropriate as the potentially dangerous roll motion. It was not possible to incorporate velocity or acceleration terms since no references could be found to even indicate what values these might take.

The investigation was able to proceed based upon the prediction of the probability of 30 degrees being exceeded at least once during the vessel's lifetime. Thus no emphasis was placed on the actual roll angles obtained; simply that they exceeded the critical value. This is an important feature of the analysis given the nonlinear nature of extreme roll motion as well as the severely nonlinear nature of the severe wave excitation which is still not fully understood.

9.1.2. Linear Motion Theory

In order to demonstrate the probabilistic framework which is being proposed for the assessment of intact stability, the spectral technique was judged to be the most suitable vehicle for the analysis. It is concerned with general ship rolling over all headings and speeds and provides the major contribution to the capsize probability using the definition of potentially dangerous motion given above. The advantage of the spectral technique for predicting this threshold value, compared with other available methods, is that it has the necessary scope to be the central core of a probabilistic stability assessment even though certain (predominantly) time domain capsize phenomena will require incorporation at a later stage. It can account for the important motion cross-coupling and the effect of varying displacement conditions as well as different headings and speeds. A further important advantage is that the method is widely understood and it is readily available to the profession.

Extensive dialogue with staff at British Maritime Technology Ltd, Wallsend was aimed at modifying the BRITSEA suite of seakeeping programs, and assessing their accuracy, for the analysis. Following many improvements a modified set of computer programs was made available to the author for predicting the linear response amplitude operators.

Correlation exercises with the fisheries protection vessel SULISKER (Lbp. 64 metres) indicated that, provided measured values of roll damping coefficient were used with Britsea, the calculated values of probable-extreme roll angle closely matched the maximum values of roll obtained on sea trials up to approximately 30 degrees. It was noted that the righting lever curve for this vessel is linear to angles of heel in excess of 35 degrees. For many vessels the restoring curve is nonlinear at much lower angles and consequently for these vessels the agreement between predicted and trial results may not be so good for the larger angles of roll. Good agreement was also obtained for the vertical motions and accelerations used to investigate compliance with seakeeping criteria, which influence the master's decision to change speed and heading.

9.1.3. Test-Tracks and Proving Ground

The most universal stability criterion should be the probability of non-capsizing of a seagoing vessel during its lifetime. In practice this would be an almost impossible task to solve for the real actual probability of capsizing because of the many varying parameters involved such as vessel characteristics, environment and service routes. Since a full treatment of these aspects is beyond the scope of this research the procedure that was finally formulated was governed by the desire to render it most useful for regulatory purposes (through simplification of important governing parameters without undue loss of realism) and to provide a basis for further work.

Major attention was focused on synthesising the component parts which must be given consideration so that a realistic assessment of the probability of extreme roll motions would be obtained. It was felt that the estimates of survivability which result should have meaningful comparative significance provided that consistent and plausible assumptions were applied. Previous authors had suggested that it would be most useful to analyse chosen critical situations of the vessel (scenarios) taking into account their probability of occurrence e.g. Kobylinski (1975). Thus using this concept, logically the stability criterion is motion based, -being the probability of non-capsizal of the vessel during several selected dangerous seagoing scenarios.

One of the first requirements was to formulate an appropriate framework that would allow any motion probabilities obtained to be compared in a standard manner (for both identical and different vessels).

In an attempt to 'trap' the worst-case scenarios, the proposed method consists essentially of a subject vessel being required successfully (without capsizing) to negotiate a series of standard analytical "test-tracks" which have been designed to represent the range of potentially capsize causing scenarios that it will encounter during its lifetime. The total test-track set is termed the "proving ground" (by analogy with a road vehicle proving ground).

The main advantages to the marine vehicle designer of using this proposed method are:

1. The full range of operating conditions, including the very important severe conditions, can be reproduced in a manner which is impossible to achieve in the open sea, thus making repeatability of results possible (even though, in practice, the results of model and full-scale trials are used for particularly difficult aspects).
2. Vehicles are tested under tightly controlled conditions where individual characteristics such as broaching-to can be assessed and compared against previous and other vehicles' performances.
3. Attention is focused on individual elements so that if a poor performance characteristic manifests itself on one particular test-track the design can be precisely retested after suitable modification.

The vessel type and intended zone or zones of operation dictate the nature of the proving ground that it will have to negotiate successfully by regulation. Indeed, some form of licensing might be envisaged for individual operational zones since this would avoid the potential overdesign (or worse, the underdesign) of vessels which the current 'blanket' regulations encourage. Alternatively appropriate levels of equipment could be specfied.

The vessel is examined over the same sea areas for different capsizing phenomena (different test-tracks) and thus the concept of a "layered test-track" approach was introduced. The test-track layers may be overlayed to give the largest roll response (the proving ground result) or else the largest response for any individual scenario. Alternatively, by separating the layers and considering individual test-track performances, the effect on the performance of selected design and operational features can be considered in detail. In principle this concept allows detail design improvements to be made for any of the layer characteristics.

Overall proving ground performance allows comparison of total performance and safety levels across a fleet of vessels though this 'average' value should be treated with caution.

By direct analogy with the case of a road vehicle which is required to perform a series of manoeuvres over varying terrain, during which time various measurements of handling, vibration, stability, power etc. may be taken simultaneously, the proving ground is subdivided with due consideration of:

1. distinct climate conditions (climate domains);
2. distinct wave conditions (climate subdomains);
3. distinct displacement conditions (domain segments);
4. distinct operating procedures.

Essentially the proposed prediction method aims to calculate $p(\phi_c < \phi)$, the cumulative probability of a 'critical roll motion' ϕ_c being exceeded at least once during the vessel's lifetime of operation. This value is represented by the proving ground result.

The cumulative probability can be obtained from a knowledge of the underlying lifetime response probability density function. This in turn can be found by computer-predicting independent trial samples of roll response together with their associated independent single trial probabilities of occurrence.

In this study, to illustrate these principles, the single test-track concerned with general ship rolling was considered. In general, less calculation will be necessary for the remaining capsize phenomena since they tend to be very heading/speed specific and thus many scenarios could be eliminated on this basis. Eventually it is envisaged that the results of the various specialist motion prediction techniques will simply 'plug-in' to the current (modular) computer program in the form of an additional/extended database of response values.

9.2. Risk Management

9.2.1. Key Factors

Key factors which were given particular attention within the simulations included climatology, seamanship and resulting response. Each factor presented different requirements in terms of their treatment so that simplifications might be made which would not unduly compromise the quality of the results.

a) Climate

Environmental demands made on the vessel are the essential element in any ship motion performance assessment, particularly when smaller vessels are being considered. During their lifetime seagoing vessels will encounter coastal seastates which are influenced by refraction and diffraction of waves by the coastline and seabed. In addition, the shape of wave spectra observed in the seas and oceans varies considerably for the same significant wave height due to geographical location, duration and fetch of wind, stage of growth and decay of a storm and co-existence of swell.

Fetch-limited and open-sea wave conditions were represented by families of wave spectra in spite of the increased computing requirements. The ability conveniently to represent a variety of spectral shapes which would be expected to occur in nature, by a mathematical representation which is based upon statistical considerations of actual data, is held to be an important feature of the simulations.

In the absence of firm data, cosine-squared wave energy spreading at ± 90 degrees to the primary wave direction was assumed. It was judged that to have used long-crested seaways would have led to unacceptably conservative results. A future refinement would be to use a variable model of wave energy spreading appropriate to individual locations, once the data becomes available.

Constraints of time meant that steady wind-heel and wind gusting effects were not considered in the study. These are recognised to have an important effect on the results obtained, particularly for small vessels having low freeboard values. One way that these effects could have been incorporated into the proposed approach is by using equivalent wind-moment spectra.

Values of the joint probability of significant waveheight and primary wave direction were used, based on results derived from the Spectral Ocean Wave Model (SOWM) which is being developed by the U.S. navy. This currently represents a 10 year (long-term) average of hindcast wave conditions in each location and season. Further work is needed to determine how best to incorporate climatic variability which will inevitably lead to relatively rare sea conditions being used which are more severe than the 10 year average values. It was suggested that individual months' data could be analysed and the 99 percentile values used in a future study to provide confidence bounds on the probabilities obtained.

b) Seamanship

Seamanship has a large influence on both the motion probabilities obtained and the motions themselves once the severe seastates have been encountered. Firstly, by manoeuvring to avoid a storm area or (in the case of small vessels in particular) by not sailing at all until the storm has passed, the master exercises avoidance seamanship which dictates the probability of encountering severe seastates. This is a function of the accuracy of weather forecasts and the skill of the ship's officers. Secondly, a vessel experiencing excessive motions and sealoads may be manoeuvred to reduce these to perceived acceptable levels. The master exercises what might be termed pacifying seamanship which is a function of the motion and seaload information available to the ship's officers and their skill in reducing these motions and loads. Both of these important effects were incorporated into the study.

Avoidance seamanship was represented by a Markov mapping i.e. $p(H_s'/H_s)$ -the probability of encountering each seastate in the absence of avoidance seamanship to the probability of encounter with avoidance seamanship. Values used in the simulations were based on correspondence with the officers commanding SULISKER and the sister ship VIGILANT. They are thus considered to be realistic for this size of vessel.

In order that the procedure may be readily incorporated into future stability regulations it was appropriate that the simulations utilise non vessel-specific seakeeping criteria. These were based on available full-scale trials data with a variety of vessels. Measures of deck wetness, number of slams, subjective motion (SM), number of propeller emergences and average roll were used. Provision was made for appropriate weighting of the criteria, based on how a master might "view" his vessel/cargo combination. An important consideration was that the criteria should concern values of motions and sealoads which are readily discernable to the master at his conning position rather than at some arbitrary position in or on the hull. It was noted that inclusion of apparent roll in the subjective motion (SM) calculation would be a distinct improvement.

A standard human behaviour pattern was assumed in this study. Although actual values of criteria may not matter in comparative work, so long as they are consistent, caution is required when two vessels which are being compared are limited by different parameters. If the subject vessel exceeded one or more of the seakeeping criteria it was caused to alter heading and/or speed conducive to the continued "success" of the mission. In this study "success" was measured by the ability to deviate from the intended heading and speed by the smallest margin which was sufficient to reduce motions and sealoads to within acceptable limits. This definition was only of secondary importance since in most cases of survivability the eventual heading and speed are not the primary concern of the master; only that the vessel survives. This was borne out by the simulations. By similar reasoning involuntary speed loss, due to added resistance and reduced propulsive efficiency, was not considered. In severe seastates, at least, the master will override these effects with his own changes of heading and speed.

Up to 48 combinations of heading/speed change were made available to the master.

Frequently, in the severest seastates, it was not possible to reduce vertical motion and seaload effects to within acceptable limits in which case an optimum heading/speed combination was chosen from among the 48 available. A major assumption was made that the master will infallibly choose the optimum heading/speed combination which most effectively reduces the motions and sealoads to be closest to the maxima allowed.

Because certain of the capsize phenomena in stern and quartering seas were not modelled the vessel tended to adopt these headings. Correspondence with the commanding officers indicated that in severe seastates the tendency is to reduce speed and to put the sea on either bow. Thus, within the main program, the master's action was further constrained so that an optimum was selected based on motions for seas forward of the beam. It was demonstrated that the effect on the probabilities obtained was small for the particularly hazardous test-track segment involving the North Atlantic. This was due in part to the uniform distribution of desired headings and speeds for the vessel when on patrol.

Masters are all individuals and it is inevitable that personality will influence seakeeping performance. A future refinement would be to incorporate a variable model of seamanship, based on a survey of ship masters and officers, in order to cater for a range of ability with appropriate weighting.

c) Independent (Bernoulli) Trial Cycles

In order to use the independent (Bernoulli) trials procedures advocated in this study the concept of an independence period was used after Hutchison (1981). It was noted that further work is required by oceanographers to provide values of the independence period, through consideration of the correlation of adjacent seastates at various geographic locations.

9.3. Results

Using the philosophy and methods described in this study the results of a calculation for the fisheries protection vessel SULISKER were presented. This vessel has operational profile characteristics similar to a naval vessel.

In order that no extreme responses were overlooked, the results of a sensitivity study were used to ensure adequate coverage of important parameters affecting roll. It was intended that the results of multi-variate (pattern recognition) analysis of casualty data (for the broad vessel type and size under consideration) would be used to ensure that no proven frequently recurring capsize scenarios had been missed, particularly in mild seas. These positively identified "capsize-nuclei" (each one representing a distillation of many similar casualties) form critical scenarios for consideration and are embedded in the test-tracks with respect to time and location. Unfortunately this proved to be not possible in practice given the poor level of detail of the casualty information that was available to the author. However, this is felt to be a very useful subject for further study.

The proving ground value of $5.0x10^{-2}$ that was obtained from the simulation represents the probability that a roll angle of 30 degrees will be exceeded at least once during the lifetime of the vessel. Factors having a major influence on this figure include:

1. the assumption that no fin stabilisers were used. This was due to a deficiency of Britsea, which is overcome in modern seakeeping computer programs.
2. the assumption that the master will infallibly choose the best heading and speed combination for any scenario.
3. the exclusion of certain of the capsize phenomena.
4. the exclusion of steady wind-heel and wind gusting effects.

The value that was obtained from the simulation is not the same as the actual risk of vessel capsize. It was argued that it is more representative of the probability of being overwhelmed by the seaway, which could eventually lead to a capsize. Unfortunately the vessel used in this study has a highly specialised role and there are few similar vessels in service. However, as a rough guide, close examination of fishing vessel casualty statistics indicated a value of $2.3x10^{-3}$ for the probability of being overwhelmed by the seaway (vessels capsized, foundered and missing). The value obtained from the simulation for the SULISKER, which is reported to have good seakeeping characteristics, represents the larger probability of exceedance of a potentially dangerous roll motion. The inadequacy of present knowledge of the basic physical processes immediately prior to capsize and lack of the required prediction methods necessarily leads to this compromise evaluation. The result should have meaningful comparative significance between different vessels provided that the 30 degree threshold value, described by seagoing personnel and used in this study, has significance as a potentially dangerous motion.

There is little point in developing a complex theoretical model of capsize until the underlying physical processes are better understood. In the event that the linear theory used in this study should be superseded, the proposed framework for assessing intact stability will be equally valid. Notwithstanding the physical processes of deck immersion, cargo shifting and downflooding etc. an improved theory which is capable of routinely predicting large-angle roll would yield a simulation probability value which is closer to the value obtained from casualty statistics.

9.4. Extensions to this Work

Researchers into ship stability have tended to concentrate their efforts into predicting the dynamic behaviour of an intact vessel in (at best) idealised environmental conditions and then formulating simple statical stability criteria with the results. This lack of realism has understandably led to concern about the criteria. Also, in practice, vessels are unlikely to be completely watertight at angles of inclination sufficient to cause capsize and a shift of cargo may be experienced. These factors are likely to be difficult to take into account in any deterministic approach to stability assessment.

This research has established the necessary rational framework and probability procedure for assessing the probability of exceedance of a potentially dangerous roll motion. For the first time a linear analysis has been used, in this way, to predict the onset of roll motion which is judged to be potentially dangerous to a vessel operating in severe seas. The method correctly recognises the physical facts and has a great advantage that it avoids the necessity to accurately predict the extreme capsize roll angles which are highly nonlinear in nature.

A further major advantage of the proposed method is its potential use as a unified design and regulatory tool in which the operability prediction is the information required by the designer and the extension into a survivability prediction may be used in future stability criteria.

Although the present study considers an enormous range of combinations of seastates, heading and speed for various seasons and operating zones each weighted according to its probability of occurence; in principle the method may be used to enable current standards of statical stability to be recast to relate to the real dynamic situation at sea. Particularly hazardous operating scenarios could be identified to enable appropriate values of metacentric height, maximum righting lever etc. to be set for any individual vessel. As an interim measure the method may also readily be used to ensure that vessels are judged comparably safe for their respective modes of operation, until more experience has been gained with the method.

Ultimately some form of indexing could be developed for certain of the more subtle design features. A semi-probabilistic approach which "credits" the provision of features beneficial to capsize resistance, with appropriate adjustment of partial safety factors, could be incorporated into the method.

In particular, the estimates of roll damping require improvement to avoid the necessity to use measured values. Agreed limiting seakeeping criteria are also required as well as an agreed procedure for incorporating subjective parameters, such as seamanship action, which can be treated as a random process. Long-term monitoring of vessel motions would enable correlation of results in order to gain confidence with the procedures that have been used.

A complete probabilistic study based on the philosophy and methods proposed would pinpoint particularly hazardous segments of the operating cycle. In this way specialist deterministic techniques can be used which lead to greatest returns for a given amount of effort. Any improvements can be gauged by precise retesting of the appropriate scenarios and the effect on the overall probability of critical motion exceedance observed. This is one of the chief strengths of the analysis.

By retrospective studies of a wide range of vessels, including those that have capsized or nearly capsized, it should be possible to formulate criteria for use with the proposed method based on a level of acceptable risk. Given that perfect safety is not achievable, it is generally agreed that an acceptable level of individual risk for shipboard fatalities is of the order of 10^{-5}. Casualty data indicated that there is a need to improve fatality rates on all fishing vessels, due to foundering <u>or</u> capsize, which currently lie at a level of around 3×10^{-4}. This is an order of magnitude larger than most shore-based risks of both a voluntary and involuntary nature. Only by comparing values of predicted risk against an acceptable risk value will it be possible to complete the rational procedure to assess the dynamic treatment of assessing intact stability that is being advocated.

The consequences of vessel loss -in terms of the loss of life, financial losses, hazards to the environment etc. have not been discussed explicitly. Nevertheless these are an extremely important element when considering the risks associated with an activity, even though the actual probability of occurence might be very small. Hence this type of procedure is increasingly being promoted for other types of marine casualty including collisions at sea e.g. Spouge (1988). Public awareness, which has been heightened by the loss of the Roll-on Roll-off passenger ferry "Herald of Free Enterprise" (193 lives) and the recent loss of the oil production platform "Piper Alpha" (167 lives), increases the likelihood that the future requirement will be for marine hazards to be routinely assessed, particularly when many lives are at risk. It is hoped that this work may contribute to this debate in order that such tragic losses will be avoided in the future.

Finally, regarding the computing requirement, it is inevitable that the real cost of the once-off calculation will fall as faster parallel processing chips, such as the INMOS transputer chip, become more widely adopted for intensive computing applications.

9.5. Future Work at Plymouth

The principles described in this study can be used to assess the stability performance of any seagoing vessel. The method is also suitable for a wide range of operability and seakeeping studies, particularly when motions lie wholly in the linear domain. The motion prediction and human behavioural aspects of this research are currently being integrated into an advanced optimum weather-routing model which is under development as one of the projects of the Ship Control Group based at Plymouth. It is envisaged that predicted vessel motions, when used in conjunction with appropriately weighted seakeeping criteria, will provide a range of heading/speed alternatives at every voyage waypoint. From among these alternatives a decision can be made for the type of route being planned, for example shortest time on passage, least fuel used etc. A six-degrees of freedom, real-time controller is then used to maintain the vessel on its optimum track. This will be compared against the actual track taken by a weather-routed container ship which has an intended great circle route across the North Atlantic.

References

Abicht W. and Kastner S. and Wendel K. (1977) Stability of Ships, Safety from Capsize and Remarks on Subdivision and Freeboard; Proceedings of the Second West European Conference on Marine Technology; London

Aertssen G. and Ferdinande V. and De Lembre R. (1965) Service Performance and Seakeeping Trials on Two Conventional Trawlers; Transactions of the North East Coast Institute of Engineers and Shipbuilders; pp 37-68

Aertssen G. (1966) Service Performance and Seakeeping Trials of MV Jordaens; Transactions of the Royal Institution of Naval Architects, Vol.108

Aldwinkle D.S. and Pomeroy R.V. (1983) Reliability and Safety Assessment Methods for Ships and Other Installations; Lloyds Register of Shipping, Publication No. 82

Andrew R.N. and Lloyd A.R.J.M. (1981) Full Scale Comparative Measurements of the Behaviour of Two Frigates in Severe Head Seas; Transactions of the Royal Institution of Naval Architects, Vol.123

Andrews K.S. and Dacunha N.M.C. and Hogben N. (1983) Wave Climate Synthesis; National Maritime Institute Report R149

Arndt B. and Roden S. (1958) Stabilitat bei vor und achterlichem Seagang; Schiffstechnik

Arnold L. (1973) Stochastic Differential Equations -Theory and Applications; Wiley, New York

Attwood (1796) Disquisition on the Stability of Ships; Philosophical Transactions of the Royal Society of London

Baitis A.E. and Applebee T.R. and McNamara T.M. (1984) Human Factors Considerations Applied to Operations of the FFG8 and Lamps Mk III; ASNE Day 1984; Source - Lloyd et al (1985)

Bales S. and Lee W.T. and Voelker J.M. (1981) Standardized Wave and Wind Environments for NATO operational areas; David W. Taylor Naval Ship Research and Development Centre; Report SPD 0919-01

Bales S.L. and Cummins W.E. and Comstock E.N. (1982) Potential Impact of Twenty Year Hindcast Wind and Wave Climatology on Ship Design; Marine Technology, Vol.19, No.2

Bales S.L. (1984) Development and Application of a Deep Water Hindcast Wave and Wind Climatology; Proceedings of the international symposium on Wind and Wave Climate Worldwide; RINA; London

Bate S.C.C. (1975) Partial Safety Factors in Structural Engineering Codes of Practice; The Structural Engineer, Vol.53, No.8, pp 333-334

Benjamin J. (1913) Uber das Mass der Stabilitat der Schiffe; Schiffbau

Bhattacharyya R. (1978) Dynamics of Marine Vehicles; Wiley Interscience Series; John Wiley and Sons (Pub.); New York

Bird H. and Morrall A. (1982) Ship Stability - A Research Strategy; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, Vol.1, pp 55-63; Tokyo, Japan

Bird H. and Morrall A. (1986) Research Towards Realistic Stability Criteria; Proceedings of the RINA Conference on the SAFESHIP Project: Ship Stability and Safety; Paper No.1, London

Bishop R.E.D. and Price W.G. and Temarel P. (1982) On the Role of Encounter Frequency in the Capsizing of Ships; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, Vol.2. pp 43-52; Tokyo, Japan

Bledsoe M.D. and Bussemaker O. and Cummins W.E. (1960) Seakeeping Trials on Three Dutch Destroyers; Transactions of the Society of Naval Architects and Marine Engineers, Vol.68

BMT (1986a) Sea Trials on F.P.V. SULISKER - Data from Manoeuvre 4SK; BMT Report on Project No. 34603

BMT (1986b) Sea Trials on F.P.V. SULISKER - Data from Manoeuvre 8SK; BMT Report on Project No. 34603

BMT (1986c) Rolling Experiments on a Model of F.P.V. SULISKER, Part 4 - Small Scale Model; BMT Report on Project 34601

BMT (1986d) ROLAS Technical Background; BMT Report of Project 34601

Boroday I.K. and Rakhmanin N.N. (1975) State of the Art of Studies on Capsizing of an intact ship in stormy weather conditions; Proceedings of the 14th International Towing Tank Conference, Appendix 8; Report of Seakeeping Committee

Boroday I.K. and Morenschildt V.A. (1986) Stability and Parametric Roll of Ships in Waves; Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Vol.1, pp 19-26; Gdansk, Poland

Bouguer P. (1746) Traite du Navire, de la construction et de les mouvemonts; Paris

Bretschneider C.L. (1959) Wave Variability and Wave Spectra for Wind Generated Gravity Waves; Beach Erosion Board, Corps of Engineers; Technical Memo No.118

Brook A.K. (1986) A Comparison of Vessel Safety Assessments based on Statical Stability Criteria and on Simulated Roll Response Characteristics in Extreme Sea States; Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Vol.II, Addendum I; Gdansk, Poland

Brown D.K. (1981) H.M.S. Captain; Design Authority and Stability Historical Group; Royal Institution of Naval Architects; October 1981

BSRA (1957) Trawler Icing Research; BSRA Report No.221

Caldeira-Saraiva F. (1986) The Boundedness of Rolling Motion of a Ship by Lyapunov's Method; Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Vol.I, pp 71-76; Gdansk, Poland

Caldwell J.B. (1983) Prospects for a 'Rational' Approach to Marine Safety; Proceedings of the international conference on Marine Safety; University of Glasgow

Caldwell J.B. and Yang Y.S. (1986) Risk and Reliability Analysis Applied to Ship Capsize, A Preliminary Study; Proceedings of the (RINA) international conference on the SAFESHIP Project: Ship Stability and Safety; London

Cartwright D.E. and Longuet-Higgins M.S. (1956) The Statistical Distribution of the Maxima of a Random Function; Proceedings of the Royal Society of London, Series A, Vol.237

Cartwright D.E. and Rydill L.J. (1956) The Rolling and Pitching of a Ship at Sea; Transactions of the Royal Institution of Naval Architects, Vol.98

Caughey T.K. (1963) Derivation and Application of the Fokker-Planck Equation to Discrete Nonlinear Dynamic Systems Subjected to White Random Excitation; Journal of the American Acoustic Society, Vol.35, No.11

Chaplin P.D. (1986) Casualties to Fishing Vessels and Deaths of Fishermen - A Review up to 1985; Sea Fish Industry Authority Industry Development Unit; Technical Report No.295

Chatfield C. (1981) Statistics for Technology; Chapman and Hall (pub.); London

Chazal E.A. (1980) Status Report on the Application of Stress and Motion Monitoring in Merchant Vessels; Society of Naval Architects and Marine Engineers; STAR Symposium

Chen H.T. (1979) The Implementation of the 20 year Hindcast Wave Data in the Design and Operation of Marine Structures; Proceedings of the 11th Offshore Technology Conference

Conolly J.E. (1975) Standards of Good Seakeeping for Destroyers and Frigates in Head Seas; International Symposium on the Dynamics of Marine Vehicles in Waves; Institute of Mechanical Engineers

Corse D.R. (1984) Personal Correspondence

Cox G.G. and Lloyd A.R. (1977) Hydrodynamic Design Basis for Navy Ship Roll Motion Stabilization; Transactions of the Society of Naval Architects and Marine Engineers, Vol.85

Cox D.C. (1981) Methods for Uncertainty Analysis: A Comparative Survey; Journal of Risk Analysis (Am.), Vol.2, No.4

Cummins W.E. and Bales S.L. (1980) Extreme and Rare Occurrence Wave Statistics for Northern Hemisphere Shipping Lanes; Proceedings of the Society of Naval Architects and Marine Engineers, Spring STAR Meeting

Dahle E.A. and Kjaerland O. (1980) The Capsizing of the M/S Helland Hansen - The Investigation and Recommendation for Preventing Similar Accidents; The Naval Architect, No.2, March 1980, pp 51-70

Dalzell J. F (1973) A note on the Distribution of Maxima of Ship Rolling; Journal of Ship Research, Vol.16

Darbyshire J. (1961) The One-Dimensional Wave Spectrum in the Atlantic Ocean and in Coastal Waters; Proceedings of Conference on Ocean Wave Spectra

DeJong B.J. (1970) Some aspects of Ship Motions in Irregular Beam and Longitudinal Seas; Ph.D. Dissertation, Delft

Denny A. (1887) On the Practical Application of Stability Calculations; Transactions of the Institution of Naval Architects, Vol.28

Dickson D.K. (1984) Personal Correspondence with officer commanding SULISKER

Draper L. and Whitaker M.A.B. (1965) Waves at Ocean Weather Ship Station Juliett; Deutsche Hydrographische Zeitschrift; Band 18, Heft 1

Draper L. and Squire E.M. (1967) Waves at Ocean Weather Ship Station India; Transactions of the Royal Institution of Naval Architects, Vol.109

DTI (1981) F.P.V. "SULISKER" -Trim and Stability Booklet; Department of Trade and Industry; File No. 45654/18/03

Fairley W.B. (1981) Assessment for Catastrophic Risks; Journal of Risk Analysis (Am.), Vol.1, No.3

Faulkner D. and Sadden J.A. (1979) Toward a Unified Approach to Ship Structural Safety; Journal of the Royal Institution of Naval Architects, January 1979

Forristal G.Z. and Wood E.G. and Cordone V.J. and Borgman L.E. (1978) The Directional Spectra and Kinematics of Surface Gravity Waves in Tropical Storm Delia; Journal of Physical Oceanography, Vol.8, No.5

Freeman N.J. (1986) Seakeeping Correlation Tests on a Model of F.P.V. SULISKER; BMT Report on Project No.14612

Freudanthal A.M. (1956) Safety and Probability of Structural Failure; Transactions of the American Society of Civil Engineers, Vol.121

Froberg C.E. (1969) Introduction to Numerical Analysis; Addison-Wesley Publishing Company Inc., pp 174-182

Froude W. (1861) On the Rolling of Ships; Transactions of the Institution of Naval Architects, Vol.2, pp 180-229

Fussell J. (1976) Fault Tree Analysis - Concepts and Techniques in Generic Techniques in Reliability Assessment; Noordhoff

Gedling P. (1983 - 1988) Personal Correspondence

Gerritsma J. and Beukelman W. (1967) Analysis of the Modified Strip Theory for the Calculation of Ship Motions and Wave Bending Moments; International Shipbuilding Progress, Vol.14, pp 319-337

Gill P.E. and Miller G.F. (1972) An algorithm for the integration of unequally spaced data; Computing Journal, Vol.15, pp 80-83

Green P.V. and Kirby J.M. (1981) Behaviour of Damp Fine Grained Bulk Mineral Cargoes; Transactions of the Institute of Marine Engineers (TM); Vol.94, Paper 19

Griesmeyer J.M. and Okrent D. (1981) Risk Management and Decision Rules for Light Water Reactors; Journal of Risk Analysis (Am.), Vol.1, No.2

Grim O. (1952) Rollschwingungen Stabilitat und Sicherheit im Seagang, Schiffstechnik, 1, 1

Grim O. (1954) Zur Stabilitat der periodischen erzwungenen Rollschwingungen eines Schiffers; Ingenieur Archiev

Gumbel E.J. (1954) Statistical Theory of Extreme Values and some Practical Applications; U.S. Department of Commerce, National Bureau of Standards, Applied Mathematics, Series 33

Haddara M.R. (1971) Capsizing Experiments with a Model of a Fast Cargo Liner in San Francisco Bay; U.S. Coast Guard; Project 723411

Hamamoto M. (1986) Transverse Stability of Ships in a Quartering Sea; Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Vol.I, pp 7-13; Gdansk, Poland

Hanssen J.L. (1982) Fishing Vessels which have capsized in Heavy Seas; Seminar on the Norwegian "Ships in Rough Seas" (SIS) Project; The Royal Institution of Naval Architects Occasional Publication No.5, pp 5-47

Hasselman K. (1966) On non-linear Ship Motions in Irregular Waves; Journal of Ship Research, Vol.9

Hasselman K. et (1973) Measurements of Wind-Wave Growth and Swell Decay During the Joint North Sea Wave Project (JONSWAP); Erganzungsheft zur Deutschen Hydrographischen Zeitschrift; Reihe A(8), No.12

Himeno Y. (1981) Prediction of Ship Roll Damping - State of the Art; University of Michigan, College of Engineering; Report No.239

Hoffman D. and Miles M. (1976) Analysis of a Stratified Sample of Ocean Wave Records at Station India; Society of Naval Architects and Marine Engineers; Technical and Research Bulletin No.1-35

Hoffman D. and Walden D.A. (1977) Environmental Wave Data for Determining Hull Structural Loadings; Ship Structural Committee Report, SSC 268

Hoffman D. and Fitzgerald V.K. (1978) Systems Approach to Offshore Crane Ship Operations; Transactions of the Society of Naval Architects and Marine Engineers; Vol.86, pp 375-412

Hogben N. and Lumb F.E. (1967) Ocean Wave Statistics; National Physical Laboratory; H.M. Stationery Office; London

Holland-Martin D. (1969) Trawler Safety - Final Report of the Committee of Inquiry into Trawler Safety; HMSO; London

Hosoda R. and Kunitake Y. and Koyama H. (1983) A method for Evaluation of Seakeeping Performance in Ship Design on Mission Effectiveness Concept; Source -Lloyd et al (1985)

Hutchison B.L. (1981) Risk and Operability Analysis in the Marine Environment; Transactions of the Society of Naval Architects and Marine Engineers; Vol.89, pp 127-154

Ikeda Y. (1978) A Prediction Method for Ship Roll Damping; Report No.00405, Dept of Naval Architecture, University of Osaka, Japan

Jasper J.H. (1956) Statistical Distribution Patterns of Ocean Waves and of Wave Induced Ship Stresses and Motions with Engineering Applications; Transactions of the Society of Naval Architects and Marine Engineers, Vol.64

Kastner S. (1969) Das Kentern von Schiffen in unregelmassiger langlaufender See; Schiffstechnik (1969-1970)

Kastner S. (1982) Simulation and Assessment of Roll Motion Stability; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, Vol.2, pp 171-184; Tokyo, Japan

Kato H. and Motoro S. and Ishikawa K. (1957) On the Rolling of Ships in Irregular Wind and Waves; Proceedings of the Symposium on the Behaviour of Ships in a Seaway; Wageningen

Katory M. (1974) A Guide to BSRA Seakeeping Computer Programs; British Ship Research Association, Technical Memorandum No.476

Kehoe J.W. (1973) Destroyer Seakeeping, Ours and Theirs; Proceedings of the U.S. Naval Institute

Kempf G. (1938) Die Stabilitatsbeanspruchung der Schiffe durch Wellen und Schwingungen; Werft, Reederei, Hafen

Kim W.D. (1963) On the Forced Oscillations of Shallow Draft Ships; Journal of Ship Research, Vol.7, pp 7-18

Kletz T.A. (1982) Hazard Analysis - A Review of Criteria; Reliability Engineering, Vol.2

Kobylinski L. (1975) Rational Stability Criteria and the Probability of Capsizing; Proceedings of the international conference on Stability of Ships and Ocean Vehicles; University of Strathclyde

Korvin-Kroukovsky B.V. and Jacobs W.R. (1957) Pitching and Heaving Motions of a Ship in Regular Waves; Transactions of the Society of Naval Architects and Marine Engineers, Vol.65, pp 590-632

Korvin-Kroukovsky B.V. (1961) Theory of Seakeeping; Society of Naval Architects and Marine Engineers; New York

Krappinger D. (1975) Stability of Ships and Modern Safety Concepts; Proceedings of the international conference on Stability of Ships and Ocean Vehicles, University of Strathclyde

Krylov A.N. (1896) A New Theory of the Pitching Motion of Ships on Waves and of the Stresses Produced by this Motion; Transactions of the Institution of Naval Architects, Vol.37, pp 326-367

Kure K. (1979) Capsize Safety; Ship's Technology and Research (STAR) Symposium; Society of Naval Architects and Marine Engineers; Spring Meeting; Houston.

Landweber L. and Maçagno M. (1957) Added Mass of two-dimensional forms oscillating in a free surface; Journal of Ship Research, Vol.1

Lazanoff S.M. and Stevenson N.M. (1978) A Twenty Year Northern Hemisphere Wave Spectral Climatology -in 'Turbulent Fluxes through the Sea Surface, Wave Dynamics and Prediction'; Favre A. and Hasselman K. (ed.); Plenum Press; New York and London

Lewis F.M. (1929) The Inertia of the Water Surrounding a Vibrating Ship; Transactions of the Society of Naval Architects and Marine Engineers

Lloyd A.R.J.M. and Andrew R.N. (1977) Criteria for Ship Speed in Rough Weather; Proceedings of the 18th American Towing Tank Conference, Vol.2; Annapolis, Maryland

Lloyd A.R.J.M. and Hanson P.J. (1985) The Operational Effectiveness of the Shipborne Naval Helicopter; Royal Institution of Naval Architects; Symposium on the Air Threat at Sea; London

Lloyds Register of Shipping (1976) Rules and Regulations for the Construction and Classification of Steel Ships

Longuet-Higgins M.S. (1952) On the Statistical Distribution of the Heights of Seawaves; Journal of Marine Research, Vol.II

Lyapunov A.M. (1892) General Problem of the Stability of Motion; Kharkov

Manning G.C. (1939) The Motions of Ships Among Waves; Principles of Naval Architecture, Vol.II; Society of Naval Architects and Marine Engineers

Mansour A.E. (1974) Approximate Probabilistic Method of Calculating Ship Longitudinal Strength; Journal of Ship Research, Vol.18, No.3. pp 203-213

Maruo H. (1957) The Excess Resistance of a Ship in a Rough Sea; International Shipbuilding Progress, Vol.4, No.35

Mirokhin B.V. and Kholodilin (1975) Probability Characteristics of Ship Inclinations due to Erupting Wave Impulse; Proceedings of 14th Towing Tank Conference

Morrall A. (1975) Simulation of Capsizing in Beam Seas of a Side Trawler; Proceedings of the international conference on Stability of Ships and Ocean Vehicles; University of Strathclyde

Morrall A. (1978) Capsizing of Small Trawlers; The Naval Architect, Vol.2, No.2, pp71-101

Morrall A. (1982) Philosophical Aspects of Assessing Ship Stability; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles; Tokyo, Japan

Mosely C. (1850) On Dynamical Stability and the Oscillation of Floating Bodies; Philosophical Transactions of the Royal Society of London

Moskowitz L. and Pierson W.J. and Mehr E. (1962) Wave Spectra Estimated from Wave Records obtained by OWS Weather Explorer and OWS Weather Reporter; New York University, College of Engineering (I) 1962, (II) 1963, (III) 1965

Muckle W. (1975) Naval Architecture for Marine Engineers; Published by Newnes-Butterworths; London

Newman J.N. (1961) A Linearised Theory for the motion of a thin ship in regular waves; Journal of Ship Research, Vol.5, pp 34-55

Newman J.N. and Tuck E.O. (1964) Current progress in the slender body theory of ship motions; Proceedings of the Fifth Symposium on Naval Hydrodynamics, pp 127-166; Norway

Ochi M.K. (1964) Extreme Behaviour of a Ship in Rough Seas -Slamming and Shipping of Green Water; Transactions of the Society of Naval Architects and Marine Engineers, Vol.72, pp 143-202

Ochi M.K. (1973a) Prediction of Slamming Characteristics and Hull Responses for Ship Design; Transactions of the Society of Naval Architects and Marine Engineers, Vol.81

Ochi M.K. (1973b) On Prediction of Extreme Values; Journal of Ship Research, Vol.17, Part 1

Ochi M.K. and Motter L.E. (1974) Prediction of Extreme Ship Responses in Rough Seas of the North Atlantic; Proceedings of the Symposium on the Dynamics of Marine Vehicles and Structures in Waves; Institute of Mechanical Engineers

Ochi M.K. and Wang S. (1976a) Prediction of Extreme Wave-Induced Loads on Ocean Structures; Proceedings of the Symposium on Behaviour of Offshore Structures, (BOSS '76); Trondheim

Ochi M.K. (1976b) Extreme Values of Surface Effect Ship Responses in a Seaway - Part 1, Estimation of Extreme Values for S.E.S. Design Considerations; David W. Taylor Naval Ship Research and Development Center; Report No. SPD-690-01

Ochi M.K. and Hubble E.N. (1976c) On Six-Parameter Wave Spectra; Proceedings of the 15th Coastal Engineers Conference; American Society of Civil Engineers

Ochi M.K. and Bales S.L. (1977) Effect of Various Spectral Formulations in Predicting Responses of Marine Vehicles and Ocean Structures; Proceedings of the 9th Offshore Technology Conference (OTC 2743); Houston

Ochi M.K. (1978a) Probabilistic Extreme Values and their Implication for Offshore Structure Design; Proceedings of the 10th Annual Offshore Technology Conference; Houston

Ochi M.K. (1978b) Wave Statistics for the Design of Ships and Ocean Structures; Transactions of the Society of Naval Architects and Marine Engineers, Vol.86

Ochi M.K. (1978c) Generalization of Rayleigh Distribution and its Application; Journal of Ship Research; Vol.22, No.44

Ochi M.K. (1979) A Series of JONSWAP Wave Spectra for Offshore Structure Design; Proceedings of the 2nd international conference on Behaviour of Offshore Structures, Paper 4; London

Odabasi A.Y. (1973) A Study on the Philosophy of Naval Hydromechanics; T.H. Scheepbouwkunde, Delft; Report No.380M

Odabasi A.Y. and Hearn G.E. (1977) Seakeeping Theories: What is the Choice?; Transactions of the North East Coast Institute of Engineers and Shipbuilders, Vol.94

Odabasi A.Y. (1978) Conceptual Understanding of the Stability Theory of Ships; Schiffstechnik BD31

Odabasi A.Y. (1982) A Morphology of Mathematical Stability Theory; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, pp7-22; Tokyo, Japan

Paulling J.R. (1961) The Transverse Stability of a Ship in a Longitudinal Seaway; Journal of Ship Research, Vol.4

Paulling J.R. and Kastner S. and Schaffran S. (1972) Experimental Studies of Capsizing of Intact Ships in Heavy Seas; Dept of Transportation U.S.C.G. Technical Report

Phillips S.R. (1986) Determining the Roll Stability of a Vessel Using Lyapunov Methods; Proceedings of the (RINA) international conference on the SAFESHIP Project: Ship Stability and Safety; London

Pierrottet E. (1935) A Standard of Stability for Ships; Transactions of the Institution of Naval Architects, Vol.76

Pierson W.J. and Moskowitz L. (1964) A Proposed Spectral Form for Fully Developed Wind Seas based on the Similarity Theory of S.A. Kitaigorodsky; Journal of Geophysical Research, Vol.69, No.24

Plaza F. and Petrov A.A. (1986) Further I.M.O. Activities in the Development of International Requirements for the Stability of Ships; Proceedings of the third international conference on Stability of Ships and Ocean Vehicles, Vol II; Gdansk, Poland

Pollard J. and Dudebout A. (1892) Theorie du Navire; Vol 3; Paris

Rahola J. (1939) The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability; Ph.D. Dissertation; Helsinki, Finland

Rattray D. (1984) Personal Correspondence with officer commanding VIGILANT

Reed E.J. (1868) On the Stability of Monitors under Canvas; Transactions of the Institution of Naval Architects, Vol 9

Reilly M.S.J. (1984) The Safety of UK Fishing Vessels, 1961-1980; Journal of Navigation, Vol.37, No.1, pp 60-82

Reilly M.S.J. (1985) Mortality from Occupational Accidents, United Kingdom Fishermen 1961-1980; British Journal of Industrial Medicine

Resolution A14/562 (1986) I.M.O. Weather Criterion; I.M.O. Publications Section

Resolution A167 (ES.IV) (1968) Recommendation on Intact Stability for Passenger and Cargo Ships under 100 metres in Length as amended by Resolution A106 (VII); I.M.O. Publications Section

Resolution A168 (ES IV)(1975) Recommendation on Intact Stability of Fishing Vessels; I.M.O. Publications Section

Roberts J.B. (1982) A Stochastic Theory for Non-linear Ship Rolling in Irregular Seas; Journal of Ship Research, Vol.26, No.4, pp 229-245

Roberts J.B. and Dacunha N.M.C. and Hogben N. (1983) The Estimation of the Long-term Roll Response of a Ship at Sea; National Maritime Institute Report No.169

Roberts J.B. (1984) Comparison between Simulation Results and Theoretical Predictions for a Ship Rolling in Random Beam Waves; International Shipbuilding Progress, Vol.31, pp 168-180

St Denis M. and Pierson W.J. (1953) On the Motions of Ships in Confused Seas; Transactions of the Society of Naval Architects and Marine Engineers, Vol.61, pp 280-357

Salveson N. and Tuck E.O. and Faltinsen O. (1970) Ship Motions and Sea Loads; Transactions of the Society of Naval Architects and Marine Engineers, Vol.78, pp 250-287

Sarchin T.H. and Goldberg L.L. (1962) Stability and Buoyancy Criteria for U.S. Naval Ships, The Society of Naval Architects and Marine Engineers, Annual Meeting

Schilling R.S.F. (1966) Trawler Fishing: An Extreme Occupation; Proceedings of the Royal Society of Medicine, Vol.59, p405

Schmitke R.T. (1978) Ship Sway, Roll and Yaw Motions in Oblique Seas; Transactions of the Society of Naval Architects and Marine Engineers, Vol.86, pp 26-46

Schmitke R.T. (1980) The Influence of Displacement, Hull Form, Appendages, Metacentric Height and Stabilization on Frigate Rolling in Irregular Seas; Society of Naval Architects and Marine Engineers; Spring Meeting, 15th STAR Symposium

Schoenberger R.W. (1975) Subjective Response to Very Low Frequency Vibration; Aviation, Space and Environmental Medicine; June 1975

Sevastanov N.B. (1970) Stability of Fishing Vessels; Izd "Sudostroenye" (in Russian); Leningrad

Skomedal N.G. (1982) Parametric Excitation of Roll motion and its Influence on Stability; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, Vol.2, pp53-64; Tokyo, Japan

Smith W.E. (1883) Hogging and Sagging Strains in a Seaway as Influenced by Wave Structure; Transactions of the Institution of Naval Architects, Vol.24

Spencer R. (1986) Black box or black art - accident investigation techniques; Transactions of the Royal Institution of Naval Architects; October 1986

Spouge J.R. (1985) The Prediction of Realistic Long-Term Ship Seakeeping Performance; Transactions of the North East Coast Institute of Engineers and Shipbuilders, Vol.102, No.1, pp 11-32

Spouge J.R. (1988) The Safety of RORO Passenger Ferries; The Royal Institution of Naval Architects; Spring Meetings, Paper No.10

Standing R.G. (1982) Wave Loading on Offshore Structures: A Review; National Maritime Institute Report R102

Steel H.E. (1956) The Practical Approach to Stability of Ships; Transactions of the Institution of Naval Architects, Vol.98

Takaishi Y. (1982) Consideration on the Dangerous Situations Leading to Capsize of Ships in Waves; Proceedings of the second international conference on Stability of Ships and Ocean Vehicles, Vol.III; Tokyo, Japan

Tasai F. (1959) On the Damping Force and Added Mass of Ships heaving and pitching; Reports of Research Institute for Applied Mechanics, Vol.7, No.26

Tasai F. (1960) Note - Formula for Calculating hydrodynamic force on a free surface (n-parameter family); Reports of Research Institute for Applied Mechanics, Vol.8, No.31

Tasai F. (1961) Hydrodynamic Force and Moment produced by Swaying and Rolling oscillation of Cylinders on the Free Surface; Reports of Research Institute for Applied Mechanics, Vol.9, No.35

Tasai F. (1969) On the Deck Wetness and Slamming of Full Ship Forms; Proceedings of the 12th International Towing Tank Conference; Rome, Italy

Tucker C.E. (1978) Inaccuracies in Practical Estimation of Ship Mass and Centre of Mass; Workshop on Stability of Small Ships; University of Strathclyde; November 1978

Tvedt J. (1983) Personal Communication and Interview

Upahl E. (1961) Betrachtungen uber Stabilitats-verfahren im Seegang; Schiffbautechnik, Pts.1 and 2

Ursell F. (1949a) On the Heaving motion of a Circular Cylinder in the Free Surface of a Fluid; Quarterly Journal of Mechanics and Applied Mathematics, Vol.2

Ursell F. (1949b) On the Rolling motion of Cylinders in the Free Surface of a Fluid; Quarterly Journal of Mechanics and Applied Mathematics, Vol.2, Part 3

U.S. Department of Defense; Procedures for Performing a Failure Mode and Effect Analysis; MIL-STD-1629A

Varheim R. and Nedrelid T. (1982) Small Cargo Vessels which have Capsized in Heavy Weather; Seminar on the Norwegian "Ships in Rough Seas" (SIS) Project; Institution of Naval Architects, Occasional Publication No.5

Vassalos D. and Kuo C. and Alexander J.G. (1986) Incorporating Theoretical Advances into Usable Ship Stability Criteria; Proceedings of the RINA Conference on the SAFESHIP Project: Ship Stability and Safety; London

Vassilpoulos L. (1967) The Application of Statistical Theory of Non-linear Systems to Ship Motion Performance in Random Seas; International Shipbuilding Progress, Vol.14

Vossers G. (1962) Some Applications of the Slender Body Theory in Ship Hydrodynamics; Dissertation; Technical University of Delft; Publ. No.214

Vugts J.H. (1969) The Coupled Roll-Sway-Yaw Performance in Oblique Seas; Delft Report No.N245

Vugts J.H. (1971) The Hydrodynamic Forces and Ship Motions in Oblique Waves; Netherlands Ship Research Centre; Report No.150S

Walden H. (1964) Die Eigenschaften der Meerswellen im Nordatlantischen Ozean; Deutscher Wetterdienst Einzelveroff-entlichungen, No.41

Wendel K. (1954) Stabilitatseinbufen im Seegang und durch Koksdeckslast; Hansa

Williams A.R. (1983) The Design and Use of the Dunlop/MIRA Handling and Stability Circuit; Proceedings of the conference on Road Vehicle Handling; Nuneaton

Yao J.T.P. (1985) Safety and Reliability of Existing Structures; Pitman Publishing Limited; London

Appendix A1

Description of Britsea

A1.1 Introduction

In order to predict vessel response in an irregular seaway, using the linear superposition principle of St. Denis and Pierson (1953), it is first necessary to predict the response of the vessel in longcrested, regular, sinusoidal waves. Considerable effort has been made to formulate an adequate theory for this and the vessel is idealised in one of several ways within the analytical methods. The essential differences between four common analytic approaches are shown in Table A1.1, Newman et al (1964).

	$\frac{B}{L}$	$\frac{T}{L}$	$\frac{\lambda}{L}$	$\omega\left(\frac{L}{g}\right)^{1/2}$	$F_n = \frac{\bar{U}}{\sqrt{gL}}$
Thin ship theory	$o(\beta)$	$o(1)$	$o(1)$	$o(1)$	zero or $o(1)$
Flat ship theory	$o(1)$	$o(\beta)$	$o(1)$	$o(1)$	zero or $o(1)$
Slender ship theory	$o(\beta)$	$o(\beta)$	$o(1)$	$o(1)$	zero or $o(1)$
Strip theory	$o(\beta)$	$o(\beta)$	$o(\beta)$	$o(\beta^{-1/2})$	zero or $o(1)$

B = ship beam

λ = wavelength

T = ship draught

ω = wave circular frequency

L = ship length

$\beta < < 1$

F_n = Froude number

$\bar{U}$ = speed

Table A1.1 Analytical Motion Theories

The entries O(1) and O(β), where $\beta < < 1$ describe the order of the ratios referred to.

The first two theories, which are relatively mathematically rigorous, do not describe the geometry of the ship adequately since usually the Beam < < Shiplength and Draught < < Shiplength in practice.

Slender ship theory attempts to account for differences in the flow condition in the fore and aft directions due to either wave effects or forward velocity. However, this refinement is achieved at the expense of neglecting any flow interaction between transverse points on the hull surface - since the beam is assumed small compared with the wavelength. Further it is assumed that the wavelength of waves striking or radiating from the ship are of the same order as, or greater than the length of the ship.

The Strip theory, which assumes two dimensional flow in transverse planes at each section of the ship, holds good only if the wavelength is small compared with the shiplength. Thus interference between the bow and stern are negligible since they are many wavelengths apart, and the three dimensional hydrodynamic problem is reduced to one in two directions. Britsea is one example of the use of a strip theory and this will now briefly be described. A fuller description is available in British Ship Research Association Memorandum No 476, Katory (1974).

A1.2 General Formulation of Equations of Motion (After Salveson et al 1970)

It is assumed that the oscillatory motions are linear and harmonic. Let (x,y,z) be a right-handed coordinate system fixed with respect to the mean position of the ship with z vertically upward through the centre of gravity of the ship, x in the direction of forward motion, and the origin in the plane of the undisturbed free surface. Let the translatory displacements in the x, y and z directions with respect to the origin be η_1, η_2 and η_3 respectively, so that η_1 is the surge, η_2 is the sway, and η_3 is the heave displacement. Furthermore, let the angular displacement of the rotational motion about the x, y and z axes be η_4, η_5 and η_6 respectively, so that η_4 is the roll, η_5 is the pitch and η_6 is the yaw angle. The coordinate system and the translatory and angular displacements are shown in Figure A1.1.

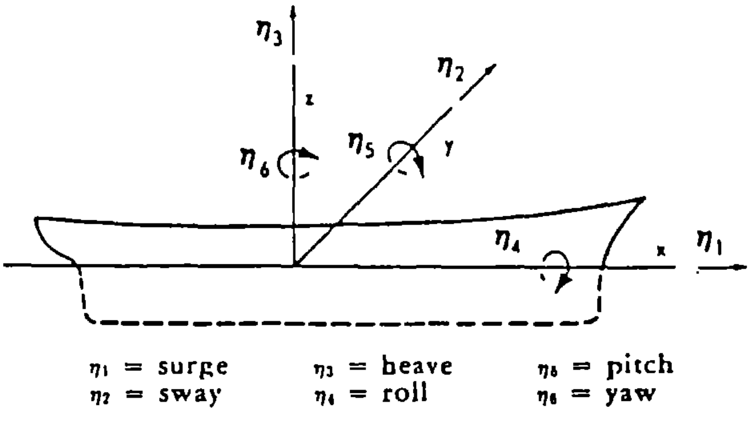


Figure A1.1 Sign Convention for Translatory and Angular Displacements

Under the assumptions that the responses are linear and harmonic, the six linear-coupled differential equations of motion can be written, using subscript notation, in the following abbreviated form:

$$\sum_{k=1}^{6} (M_{jk}+A_{jk})\ddot{\eta}_k+B_{jk}\dot{\eta}_k+C_{jk}\eta_k=F_j e^{i\omega t}\ ; \quad j=1....6$$

(1)

where M_{jk} are the components of the generalized mass matrix for the ship, A_{jk} and B_{jk} are the added-mass and damping coefficients, C_{jk} are the hydrostatic restoring coefficients, and F_j are the complex amplitudes of the exciting force and moment, with the force and moment given by the real part of $F_j e^{i\omega t}$.

Note that A_{jk} (for $j \neq k$) are the added-mass cross-coupling coefficients for the kth mode coupled into the jth mode of motion, so that for example A_{35} is the added-mass coefficient for pitch coupled into heave.

Here C_{jk} are defined as the hydrostatic restoring coefficients and hence independent of frequency, while the added-mass coefficients A_{jk} are so defined that they include all the oscillatory hydrodynamic forces proportional to the acceleration. Some other authors prefer to include certain hydrodynamic terms in the C_{jk}'s which are included in the A_{jk}'s here. It is understood the real part is to be taken in all expressions involving $e^{i\omega t}$.

F_1, F_2 and F_3 refer to the amplitudes of the surge, sway, and heave exciting forces, while F_4, F_5 and F_6 are the amplitudes of the roll, pitch, and yaw exciting moments; ω is the frequency of encounter and is the same as the frequency of the response. The dots stand for time derivatives so that $\dot{\eta}_k$ and $\ddot{\eta}_k$ are velocity and acceleration terms.

If it is assumed that the ship has lateral symmetry (symmetric about the x,z plane) and that the centre of gravity is located at $(0,0,z_c)$, then the generalized mass matrix is given by

$$M_{jk} = \begin{bmatrix} M & 0 & 0 & 0 & Mz_c & 0 \\ 0 & M & 0 & -Mz_c & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & -Mz_c & 0 & I_4 & 0 & -I_{46} \\ Mz_c & 0 & 0 & 0 & I_5 & 0 \\ 0 & 0 & 0 & -I_{46} & 0 & I_6 \end{bmatrix}$$

(2)

where M is the mass of the ship, I_j is the moment of inertia in the jth mode, and I_{jk} is the product of inertia. Here the inertia terms are with respect to the coordinate system shown in figure A1.1. The only product of inertia which appears is I_{46}, the roll-yaw product, which vanishes if the ship has fore-and-aft symmetry and is small otherwise. The other non-diagonal elements all vanish if the origin of the coordinate system coincides with the centre of gravity of the ship;

however, it is frequently more convenient to take the origin in the waterplane, in which case z_c is not equal to zero.

For ships with lateral symmetry it also follows that the added-mass (or damping) coefficients are:

$$A_{jk} \text{ (or } B_{jk}) = \begin{bmatrix} A_{11} & 0 & A_{13} & 0 & A_{15} & 0 \\ 0 & A_{22} & 0 & A_{24} & 0 & A_{26} \\ A_{31} & 0 & A_{33} & 0 & A_{35} & 0 \\ 0 & A_{42} & 0 & A_{44} & 0 & A_{46} \\ A_{51} & 0 & A_{53} & 0 & A_{55} & 0 \\ 0 & A_{62} & 0 & A_{64} & 0 & A_{66} \end{bmatrix}$$

(3)

Furthermore, for a ship in the free surface the only non-zero linear hydrostatic restoring coefficients are:

$$C_{33},\ C_{44},\ C_{55} \text{ and } C_{35} = C_{53}$$

(4)

If the generalized mass matrix (2), the added-mass and damping coefficients (3), and the restoring coefficients (4) are substituted in the equations of motion (1), it is seen that for a ship with lateral symmetry, the six coupled equations of motion (1) reduce to two sets of equations: one set of three coupled equations for surge, heave, and pitch and another set of three coupled equations for sway, roll and yaw. Thus, for a ship with lateral symmetry, surge, heave, and pitch are not coupled with sway, roll, and yaw.

If one assumes that the ship has a long slender hull form in addition to lateral symmetry, then it can be shown that the hydrodynamic forces associated with the surge motion are much smaller than the forces associated with the five other modes of motion so that it is consistent within these assumptions not to include surge. Hence the three coupled equations of motion for surge, heave, and pitch reduce to two coupled equations for pitch and heave.

A1.2.1 Heave and Pitch Motions

Under the assumption that the oscillatory motions are linear and harmonic, it follows from equations (1) through (4) that for a ship with lateral symmetry and a slender hull form the coupled equations of motion for heave and pitch can be written in the form:

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 e^{i\omega t}$$

(5)

$$A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 + (I_5 + A_{55})\ddot{\eta}_5 + B_{55}\dot{\eta}_5 + C_{55}\eta_5 = F_5 e^{i\omega t}$$

(6)

A1.2.2 Sway, Roll and Yaw Motions

It follows from the general formulation of the equations of motion [equations(1) through (4)] that for a ship with lateral symmetry the coupled differential equations governing the sway, roll, and yaw motions can be written in the form:

$$(A_{22}+M)\eta_2''+B_{22}\eta_2'+(A_{24}-Mz_c)\eta_4''+B_{24}\eta_4'+A_{26}\eta_6''+B_{26}\eta_6'=F_2 e^{i\omega t}$$

(7)

$$(A_{42}-Mz_c)\eta_2''+B_{42}\eta_2'+(A_{44}+I_4)\eta_4''+B_{44}\eta_4'+C_{44}\eta_4+(A_{46}-I_{46})\eta_6''+B_{46}\eta_6'=F_4 e^{i\omega t}$$

(8)

$$A_{62}\eta_2''+B_{62}\eta_2'+(A_{64}-I_{46})\eta_4''+B_{64}\eta_4'+(A_{66}+I_6)\eta_6''+B_{66}\eta_6'=F_6 e^{i\omega t}$$

(9)

A1.3 Evaluation of the Hydrodynamic Coefficients and Forces

A1.3.1 Formulation of the Problem within Britsea

The ideal linearised theory for calculating the hydrodynamic coefficients would make allowances for three dimensional flows satisfying boundary conditions on the hull while the ship is moving ahead and simultaneously performing the appropriate parasitic motion. Unfortunately such a theory does not exist and the various coefficients have to be derived by an appropriate stripwise integration method. The ship, which is treated as a rigid body, is represented by a number of transverse strips. Each strip is considered as a part of an infinitely long cylinder, with constant cross section, whose axis lies initially on the still water surface. Consequently it is possible-to obtain the hydrodynamic coefficients necessary to define the ship motion and the forces acting on it from the hydrodynamic forces and moments acting on a heaving, swaying and rolling cylinder due to waves. The six modes of ship motion are classified into three types of oscillation for this purpose:

a) Vertical oscillations, in the z-direction, which represent heaving and pitching motions when the pitching amplitude is assumed small.

b) Lateral oscillations in the y-direction, which represent swaying and yawing motions when the yawing amplitude is assumed small.

c) Rotational oscillations about the x-axis which represent rolling motions.

The motion of a cylinder executing simple harmonic oscillations with small amplitude in comparison with the cylinder diameter, about the mean position, was studied by Ursell (1949a) for vertical oscillations (circular sections) and for rotational oscillations (elliptical sections), Ursell (1949b). Tasai extended this work to provide a solution for a cylinder having a cross-section which is represented by a Lewis (1929) section for the three cases of vertical, lateral and rotational oscillations [Tasai (1959, 1961)]. Tasai also provided a general solution for the case of vertical oscillations of a cylinder having a cross-section represented by a multi-coefficient section using close-fit techniques, Tasai (1960). This aspect was extended by Katory (1974) for use in the Britsea programs to provide an analogous general solution for the case of lateral and rolling oscillations. In the present work the representation of ship sections by Lewis coefficients has been used throughout since this was the version of Britsea supplied by BMT Ltd. In this method the geometrical shape of the section is mathematically defined by a Lewis form which has the same beam, draught and sectional area as the given ship section but not necessarily the same shape as the section. The method is recognised to be 'accurate' for many common ship sections but breaks down at sections with large bulbs or small sectional area, Odabasi et al (1977).

The fluid motion is assumed to be non-viscous, irrotational and the surface tension is neglected. Linear wave theory is assumed. Consequently a velocity potential Φ and a conjugate stream function Ψ will exist, both satisfying Laplace's equation.

For the purpose of defining the velocity potential Φ and the stream function Ψ around the unit cylinder in the ζ-plane whose transformed cross-section represents a ship section in the y-z plane the following mapping function is used:

$$y+iz=M\{\zeta+\sum_{n=1}^{N} a_{2n-1}\zeta^{-(2n-1)}\}$$

(10)

where

$M=B/2(1+a_1+a_3)$

$\zeta=ie^{\alpha}e^{i\beta}$

$B=$ section beam

The original ship shaped section is described by the coordinates (y,z) and the a_{2n-1} are the transformation variables.

For the Lewis method (used in this work) N=2 and the contour of the Lewis form section ($\alpha=0$) is expressed as follows:-

$$\frac{y}{M}=(1+a_1)\cos\beta+a_3\cos 3\beta$$

(11)

$$\frac{z}{M}=(1-a_1)\sin\beta-a_3\sin 3\beta$$

(12)

Laplace's equation, which is the condition for the flow being incompressible, irrotational and inviscid, in two-dimensional form is:

$$\frac{\delta^2 \Phi}{\delta y^2}+\frac{\delta^2 \Phi}{\delta z^2}=0$$

(13)

and

$$\frac{\delta^2 \Psi}{\delta y^2}+\frac{\delta^2 \Psi}{\delta z^2}=0$$

(14)

The linearised free surface dynamic boundary condition is:

$$\frac{\delta^2 \Phi}{\delta x^2}+(g/U^2)\frac{\delta \Phi}{\delta z}=0 \quad \text{at } z=0$$

(15)

which implies that the disturbance caused by the movement of the ship has a small effect on the surrounding fluid surface.

The linearised ship surface boundary conditions are:

$$\frac{\delta \Phi}{\delta \bar{n}}=U_n$$

(16)

and

$$\frac{\delta \Phi}{\delta y}=U\frac{\delta\{y(x,z)\}}{\delta x}$$

(17)

The first of these means that the derivitive, with respect to the direction normal $\bar{n}$ at any point on the ship surface $y(x,z)$, of the velocity potential Φ is equal to the normal velocity at that point. The second expression is to make the velocity potential Φ satisfy the ship surface boundary condition.

The progressive wave (related to motion damping) which dominates at a large distance from the cylinder, with amplitude $\bar{\eta}$, is assumed to be expressed as a function of the geometry of the cylinder section by means of a stream function in the following form:

$$\Psi_0=\frac{g\bar{\eta}}{\pi\omega_e}\{\Psi_c \cos \omega_e t+\Psi_s \sin \omega_e t\}$$

(18)

where Ψ_c is the conjugate of the standing wave potential Φ_c and Ψ_s is the conjugate of the source potential Φ_s.

The velocity potential for each of the motion modes is arrived at as follows:

a) Vertical Oscillation.

The equation of motion for the vertical oscillations assuming a regular harmonic motion is given by:

$$z = z_a \cos(\omega_e t + \varepsilon_{z_a})$$

(19)

The linearised boundary condition on the surface of the cylinder is given by:

$$\frac{\delta \Phi}{\delta \bar{n}} = -z_a \omega_e \sin(\omega_e t + \varepsilon_{z_a}) \frac{\delta z}{\delta \bar{n}}$$

(20)

and

$$\frac{\delta \Phi}{\delta \bar{n}} = 0$$

(21)

The velocity potentials Φ_c and Φ_s of the standing wave created by the cylinder oscillations, and of an equivalent source representing the cylinder are given by:

$$\Phi_c = \pi e^{-Kz} \cos Ky$$

(22)

$$\Phi_s = \pi e^{-Kz} \sin Ky - \int_0^\infty \frac{e^{-ky}}{K^2 + k^2} \{k \cos kz - K \sin kz\} \; dk$$

(23)

- Ursell (1949a), Tasai (1959)

where

$K = \omega_e^2 / g$

k = integration parameter.

b) Lateral Oscillation

By similar argument for vertical motion the required velocity potentials are given by:

$$\Phi_c = -\pi e^{-Kz} \sin Ky$$

(24)

and

$$\Phi_s = \pm \pi e^{-Kz} \cos Ky + \frac{y}{K(y^2+z^2)} \mp \int_0^\infty \frac{e^{\pm ky}}{K^2+k^2} \{K \cos ky + k \sin ky\} \; dk$$

(25)

-Tasai (1961)

where the upper sign is for $y > 0$ and the lower sign is for $y < 0$.

c) Rotational Oscillation.

The required velocity potentials are given by

$$\Phi_c = -\pi e^{-Kz} \sin Ky$$

(26)

and

$$\Phi_s = \pm \pi e^{-Kz} \cos Ky + \frac{y}{K(y^2+z^2)} \mp \int_0^\infty \frac{e^{\mp ky}}{K^2+k^2} \{K \cos ky + k \sin ky\} \; dk$$

(27)

-Tasai (1961)

where the upper sign is for $y > 0$ and the lower sign for $y < 0$.

d) Total Velocity Potential

In each case of the above three types of motion the total velocity potential Φ is fitted by the series:

$$\Phi = \Phi_c + \{\sum_{m=1}^{\infty} p_{2m} \Phi_{2m} + \sum_{m=1}^{\infty} q_{2m} \overline{\Phi}_{2m}\} \cos \omega_e t + \Phi_s + \{\sum_{m=1}^{\infty} p_{2m} \overline{\Phi}_{2m} + \sum_{m=1}^{\infty} q_{2m} \Phi_{2m}\} \sin \omega_e t$$

(28)

where Φ_{2m} is a multipole potential and $\overline{\Phi}_{2m}$ the associated standing wave potential, both of which take into account the shape of the cylinder cross section and the boundary conditions of the free surface.

p_{2m} and q_{2m} are the polynomial coefficients which are functions of the ship section and frequency of oscillation.

Hydrodynamic pressure on the surface of the cylinder is calculated by:

$$p=-\rho\frac{\delta\Phi}{\delta t}=p_c\cos\omega_e t+p_s\sin\omega_e t$$

(29)

where p_c is the amplitude in phase with the acceleration and p_s is the amplitude in phase with the velocity.

A1.3.2 Hydrodynamic Coefficients

a) Added Mass

Physically the added mass is associated with the stationary wave system created by the ship. The hydrodynamic force per unit length acting on the cylinder is found by integrating the pressure. By definition the hydrodynamic force component in phase with the acceleration over the acceleration is the added mass m'. For a ship floating at a free surface there are two coefficients of added mass C_V and C_H where:

$$C_V=\frac{m_V'}{\pi\rho B^2/8}$$

(30)

and

$$C_H=\frac{m_H'}{\pi\rho T^2/2}$$

(31)

for vertical (symmetric) motion and for horizontal (antisymmetric) motion respectively.

B is the beam and T the draught of the section; m_V' and m_H' are the respective vertical and horizontal added masses. Landweber et al (1957) have shown that the added mass of a symmetrical hull sectional shape is given by the following expressions when the oscillatory motion is of high frequency:

$$m_V'=\frac{\pi\rho}{2}\left(1+2a_1+\sum_{p=1}^{N}(2p-1)a_{2p-1}^2\right)$$

(32)

in vertical oscillatory motion and

$$m_H' = \frac{\pi\rho}{2} \left(1 - 2a_1 + \sum_{p=1}^{N} (2p-1) a_{2p-1}^2\right)$$

(33)

in horizontal oscillatory motion. For Lewis forms N=2.

Thus the coefficients C are given as:

$$C_V = 8m_V'/\pi\rho B^2 = (1+a_1)^2 + 3a_3^2/(1+a_1+a_3)^2$$

(34)

$$C_H = 2m_H'/\pi\rho T^2 = (1-a_1)^2 + 3a_3^2/(1-a_1+a_3)^2$$

(35)

b) Wave-making Damping

Physically the damping coefficients are associated with a travelling wave system set in motion by the ship which dissipates energy from the ship-wave system. It is a function of the amplitude of the progressive wave $\bar{\eta}$ of equation (18). Linear wave-making damping which is proportional to motion velocity is given by:

$$N_R = \frac{\rho g^2}{\omega^3} \bar{A}^2 \quad (B/2)^2 \quad \text{for roll}$$

(36)

-Tasai (1961)

where $\bar{A}$ is the ratio of travelling wave amplitude to body motion amplitude and B is the beam. This and other representations are discussed in Himeno (1981). The wave roll damping tends to be small due to cancelling effects for normal ship sections.

c) Exciting Force

Integration of the time-dependent pressure on the hull over the hull surface yields the hydrodynamic force and moment amplitudes. These values may be divided into two parts as the exciting force and moment and the force and moment due to the six degrees of body motion.

Calculation of the hydrodynamic properties for the ship are obtained by integration of the above two-dimensional sectional properties over the length of the ship.

d) Viscous damping

Added mass and damping coefficients obtained using linear potential flow theory cannot be used for the case of sway, yaw and roll without including a correction for viscous damping. Comparison between theory and experiment shows that the roll damping coefficient is significantly affected by viscosity even in the absence of bilge keels e.g. Vugts (1969).

The original version of Britsea was supplied with an empirical method by Inoue for predicting roll damping. This used the ship sectional area coefficients at each station together with the bilge keel position and extent to predict the bilge keel contribution to damping.

Subsequently an updated version was received from BMT Ltd which uses theoretical estimates by Ikeda (1978) to predict contributions due to lift, eddy, bilge keels and friction. The eddy, bilge and friction components are non-linear and can be assumed proportional to the square of the roll velocity. The eddy and friction contributions are usually negligible in comparison with the wave making, lift and bilge contributions.

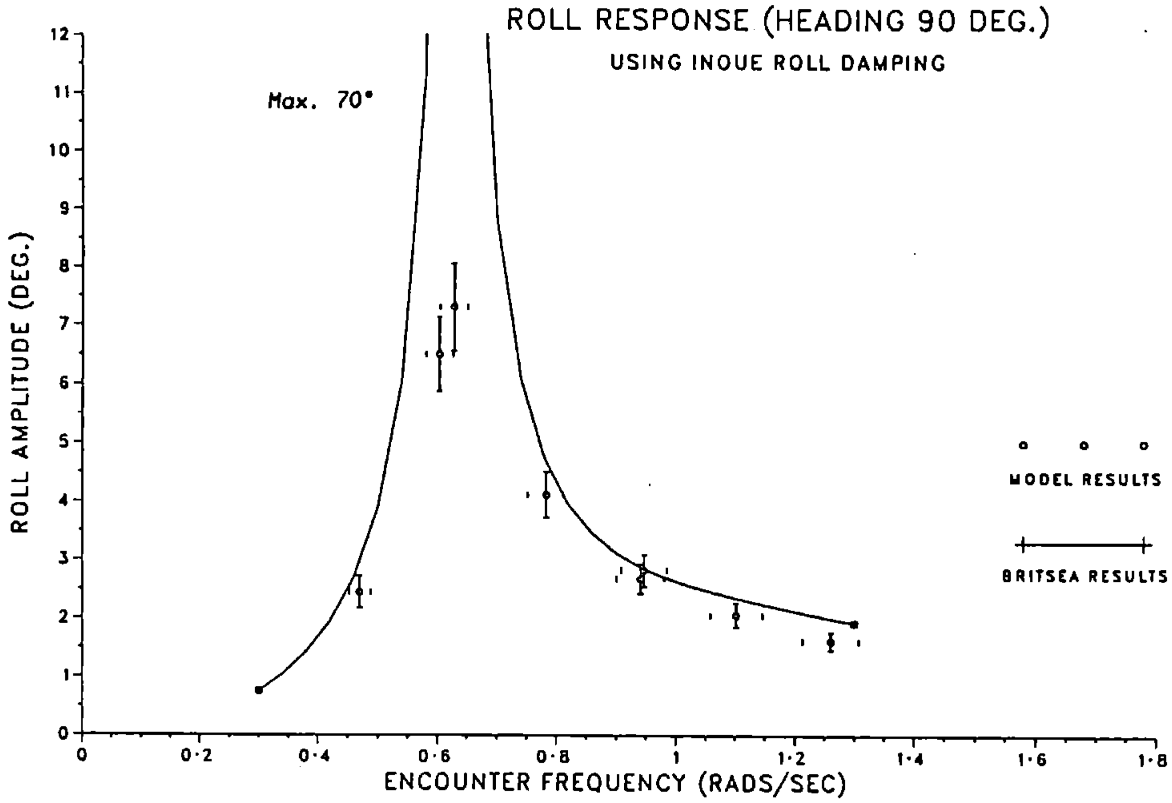
The later version of Britsea can also accept experimental values of (linear + quadratic) roll damping if required.

Solution of the linear second order motion equations yields the amplitudes of pitch, heave, roll, sway and yaw motions for unit wave amplitude together with their phase relationships with the wave. For the purposes of the risk analysis, selected amplitude and phase values are stored in a database for subsequent use within the main computer program RISK.F77.

Appendix A2

Results of Correlation Study

FIGURE A2.1



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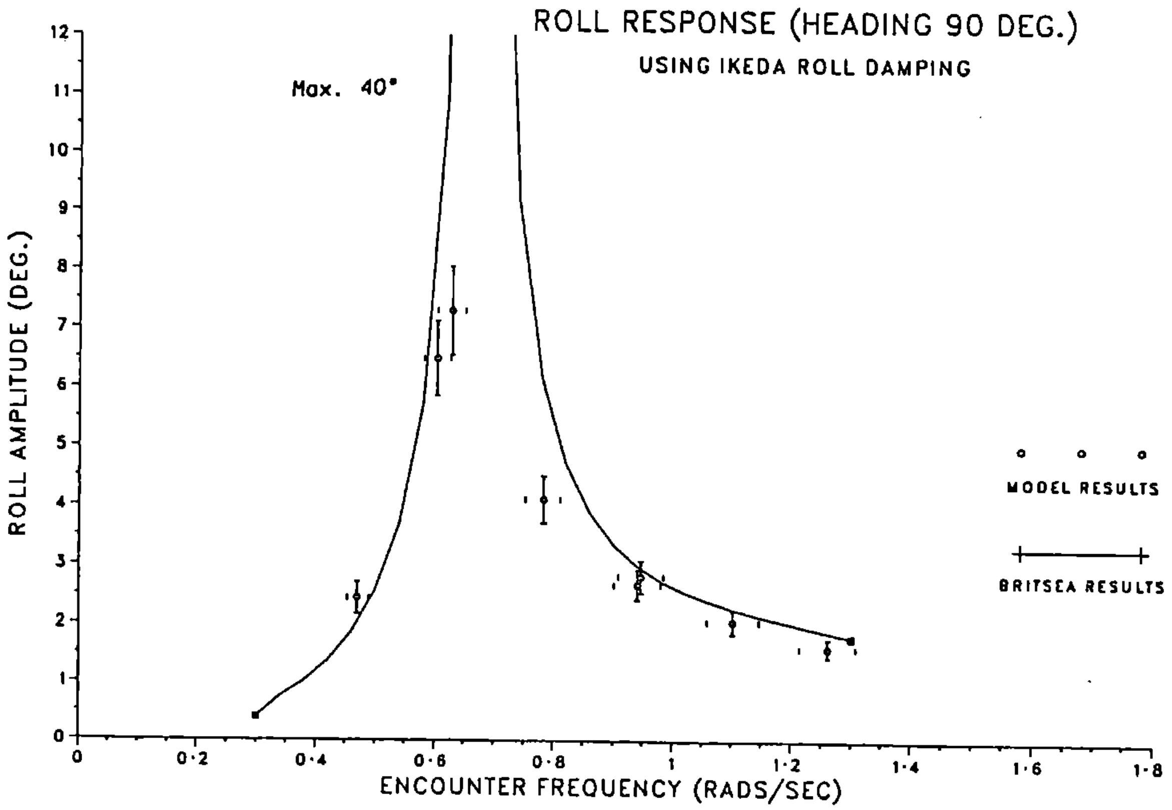

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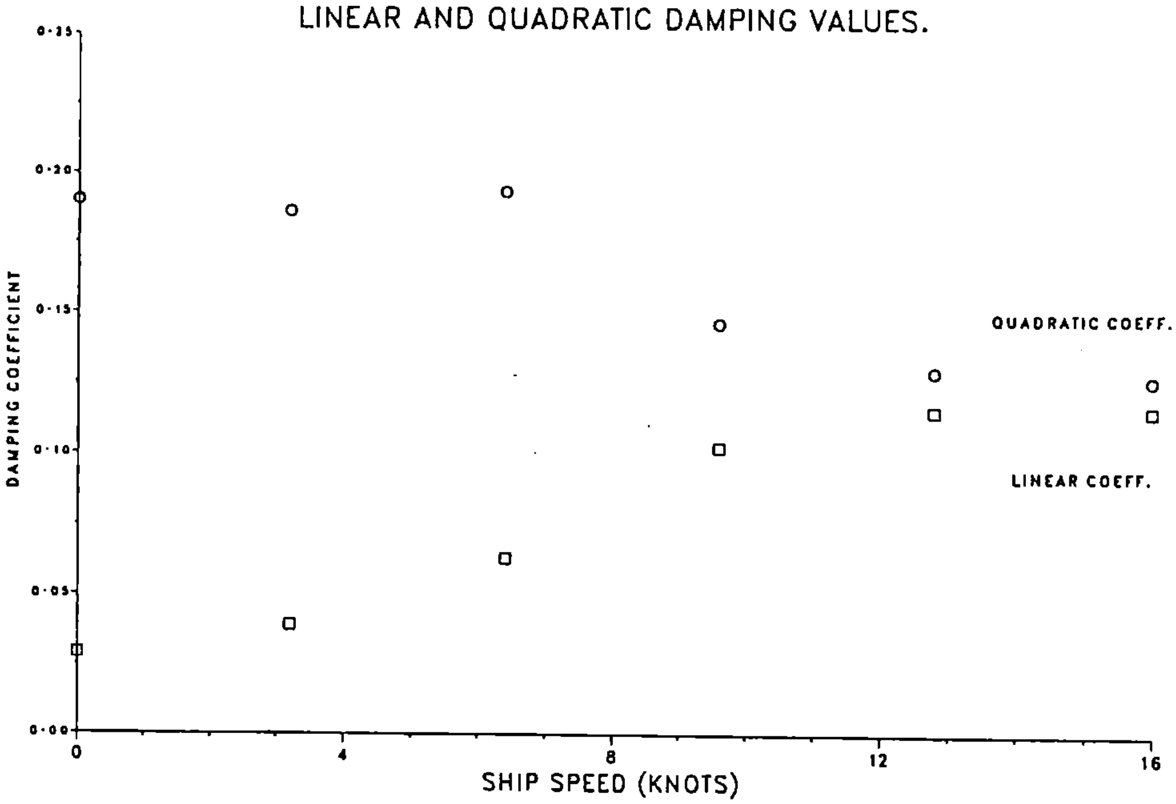

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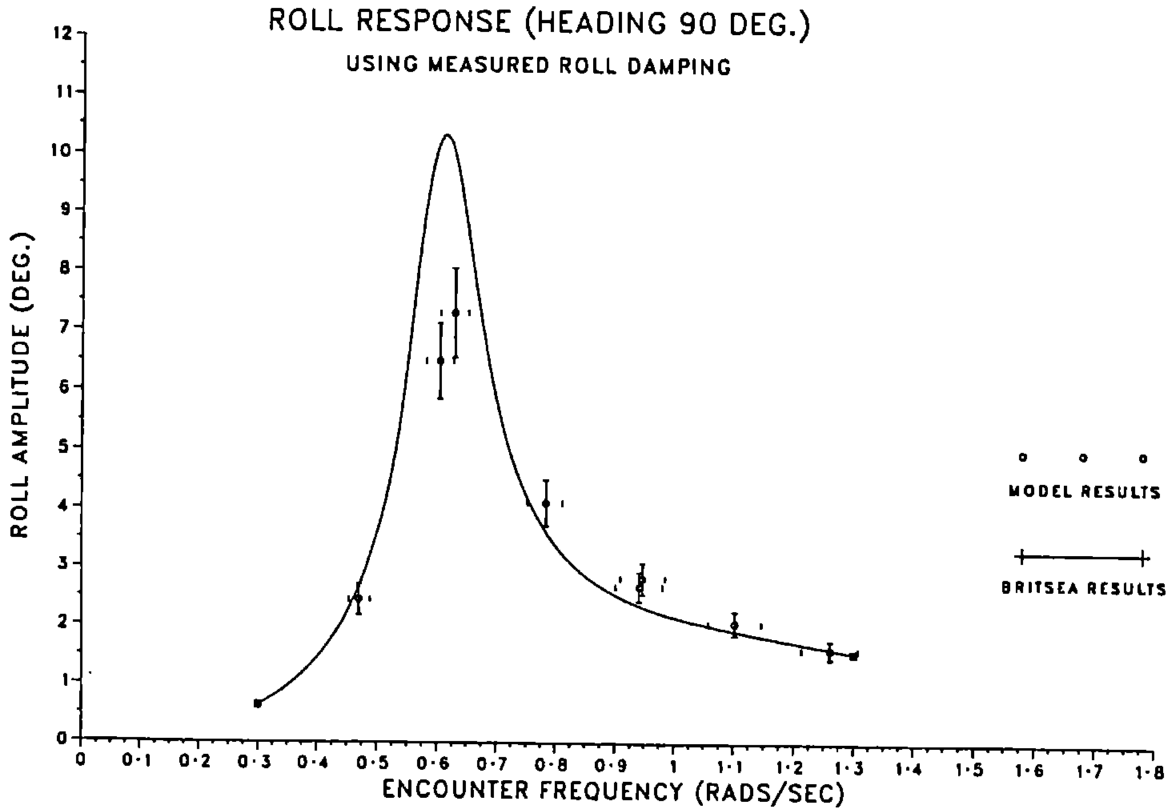

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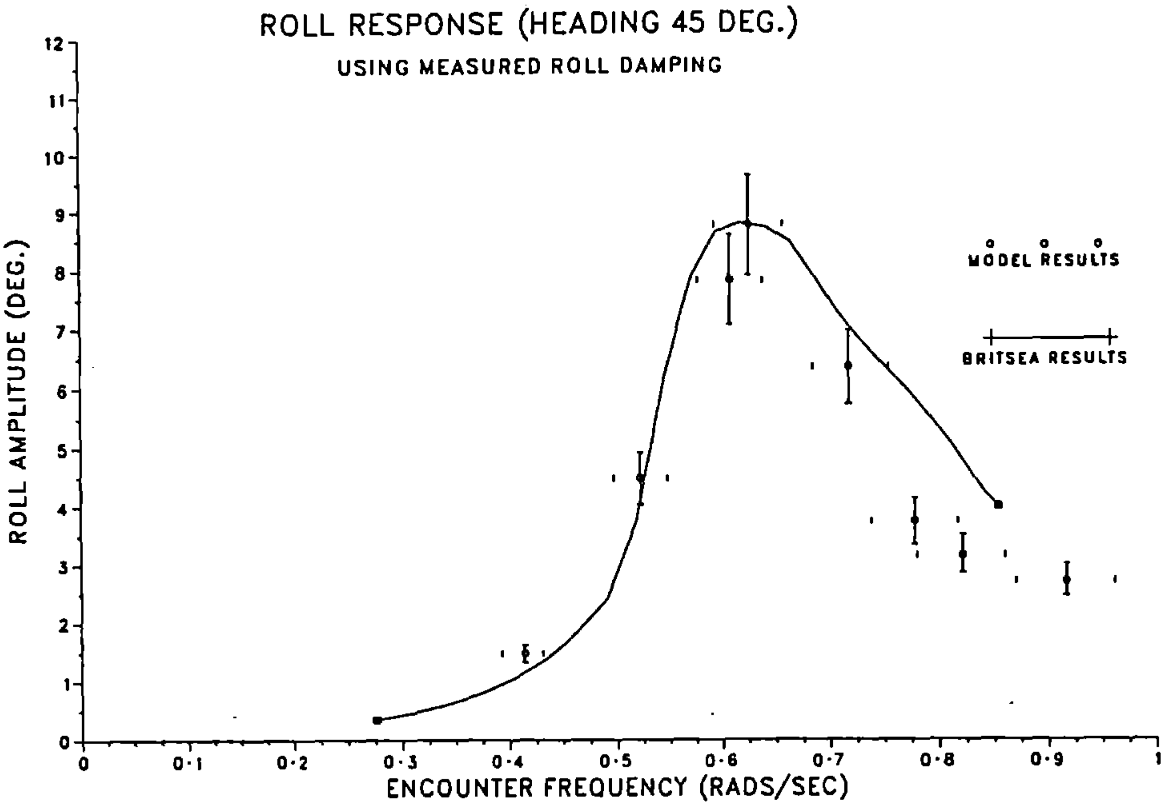

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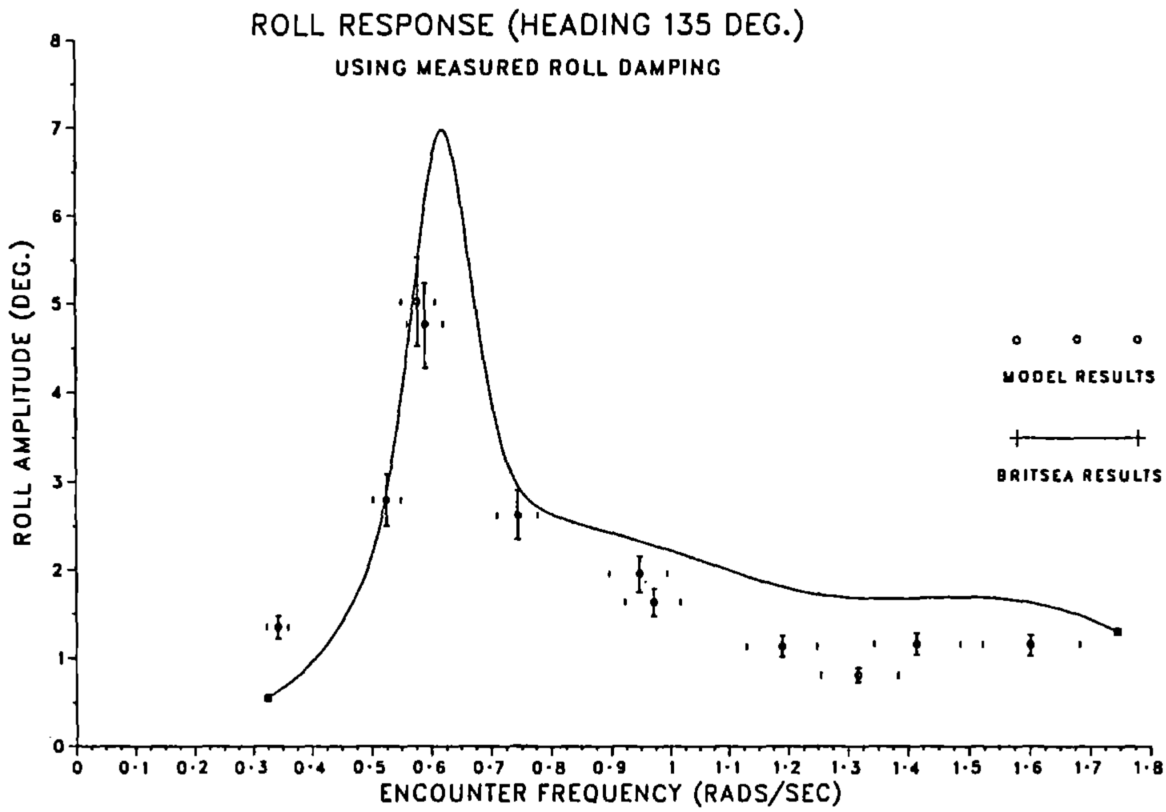

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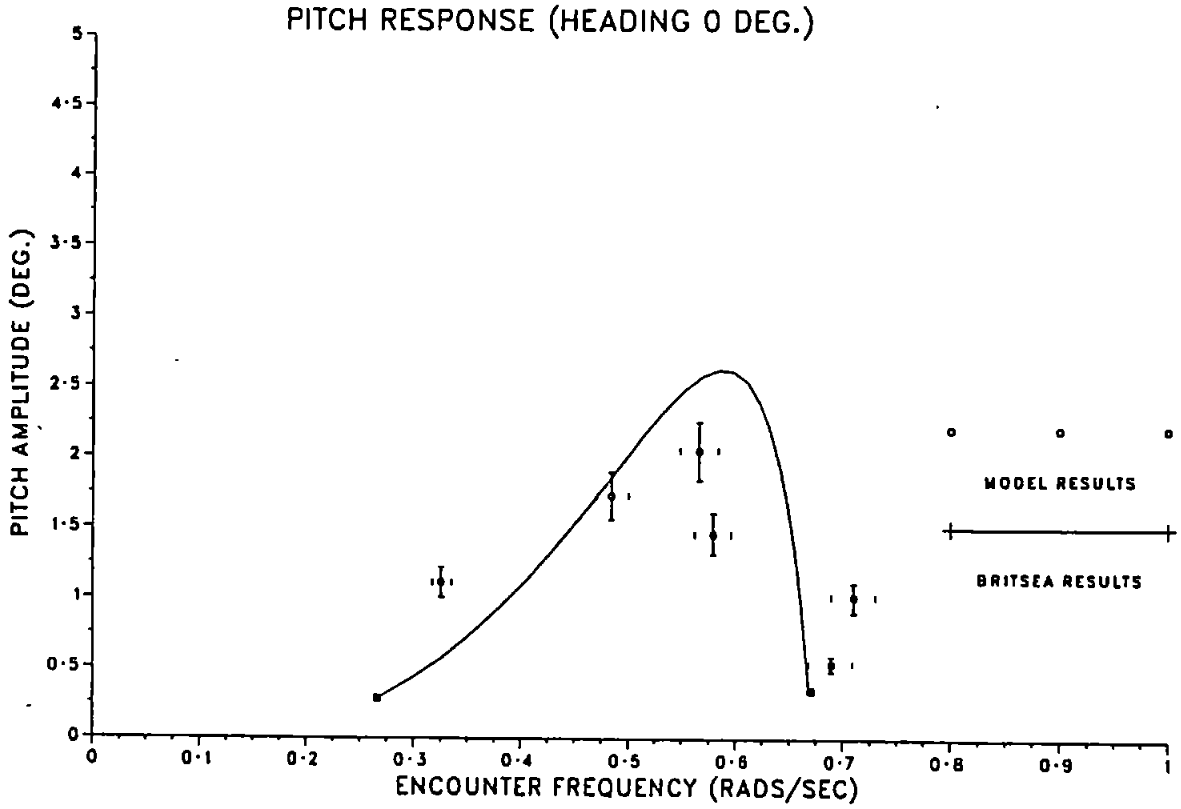

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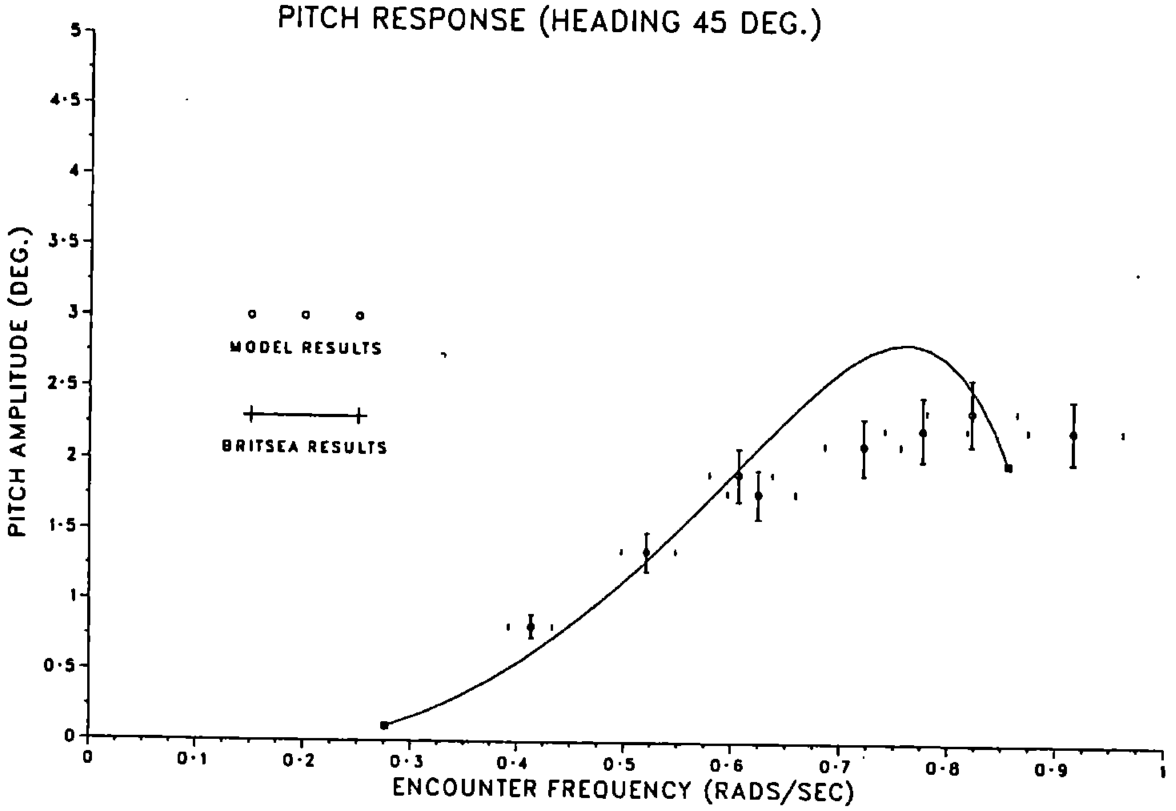

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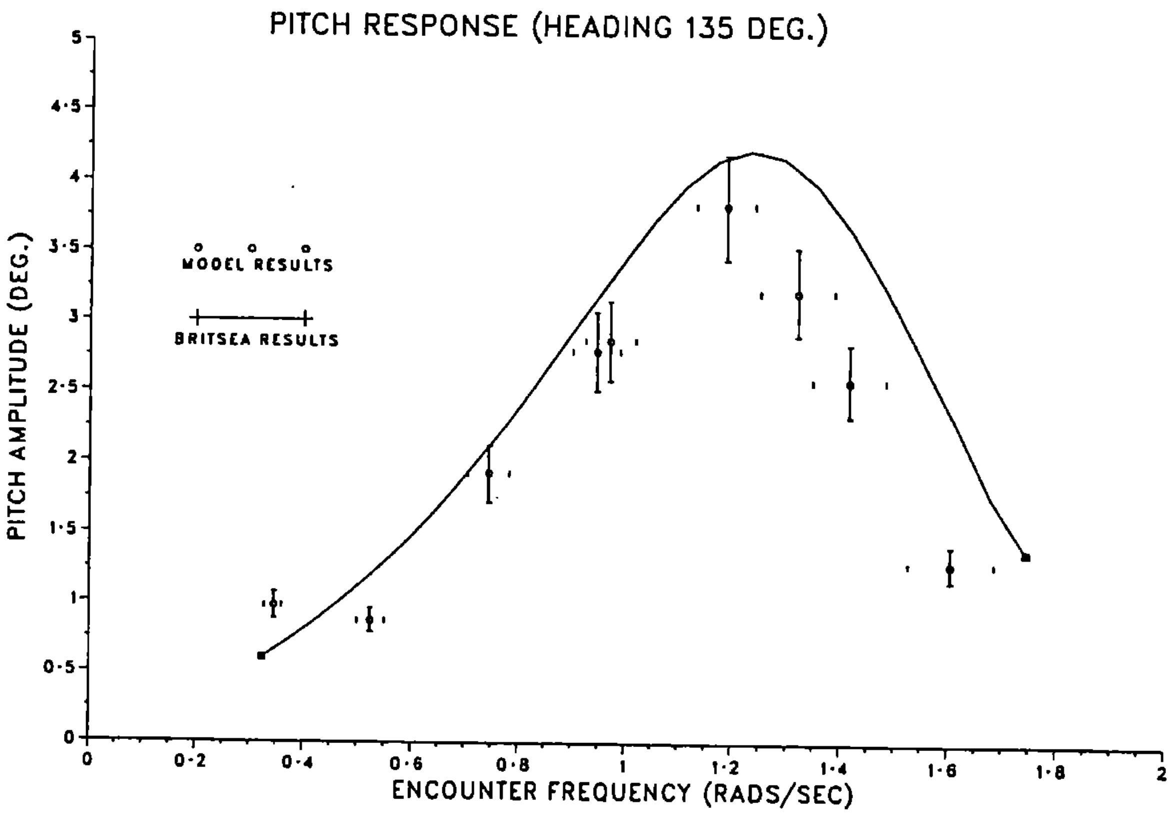

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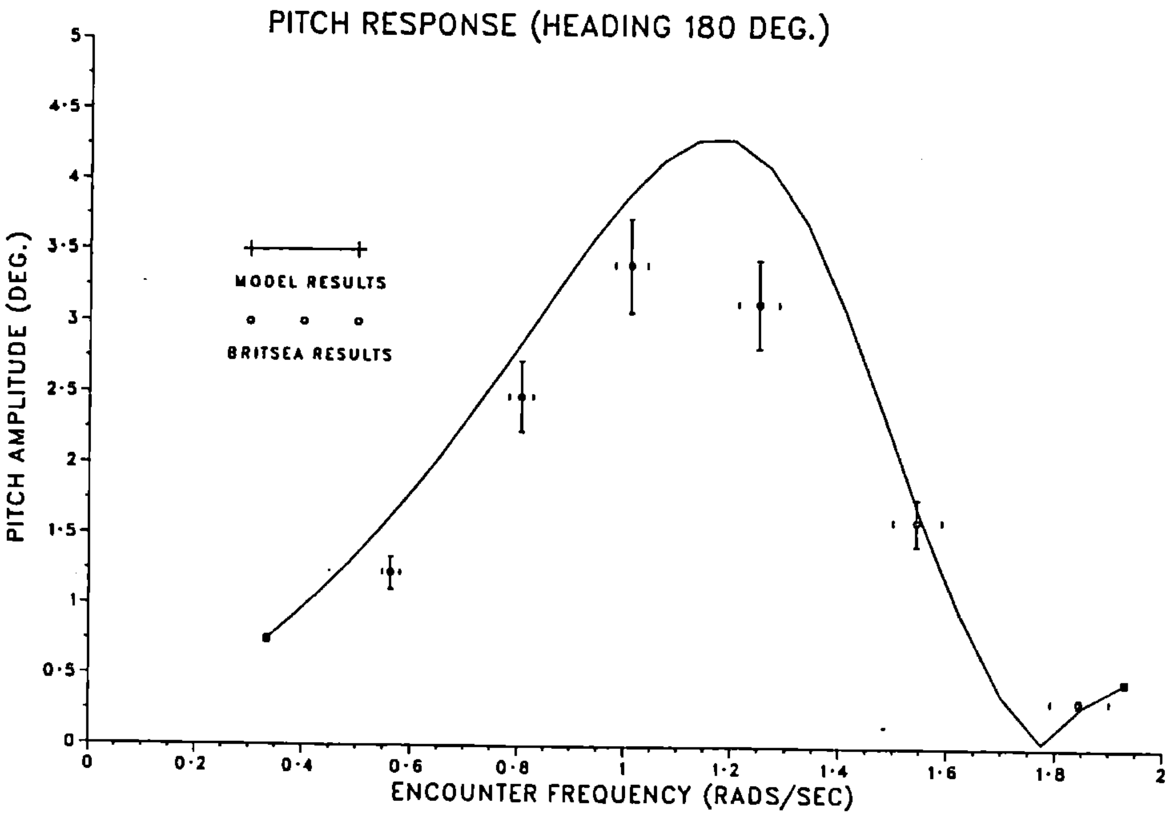

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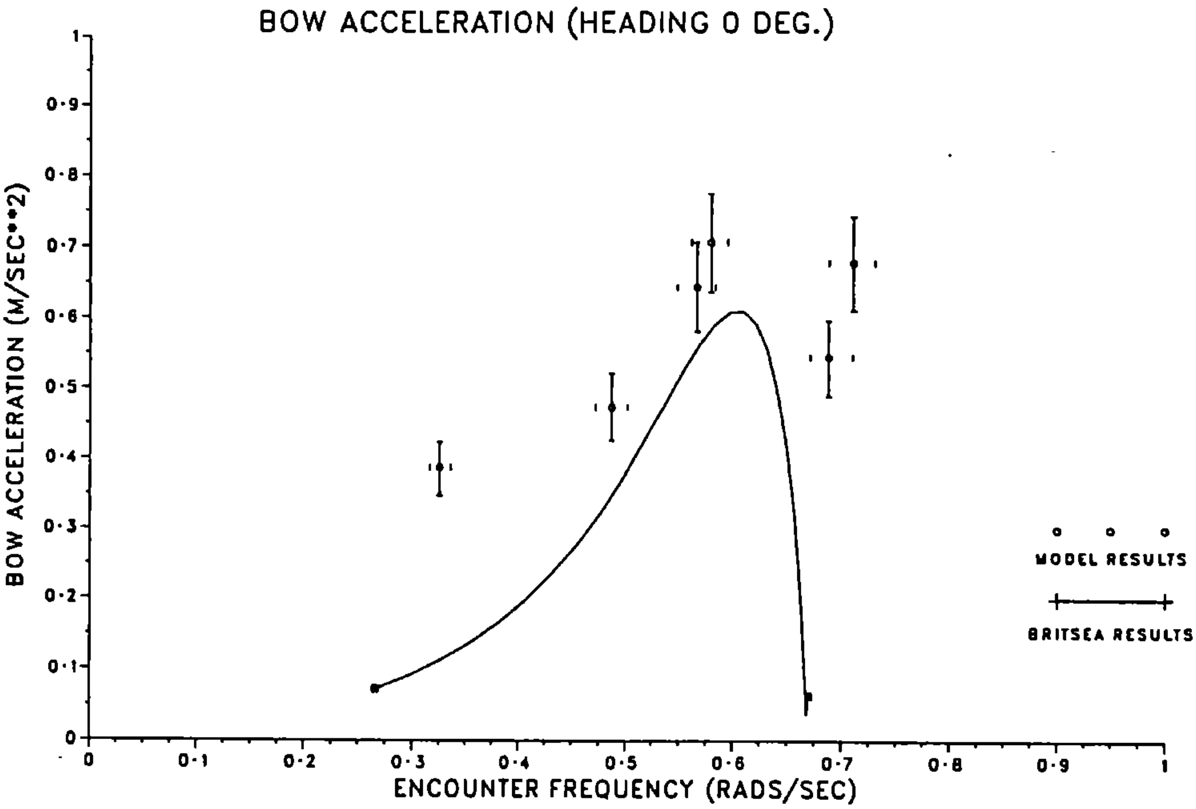

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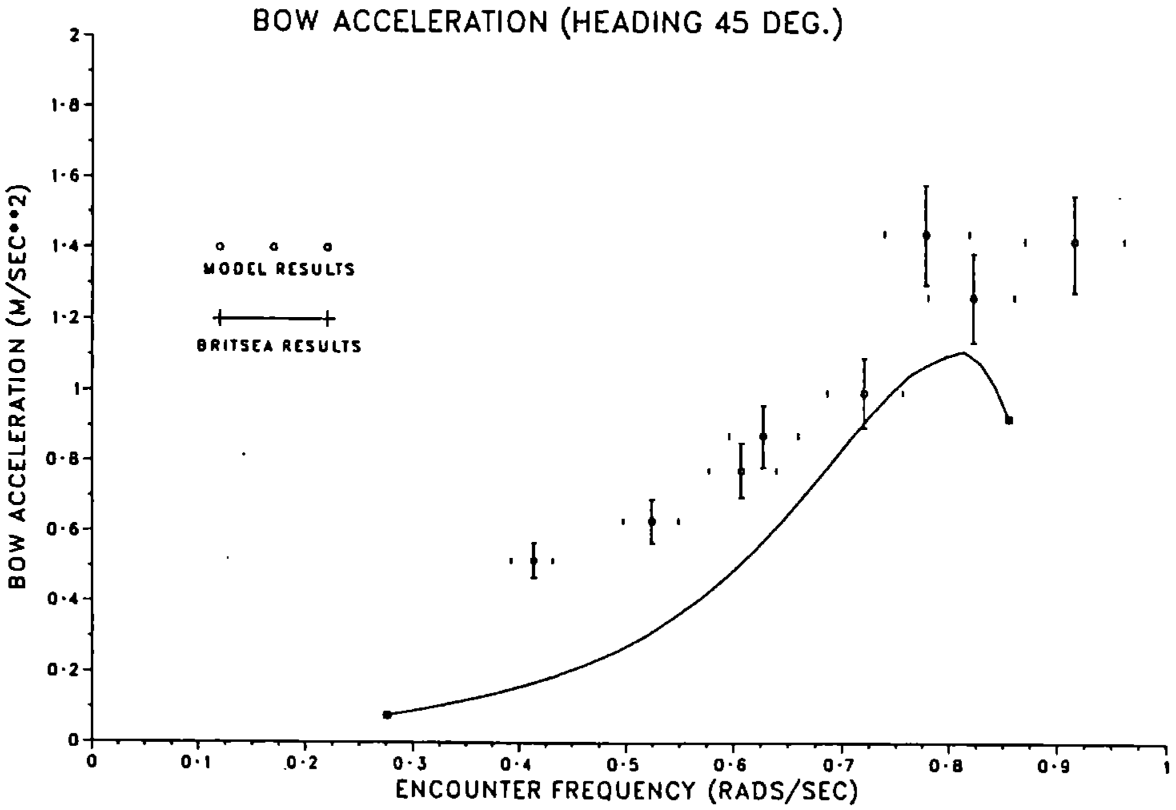
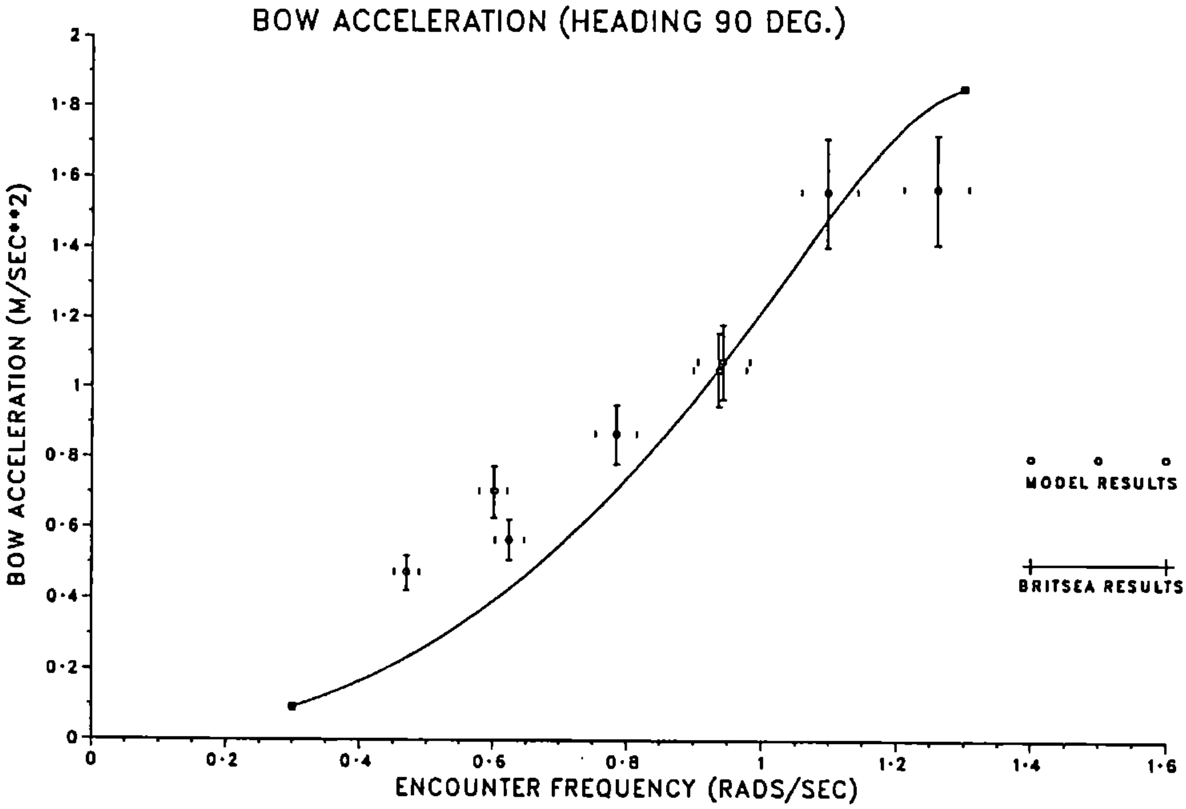


FIGURE A2.13



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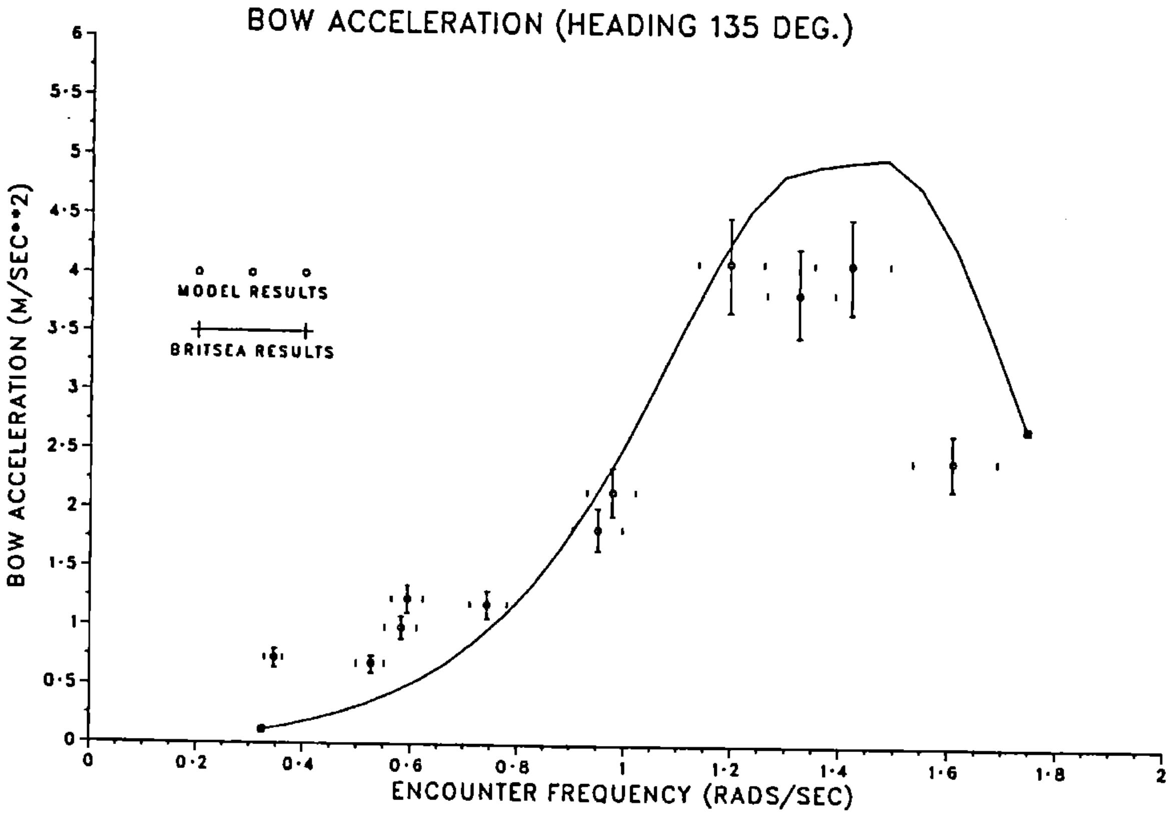

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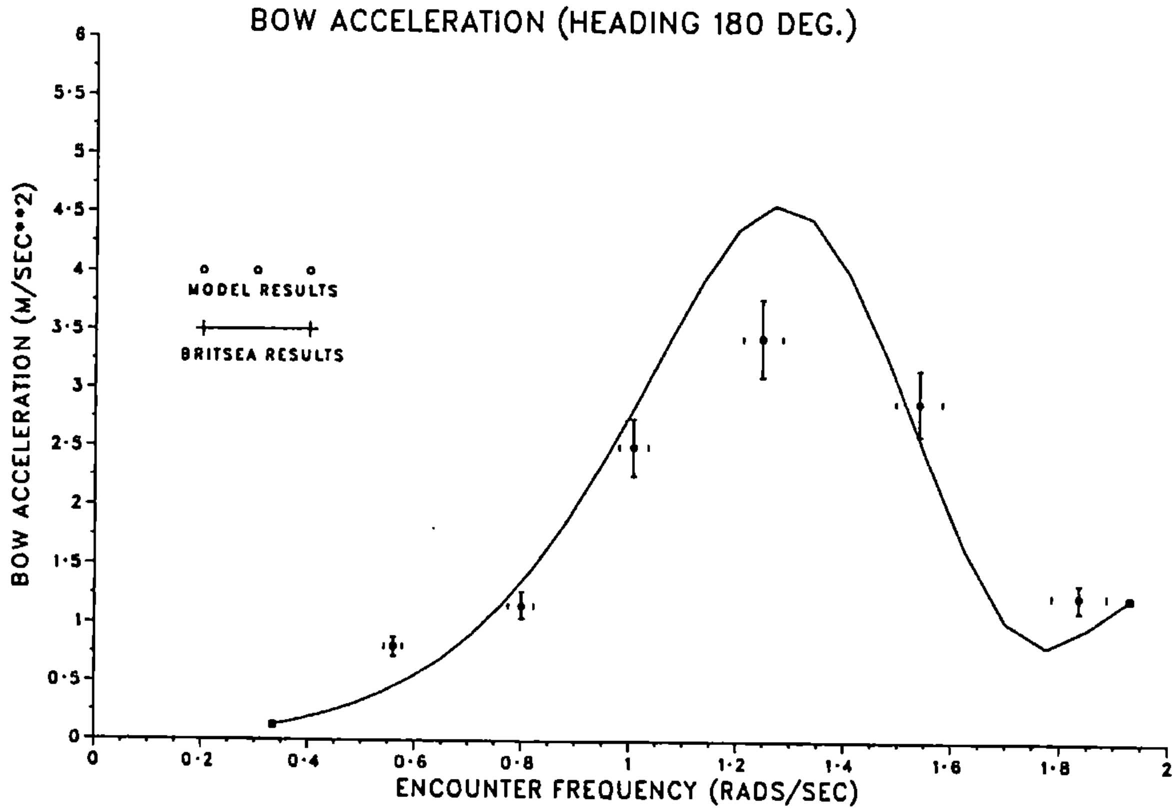

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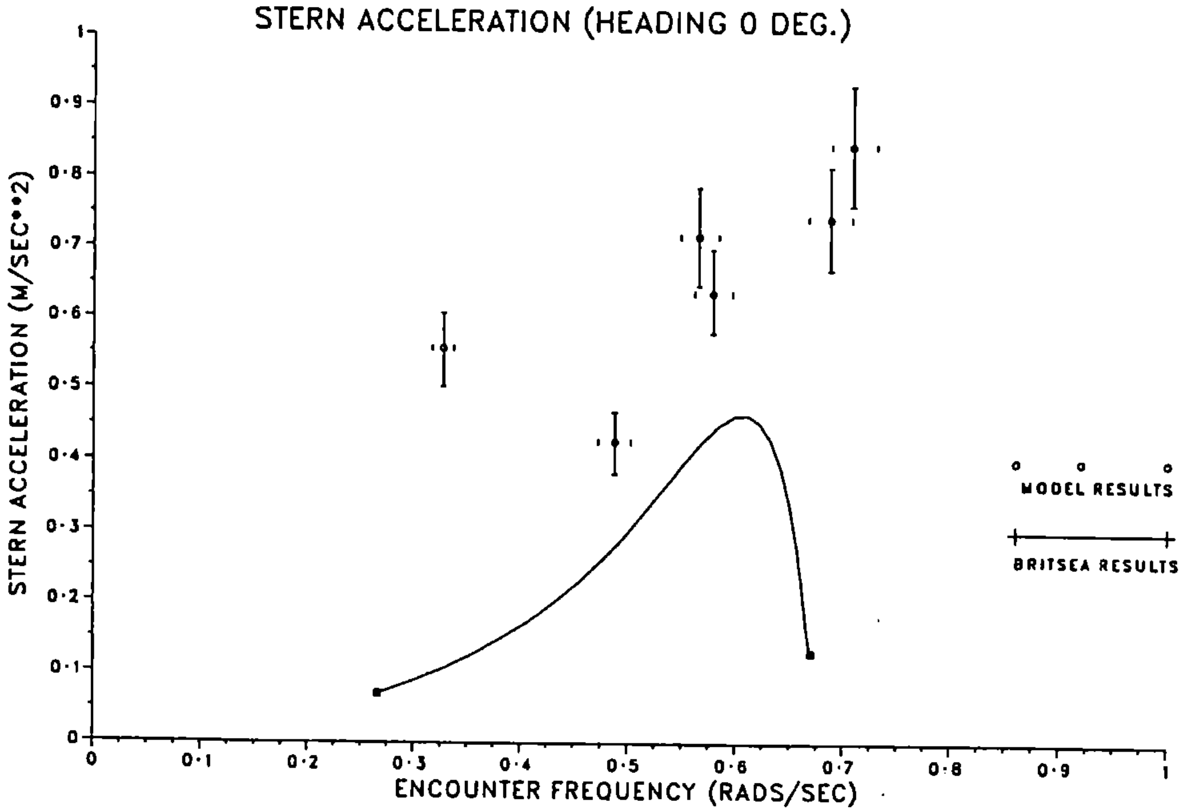

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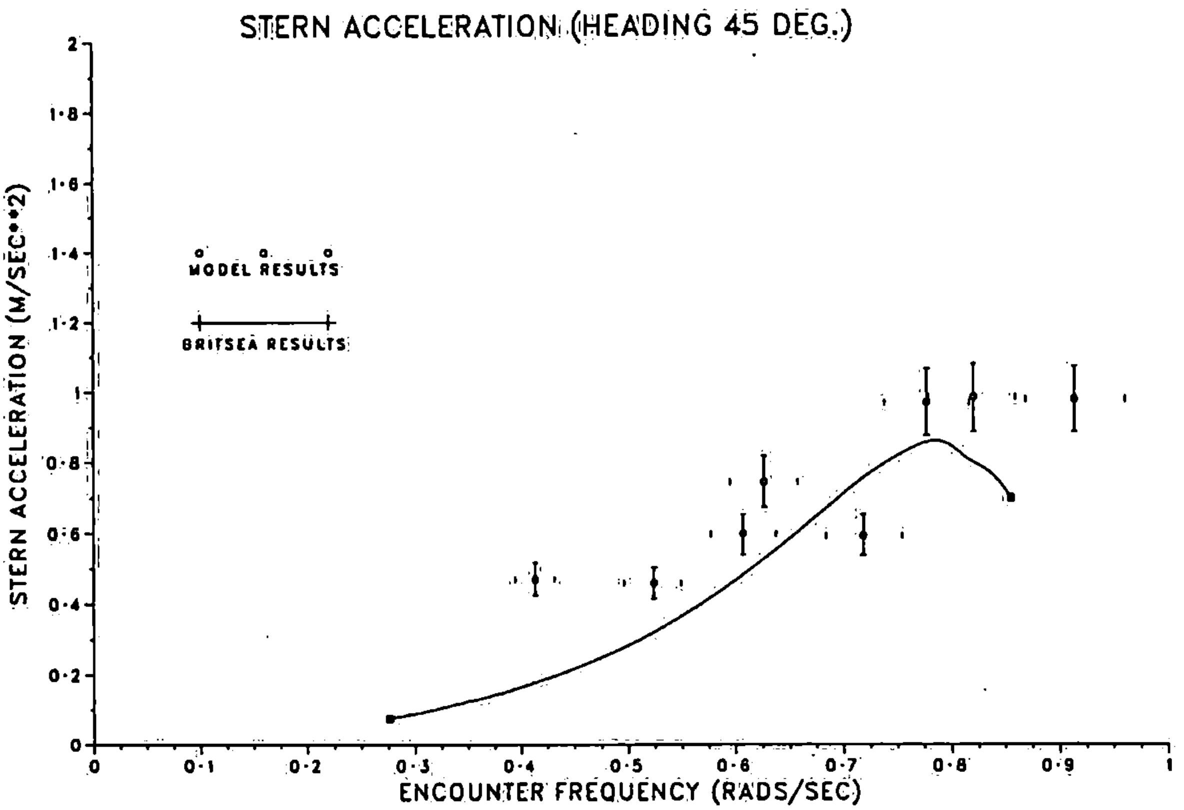

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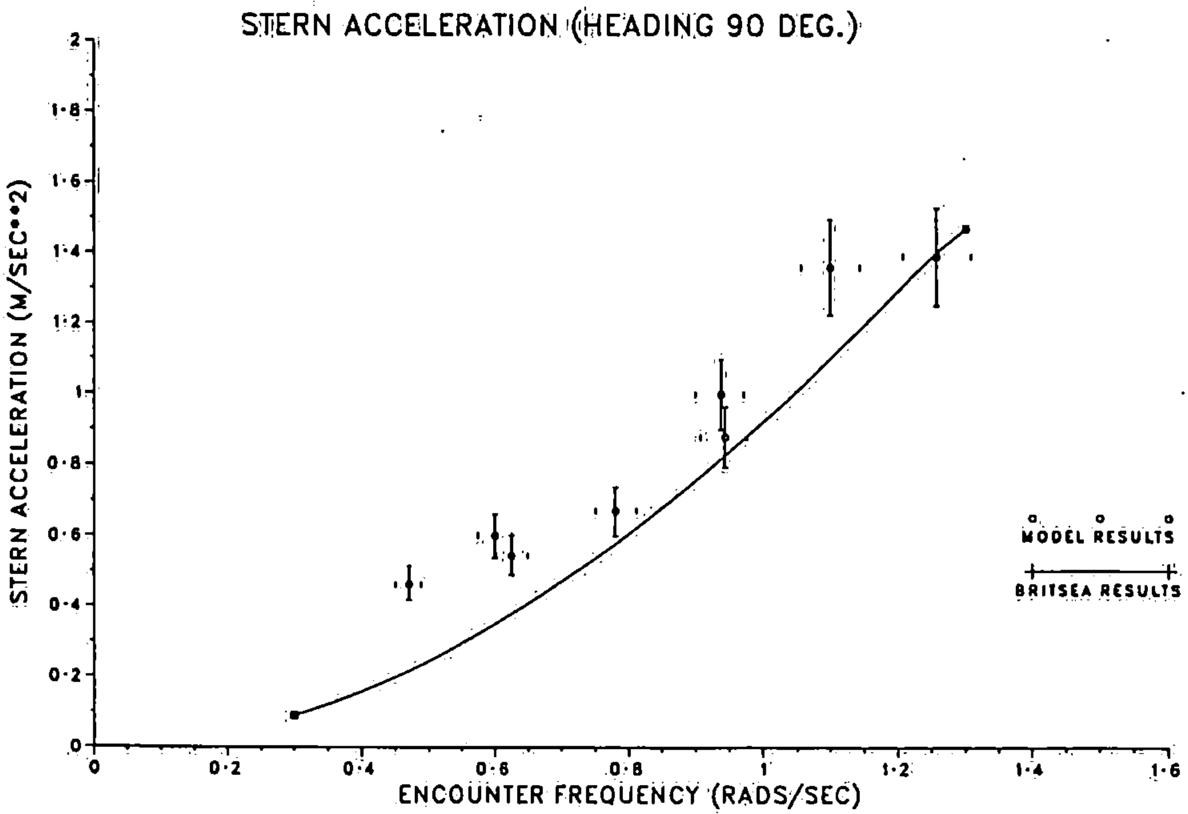

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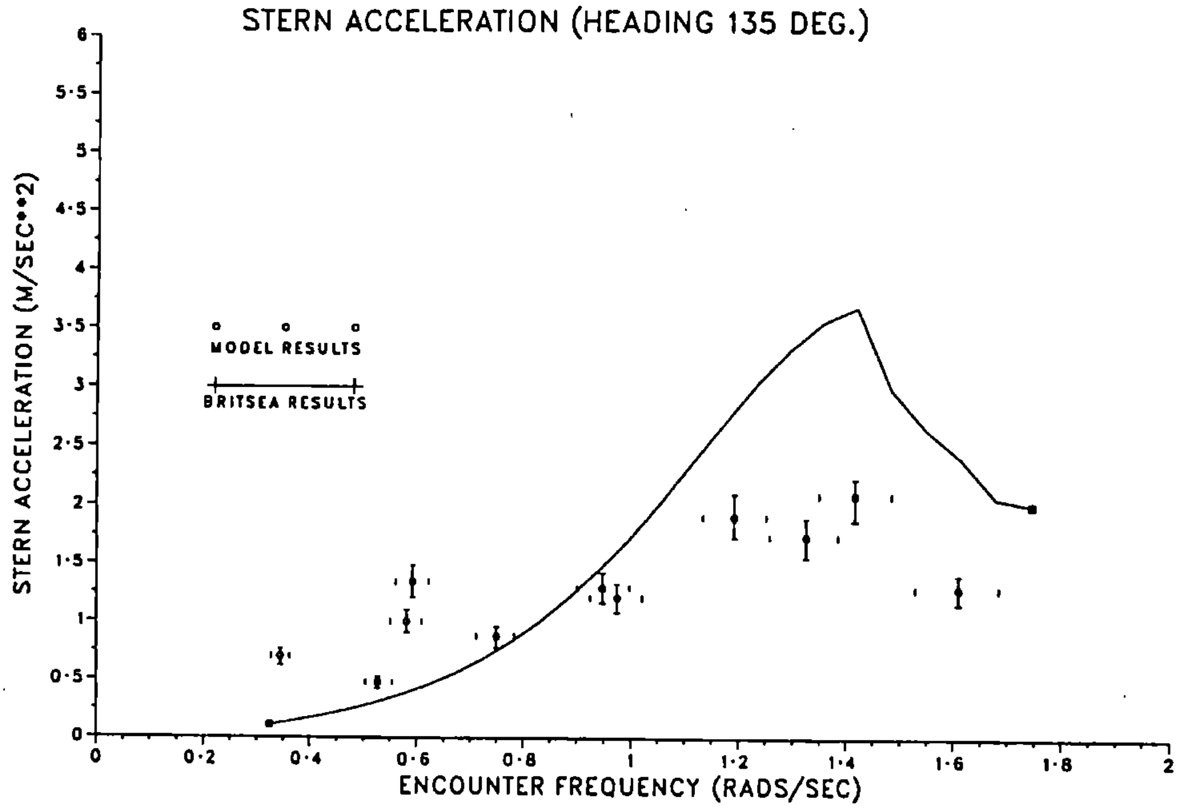

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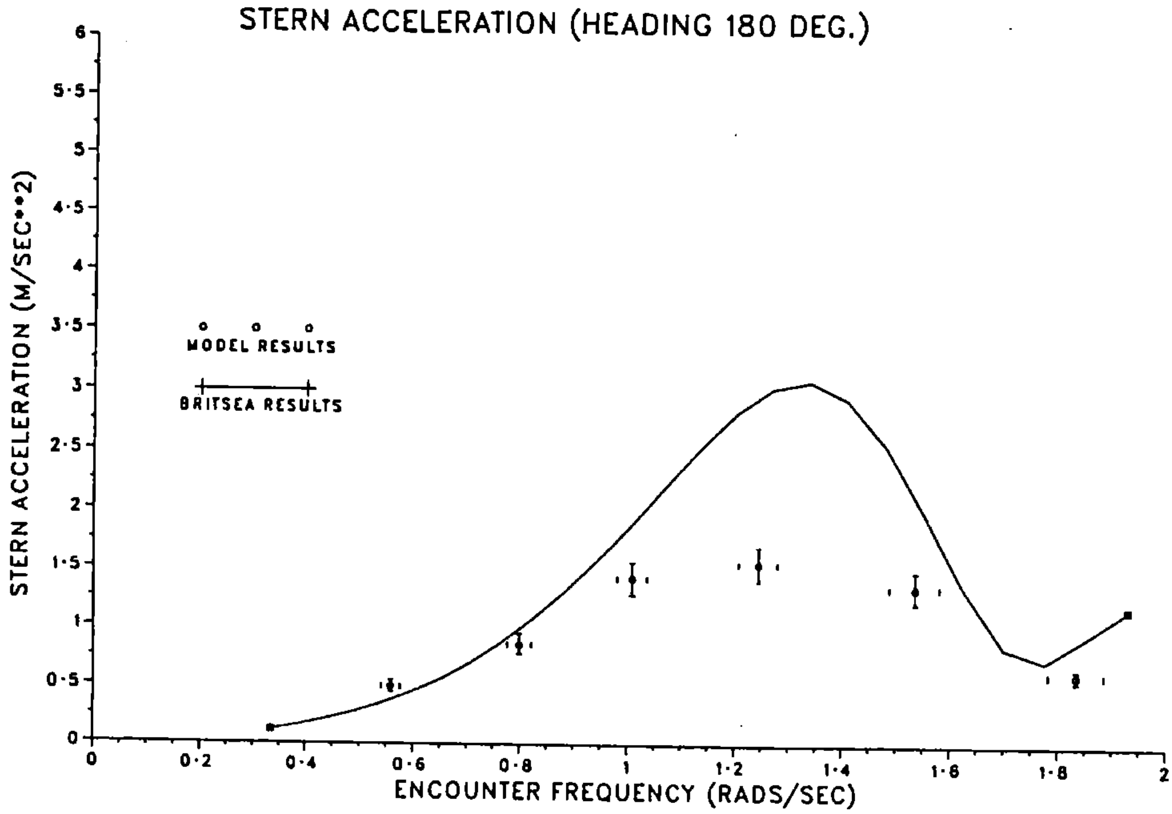

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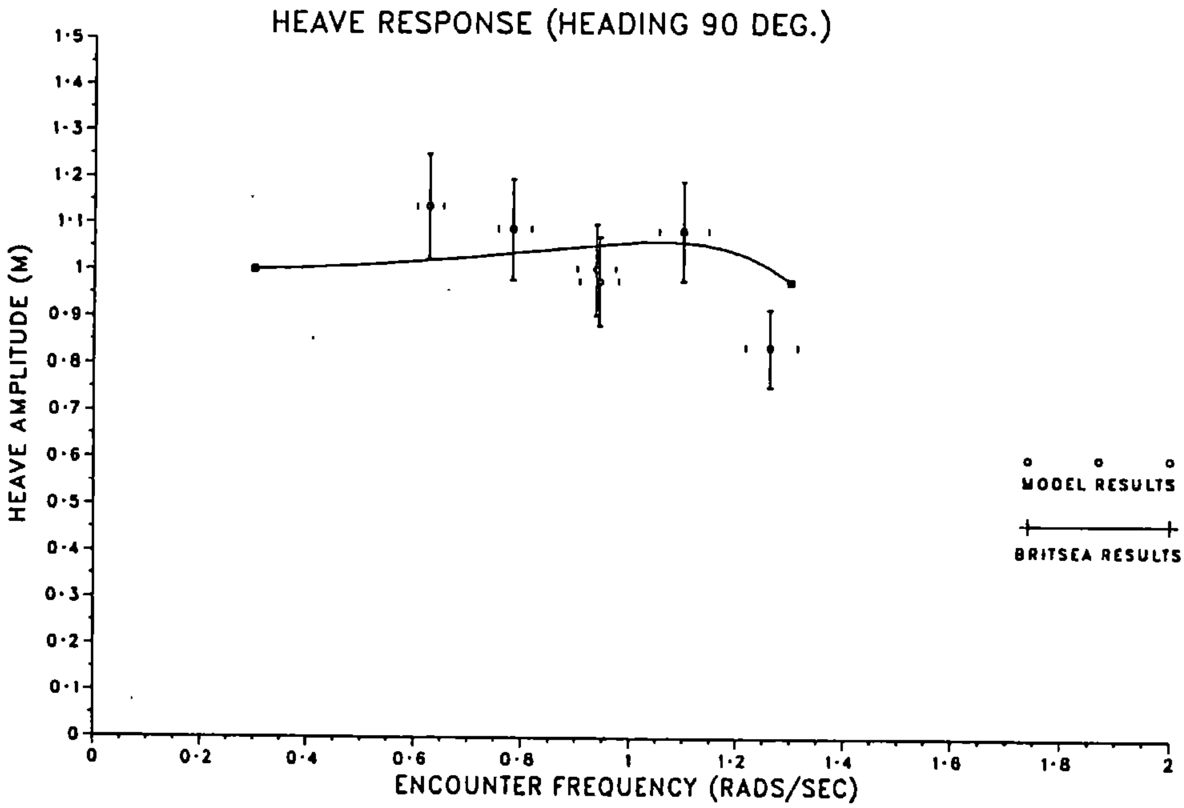

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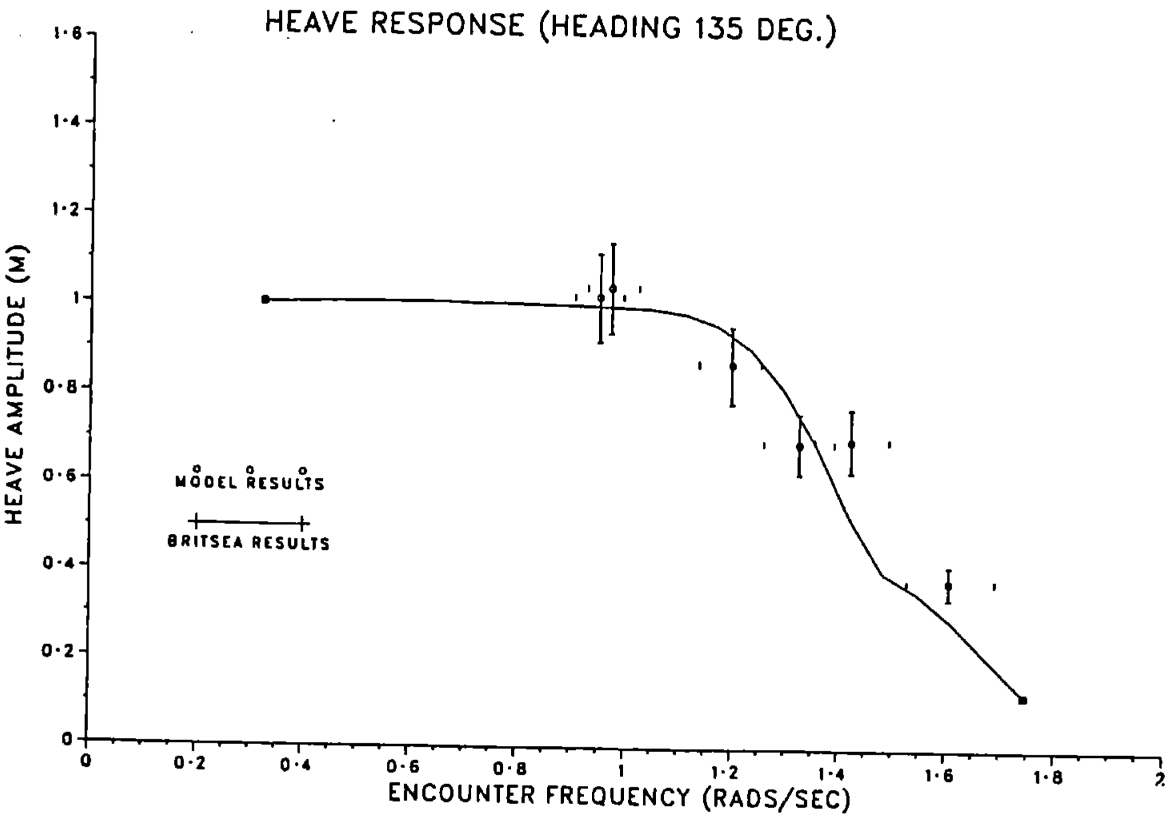

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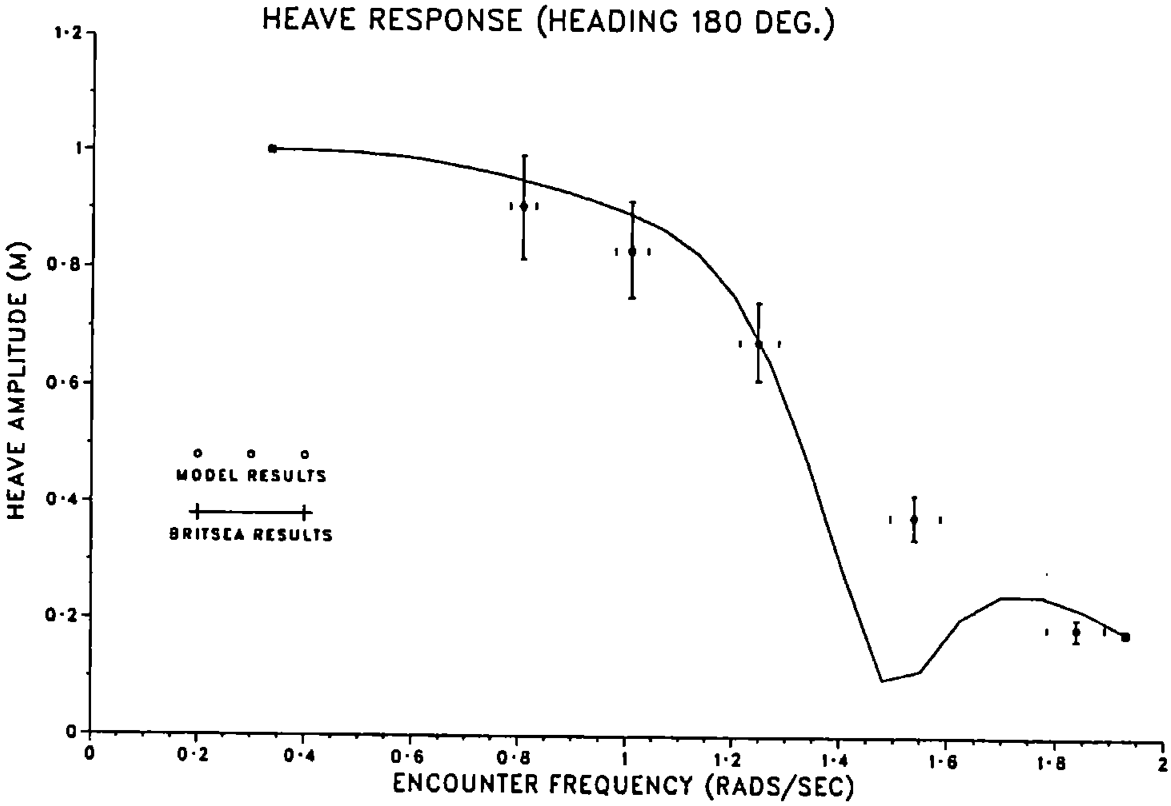

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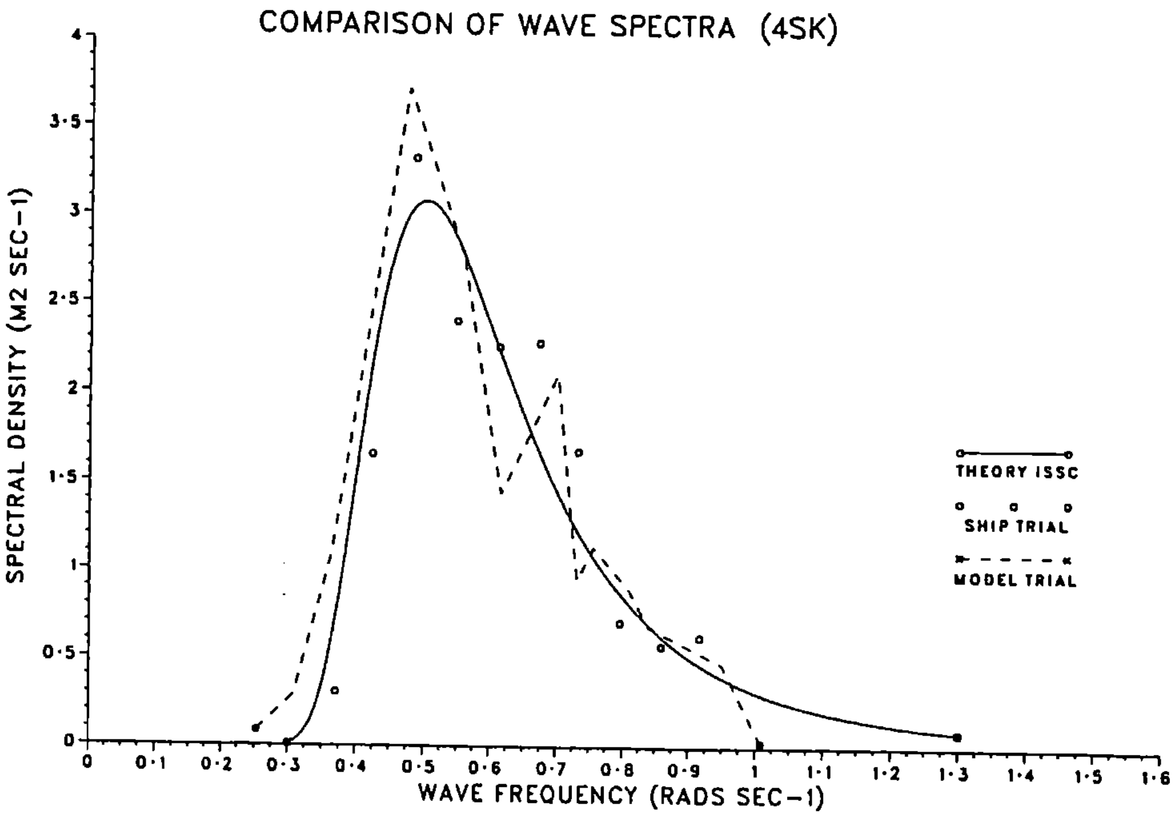

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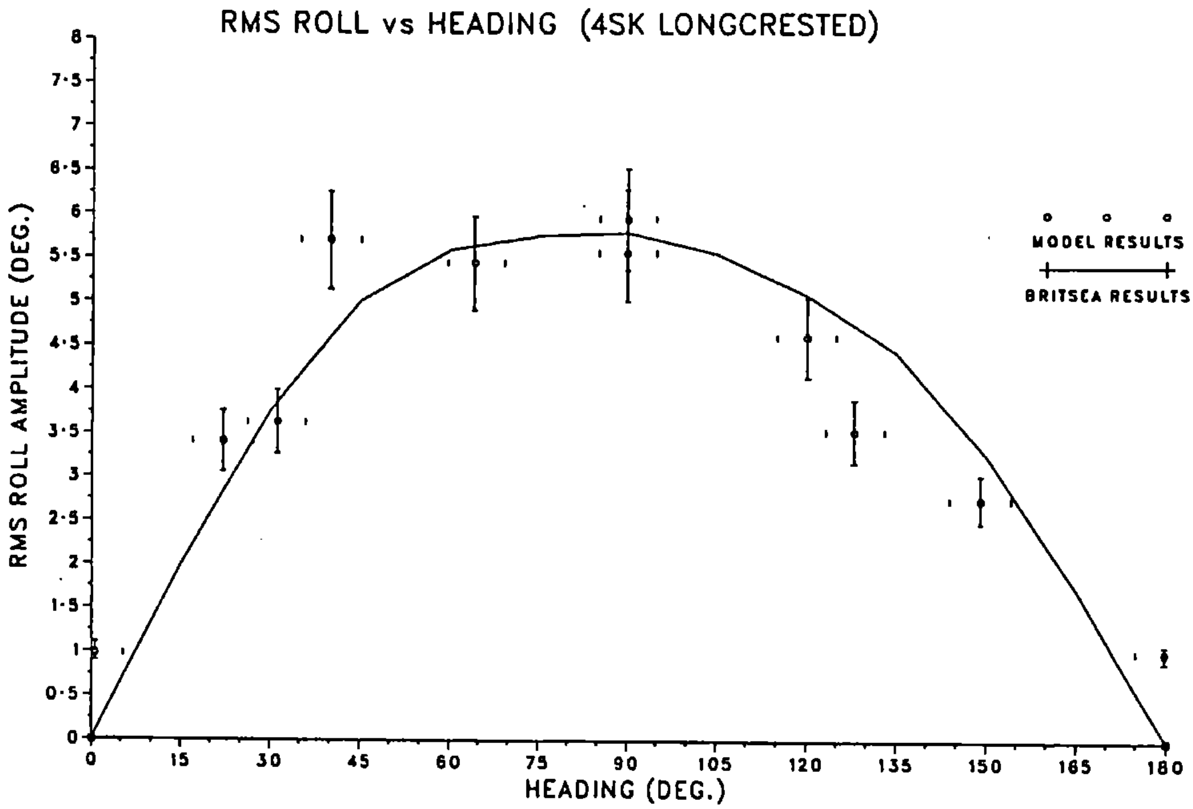

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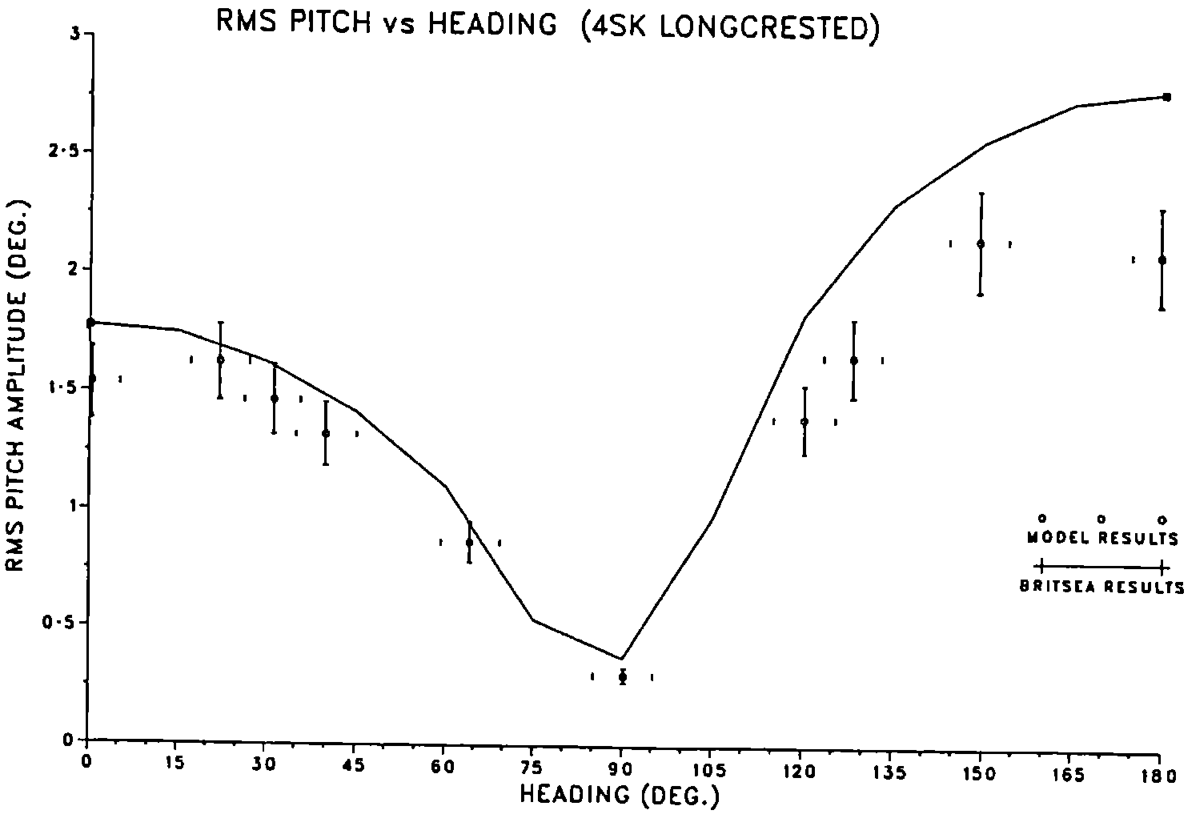

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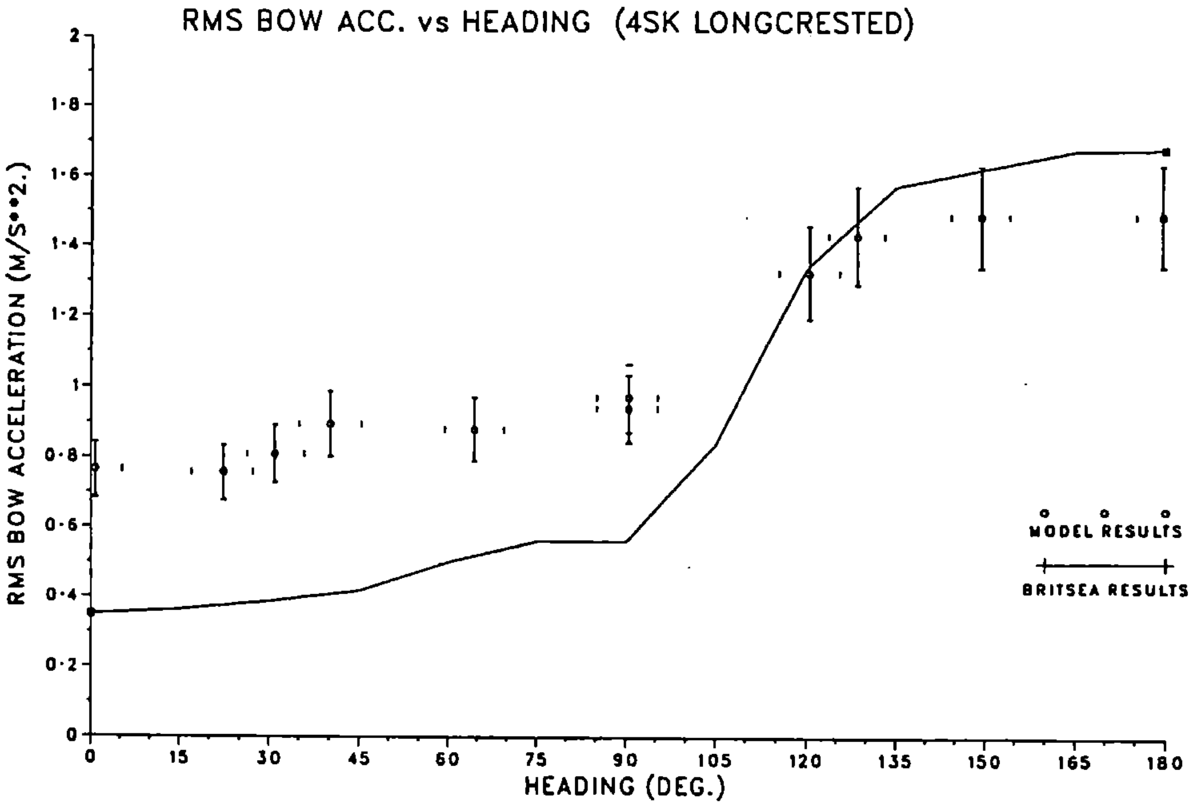

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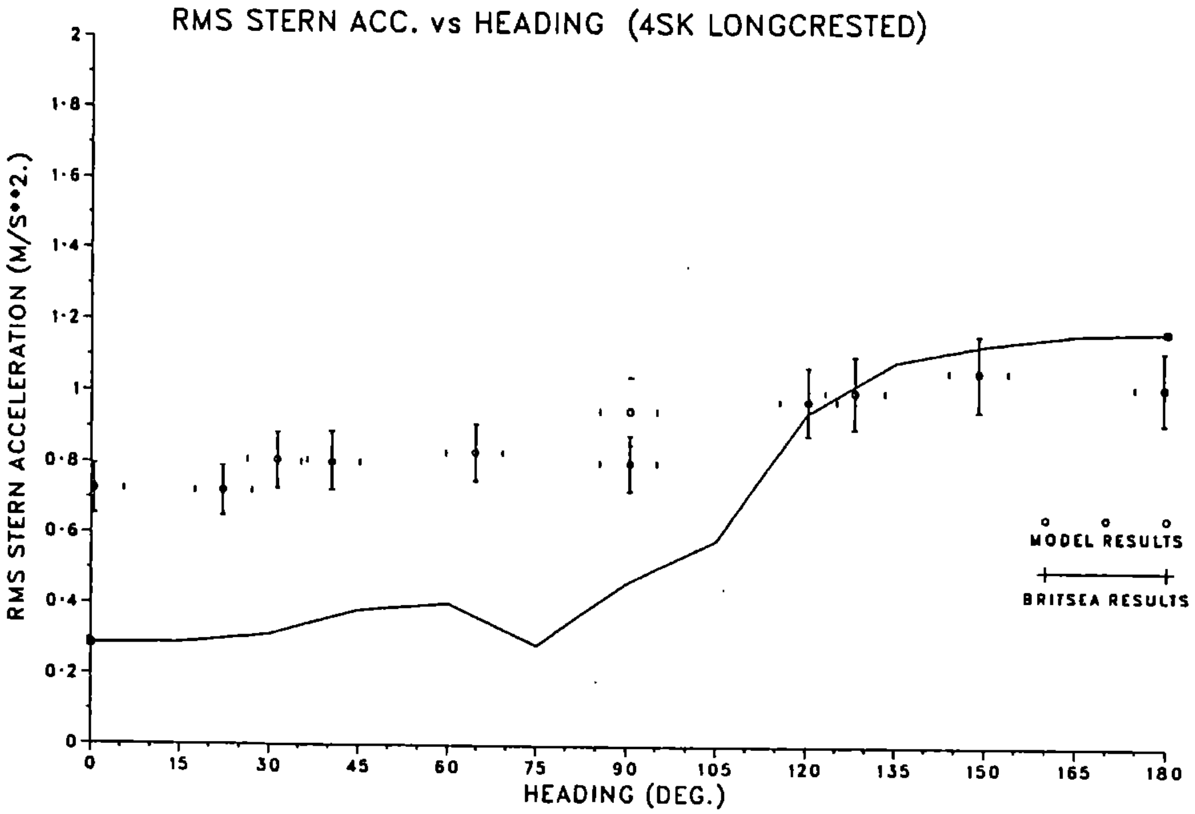

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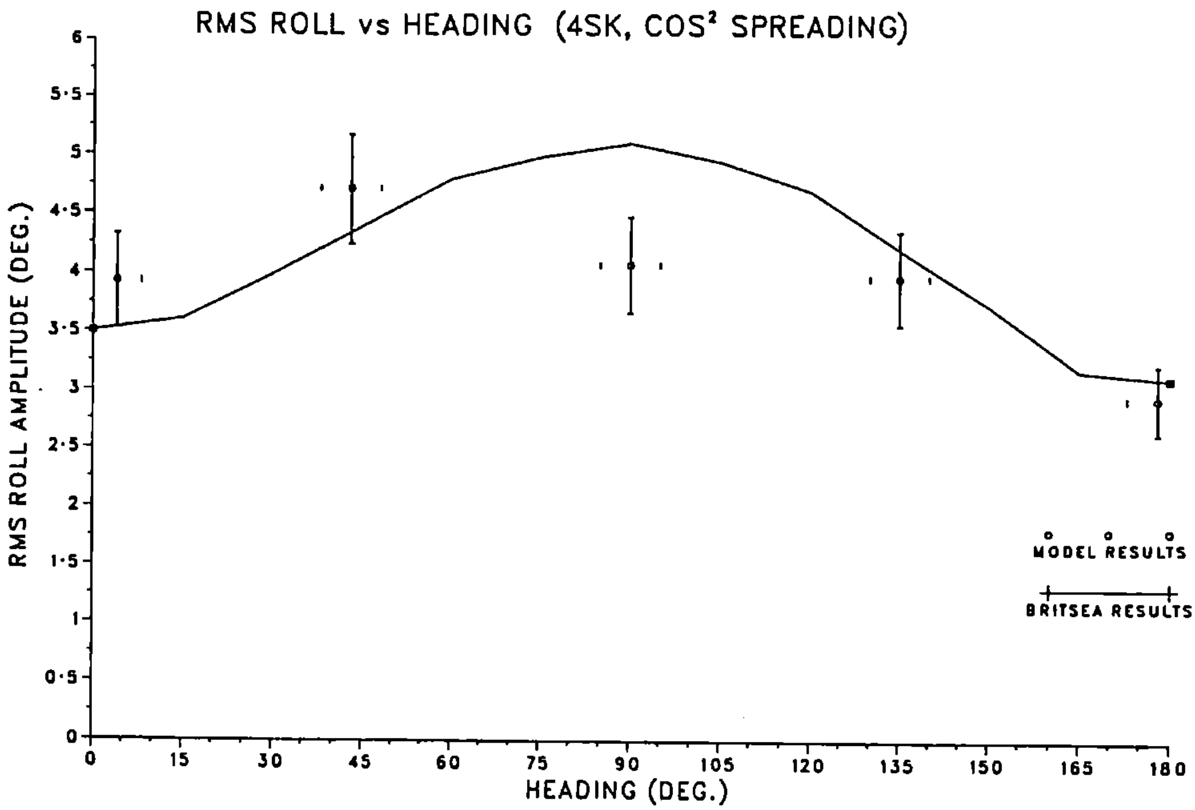

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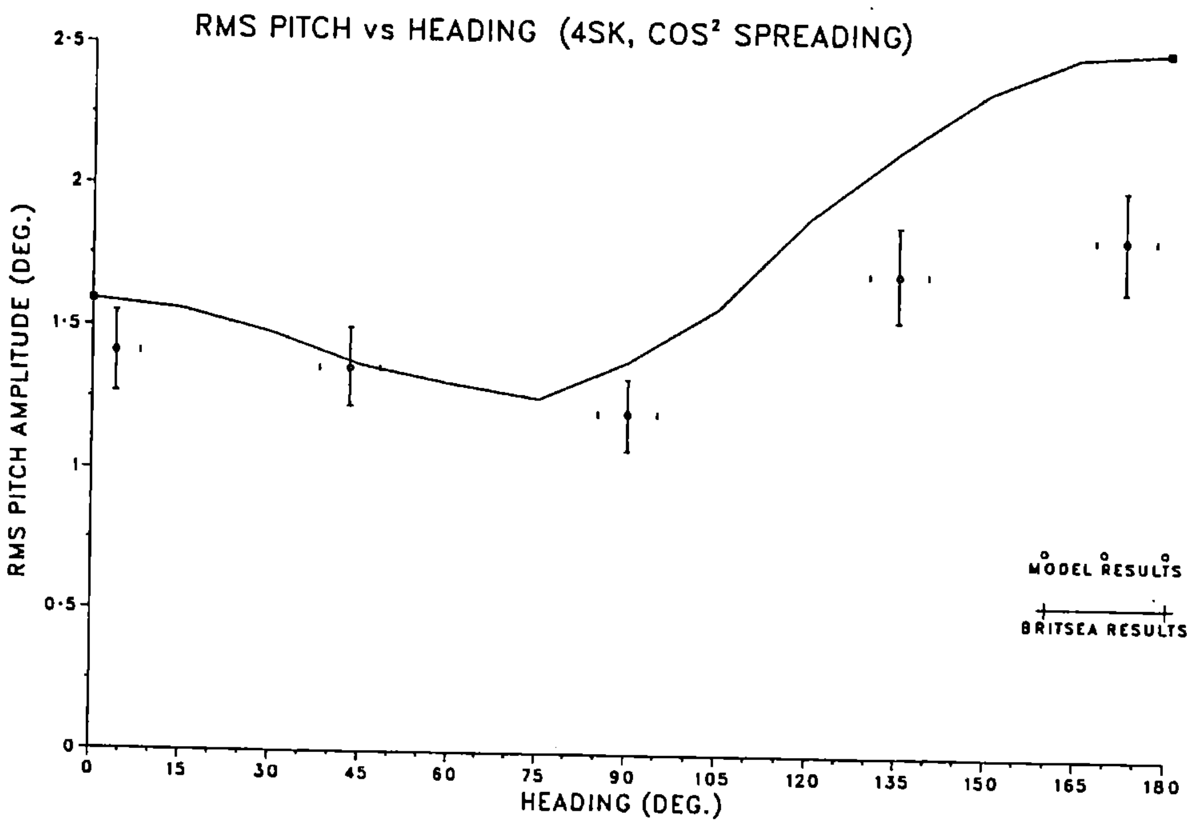

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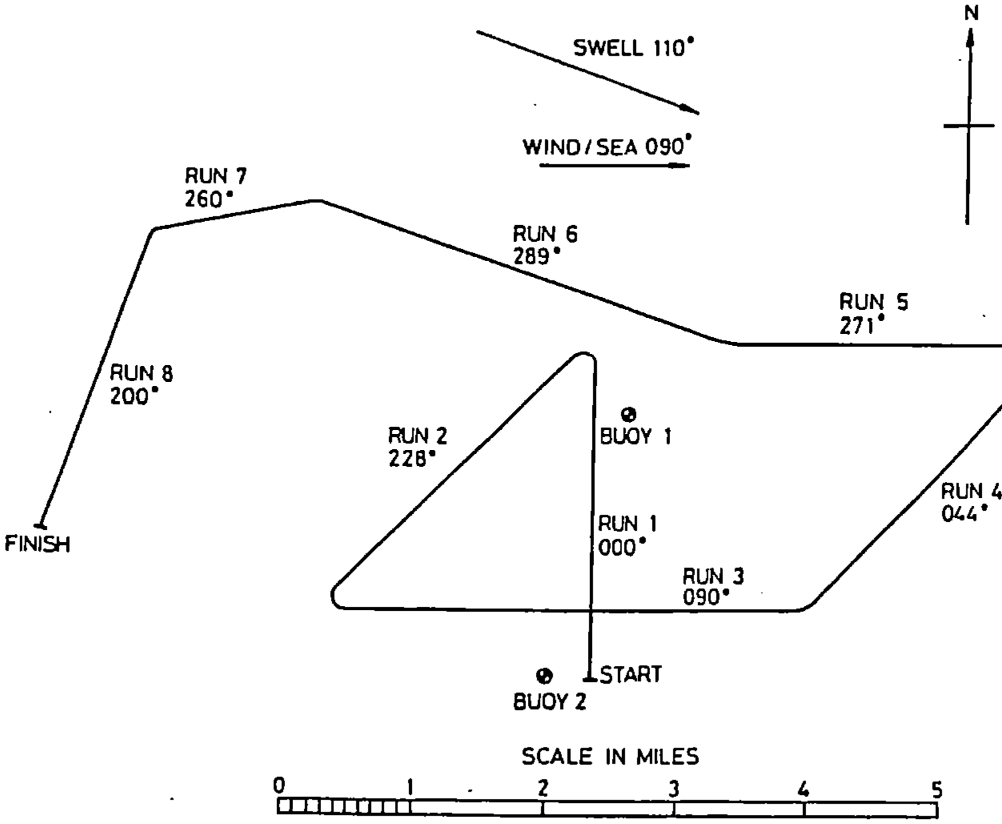
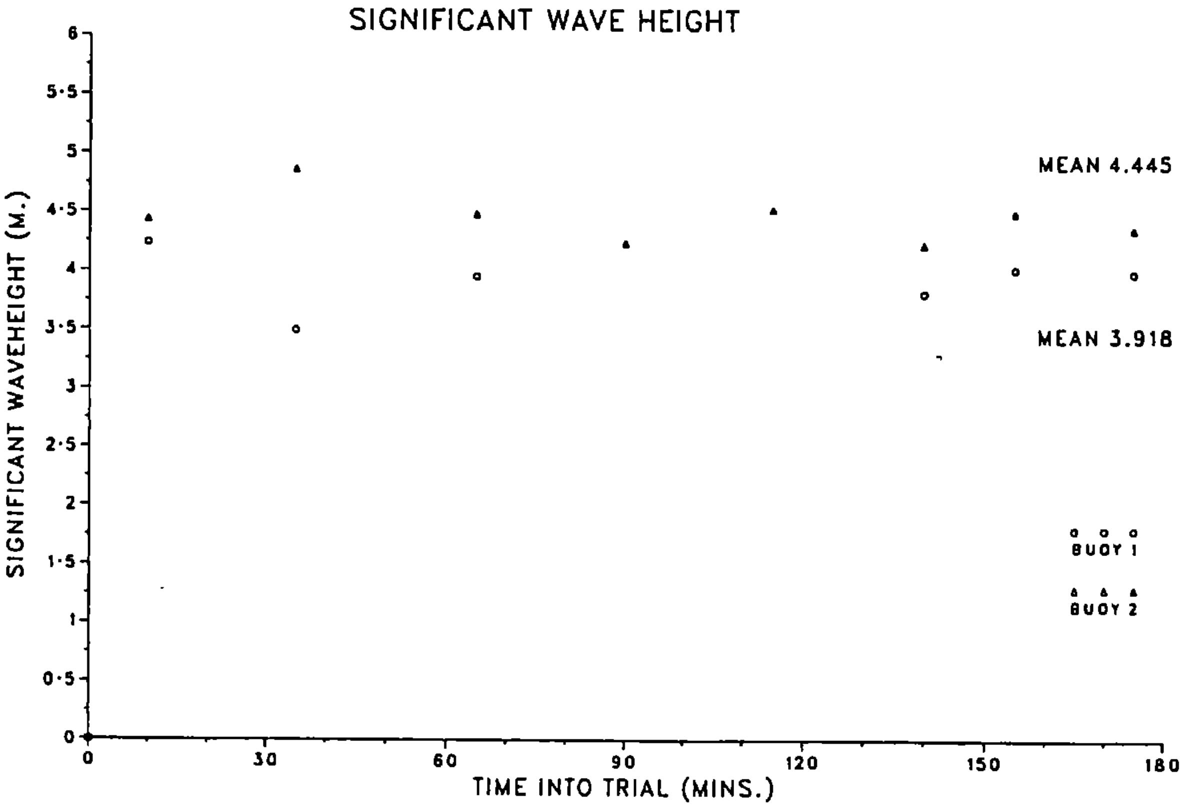


PLAN OF MANOEUVRE

FIGURE A2.32



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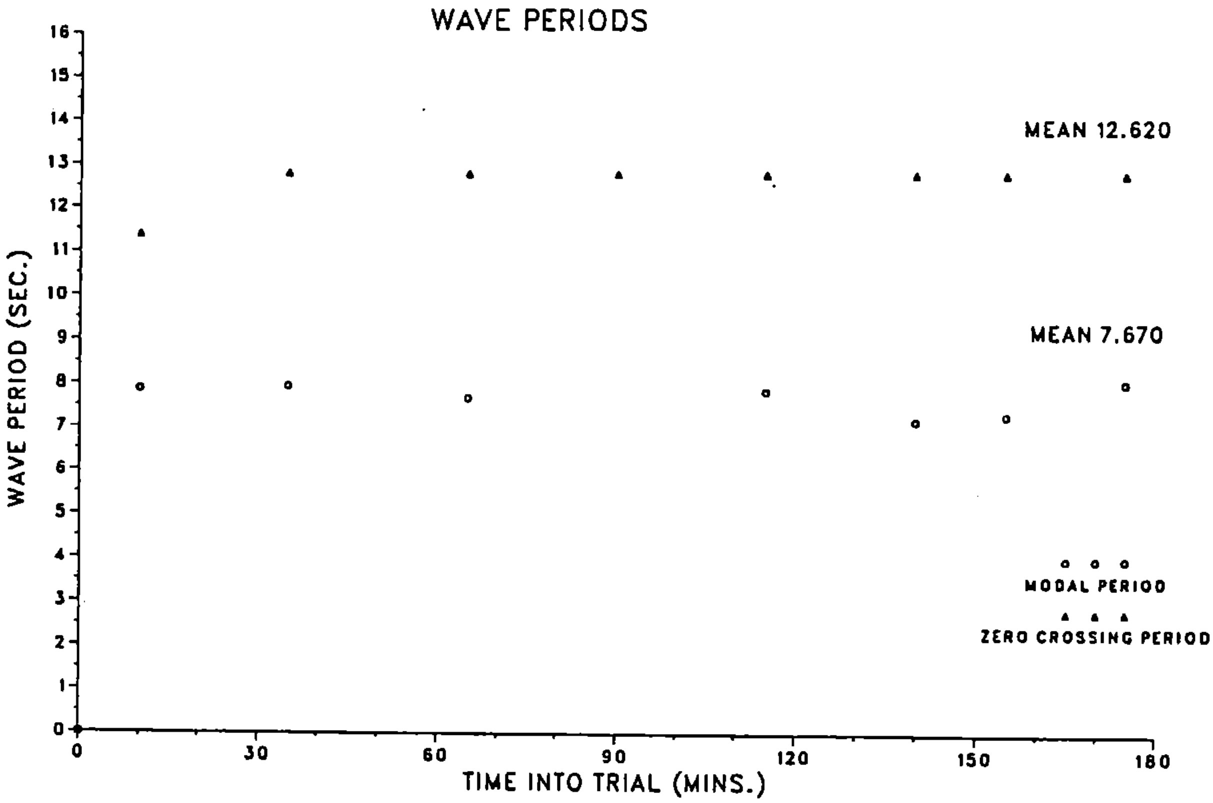

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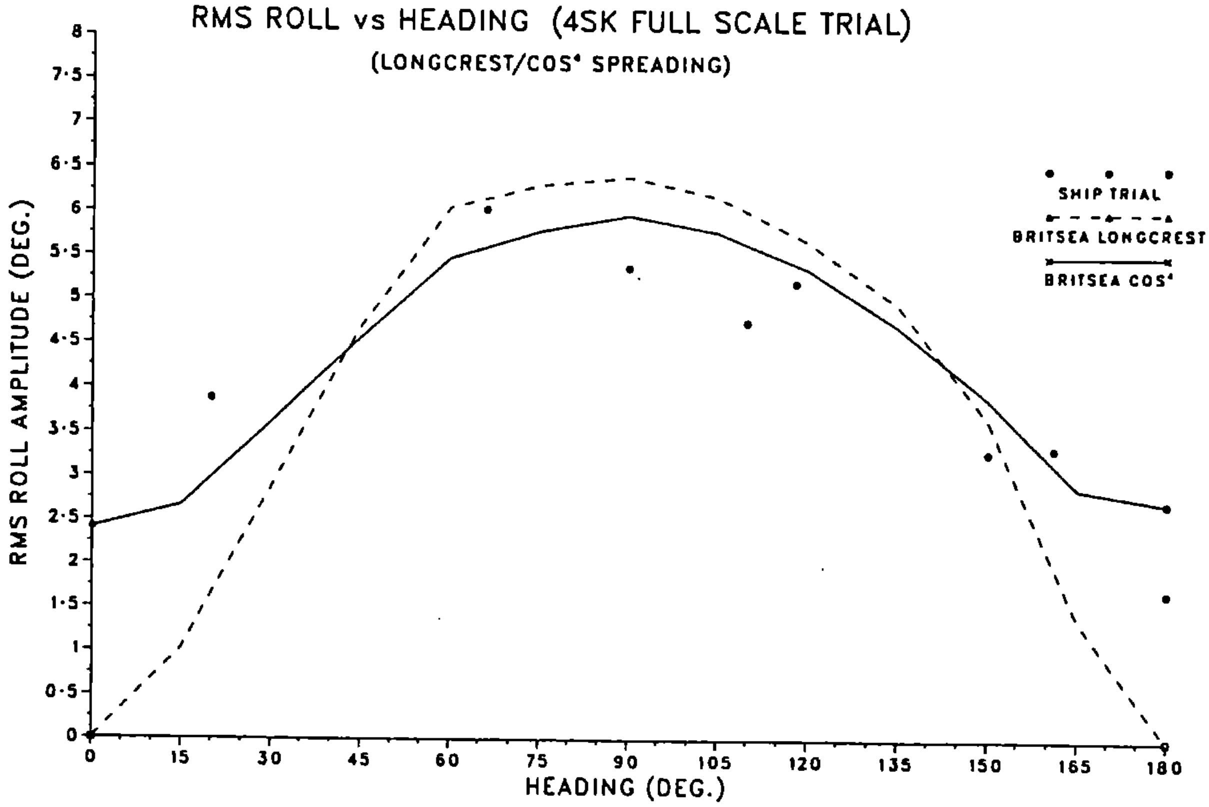

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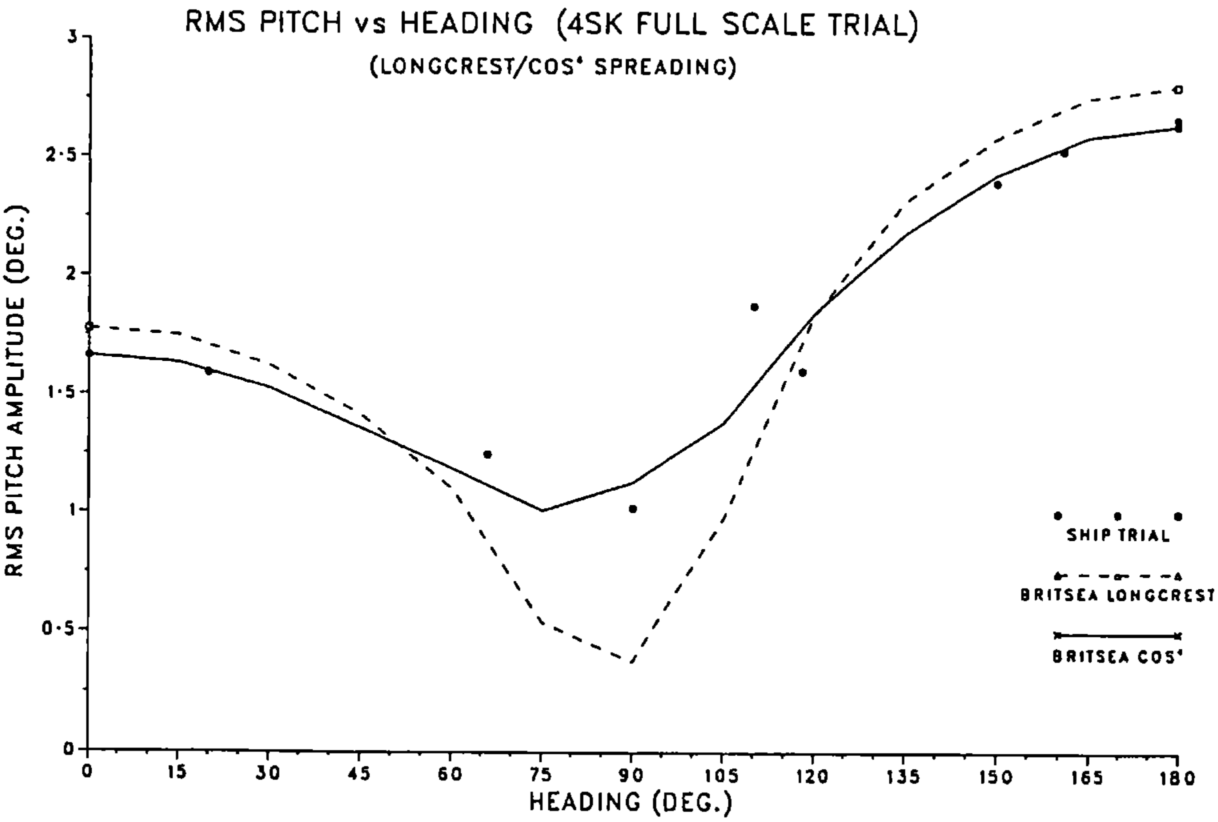

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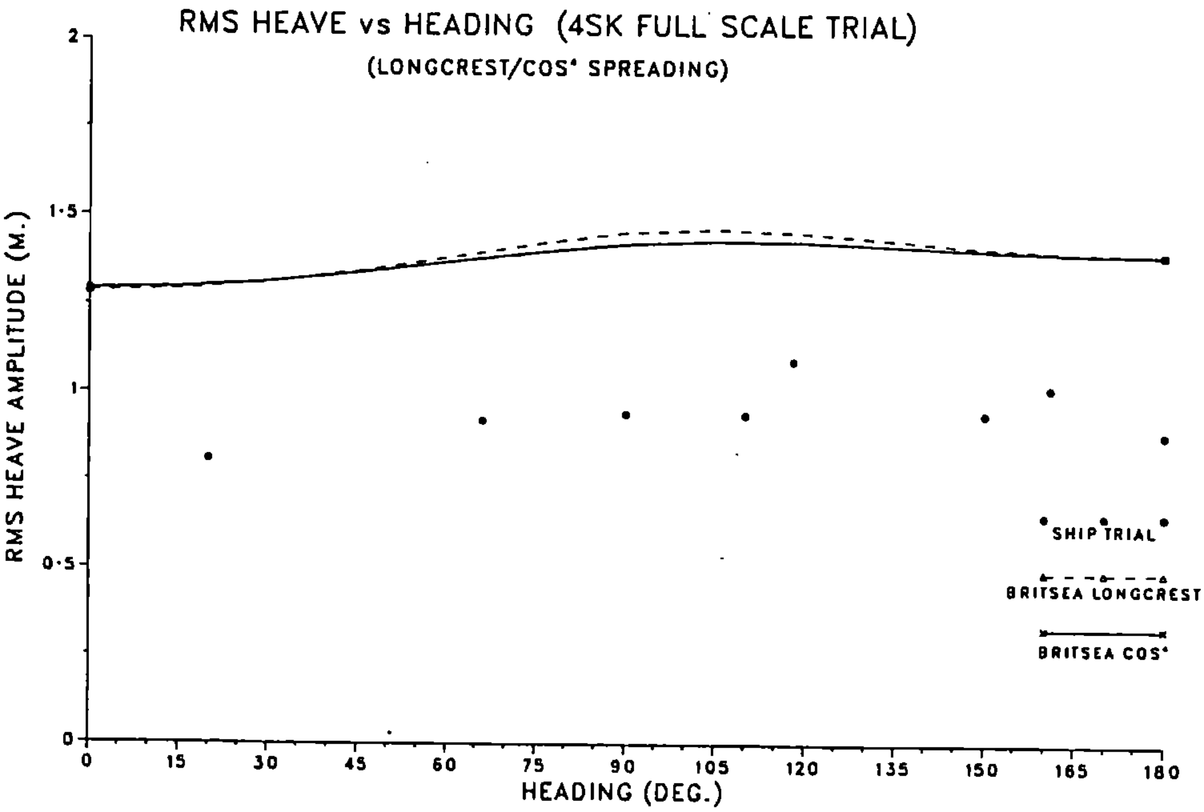

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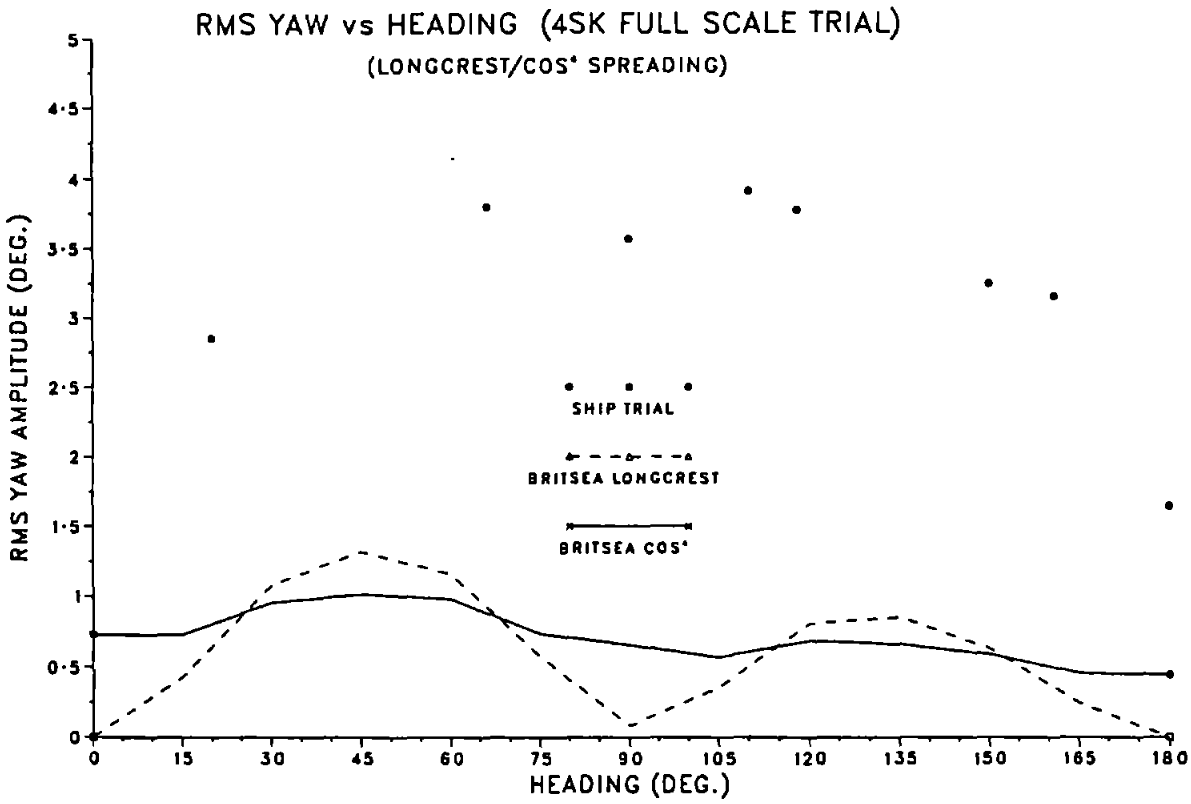

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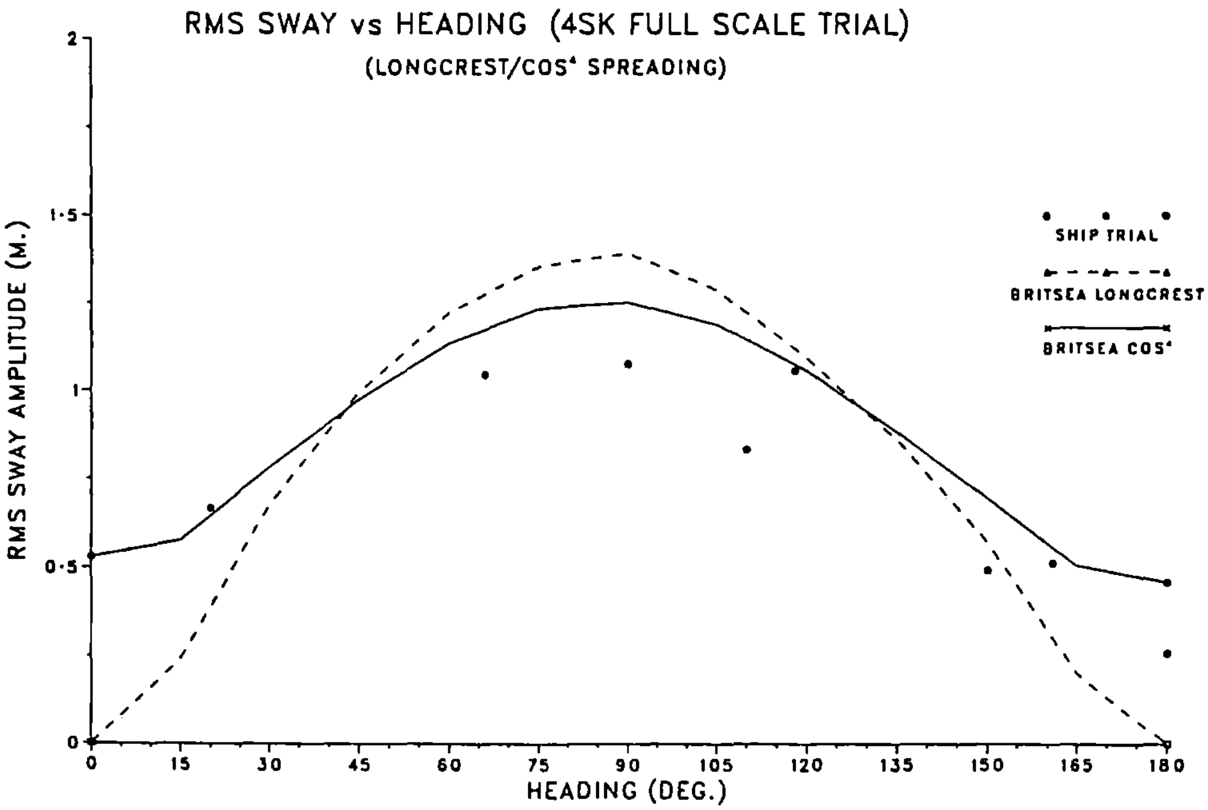

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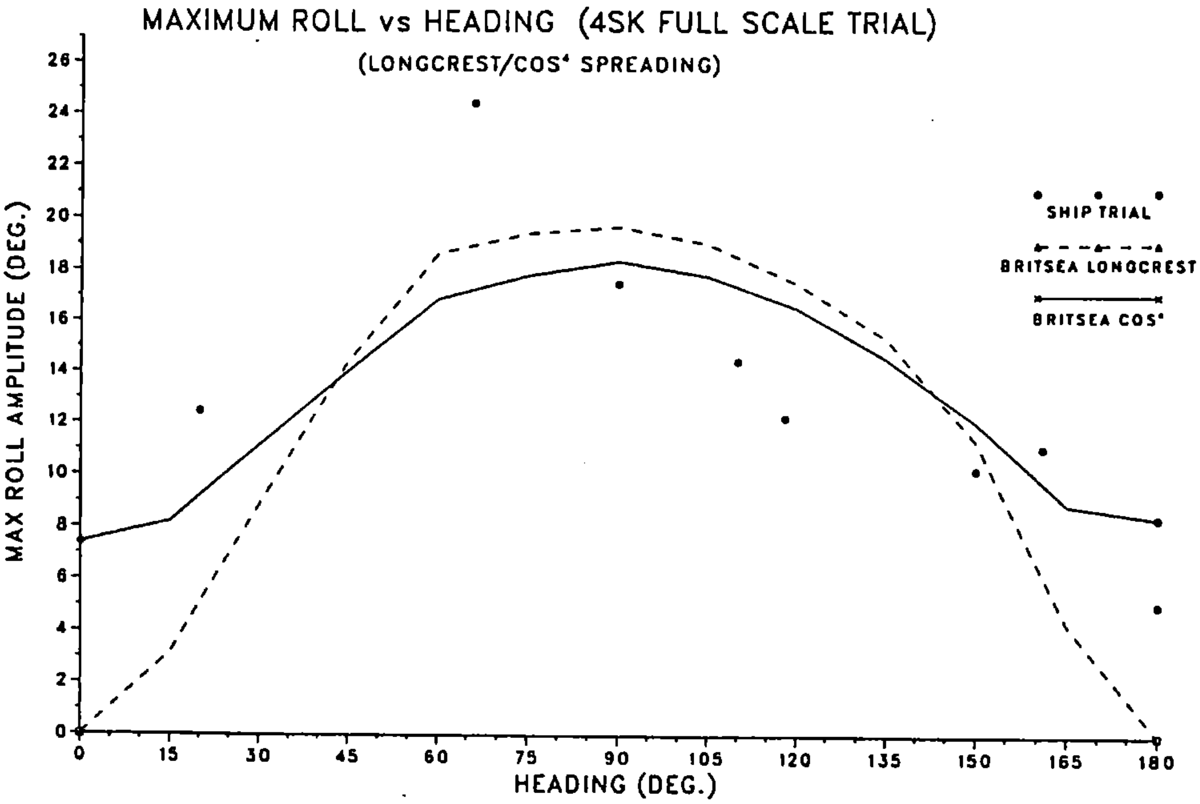

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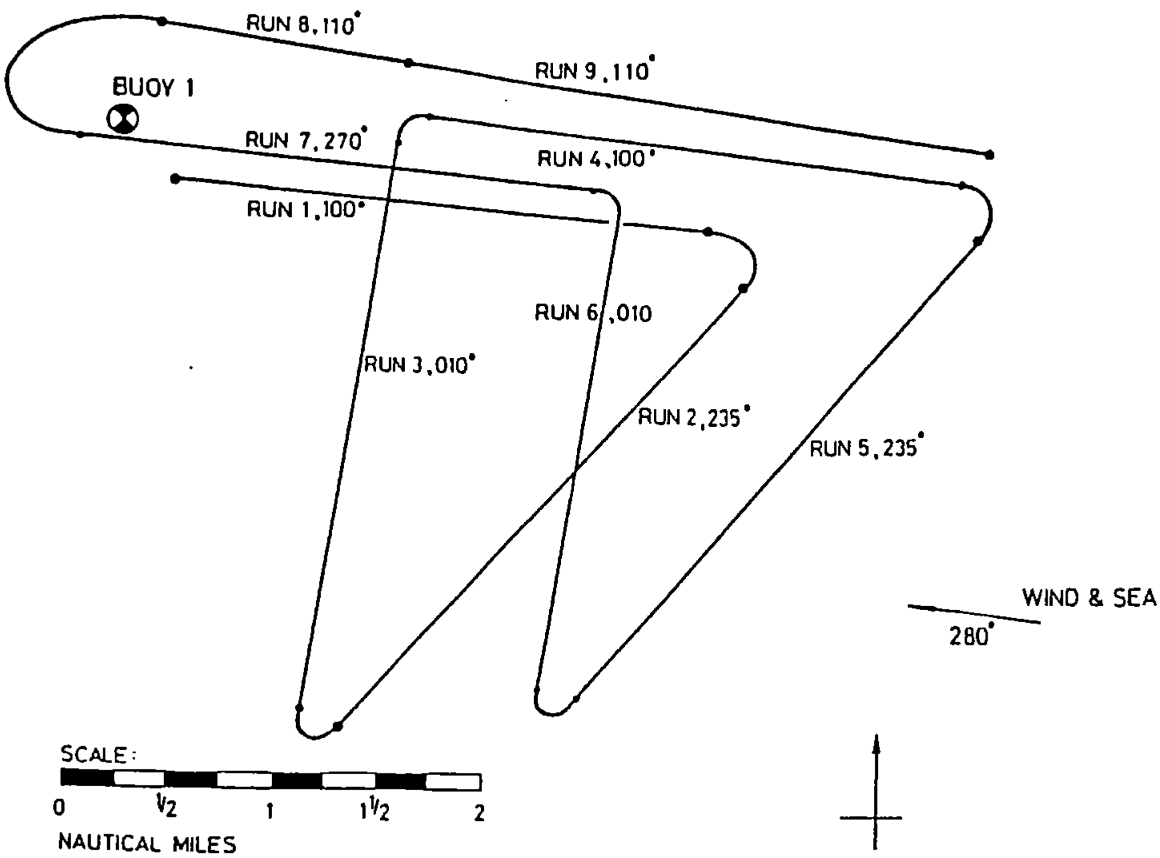

PLAN OF MANOEUVRE

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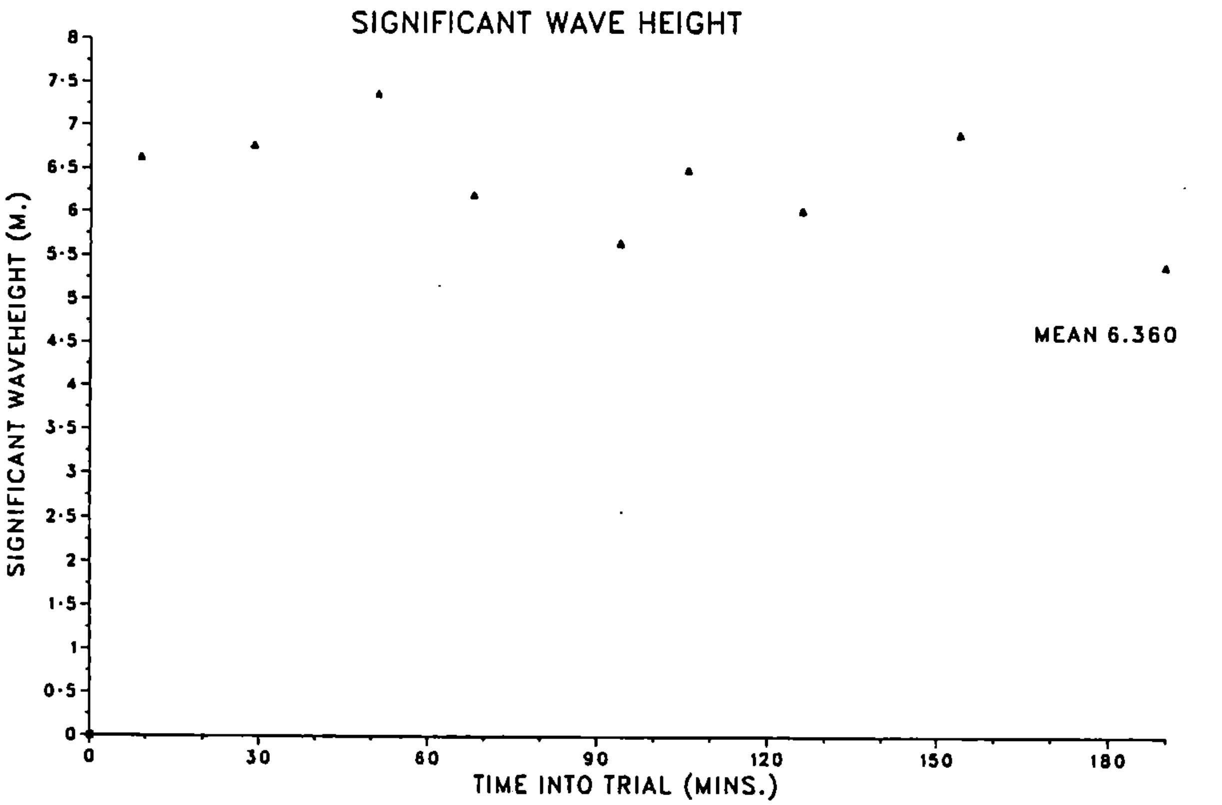

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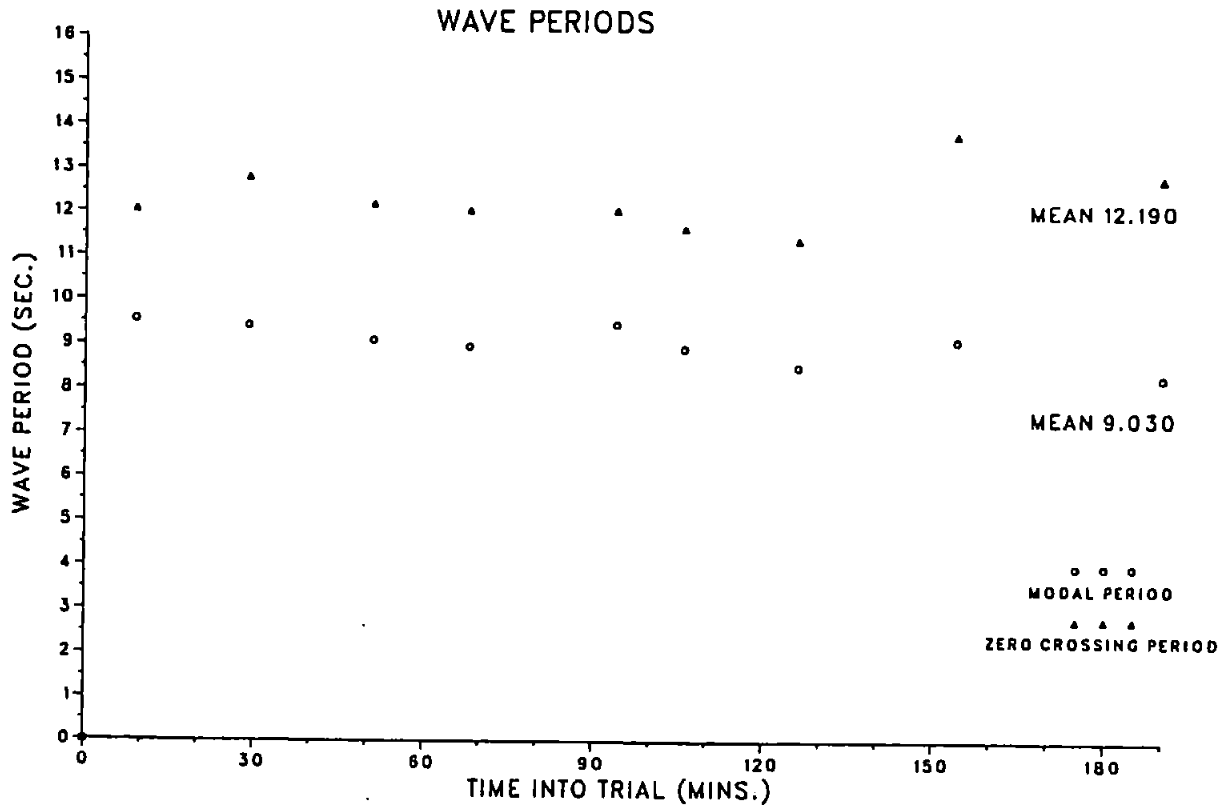

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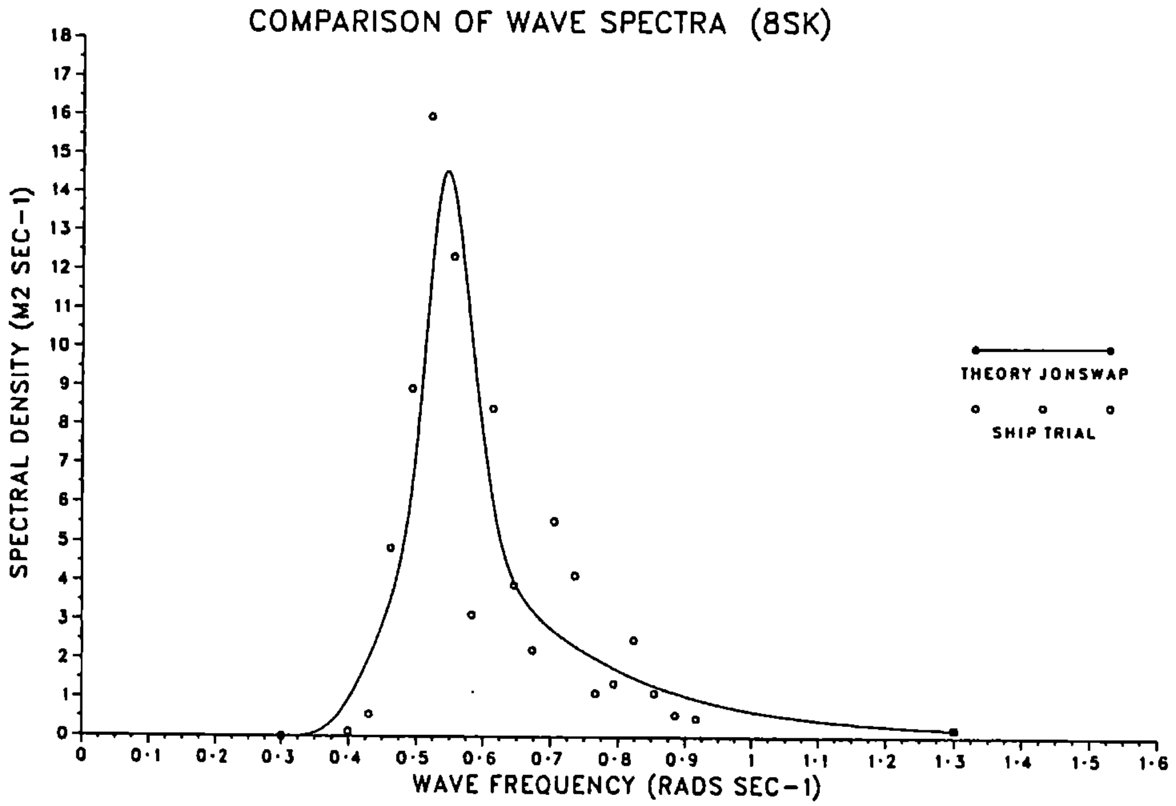

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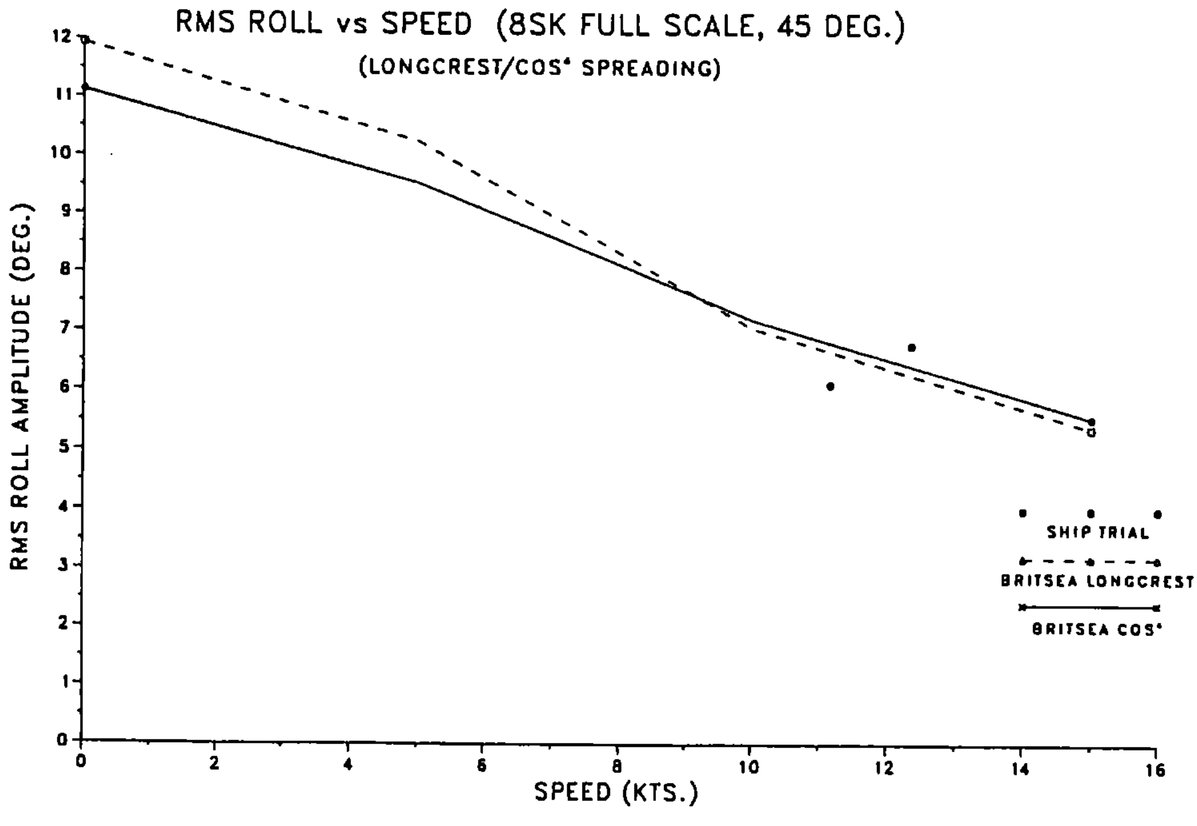

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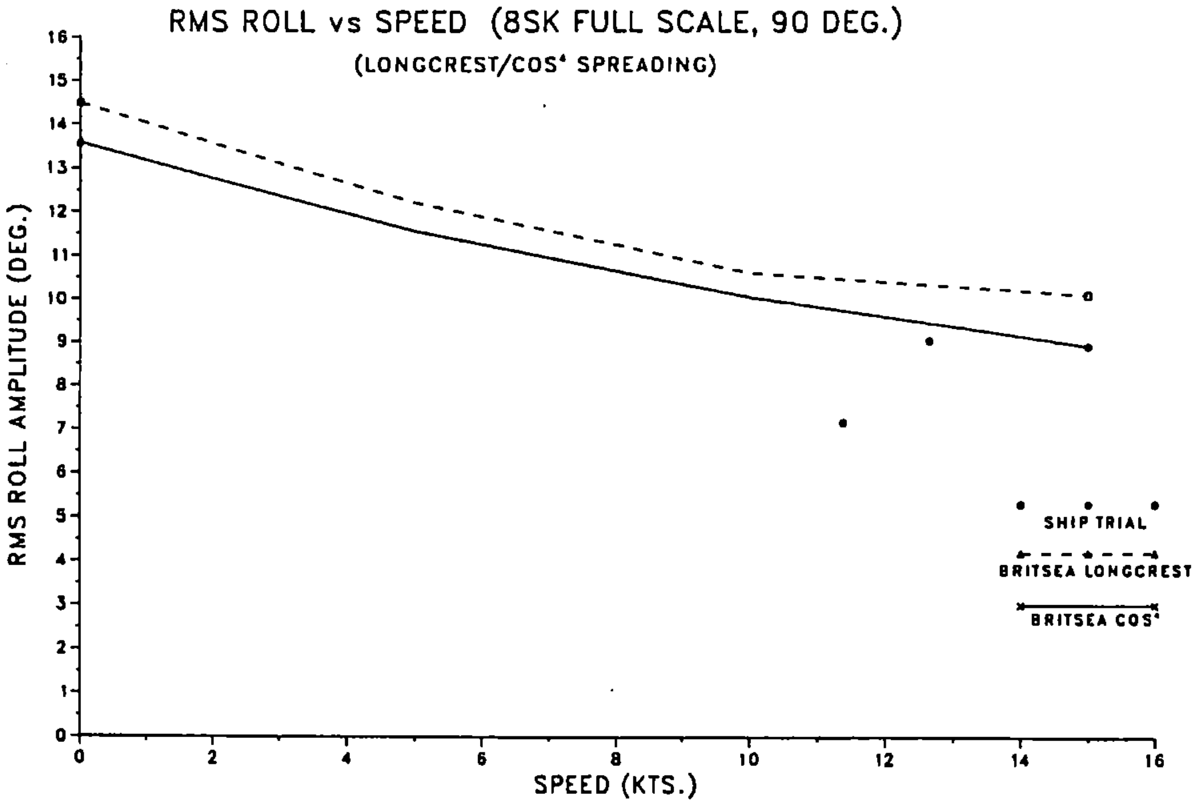

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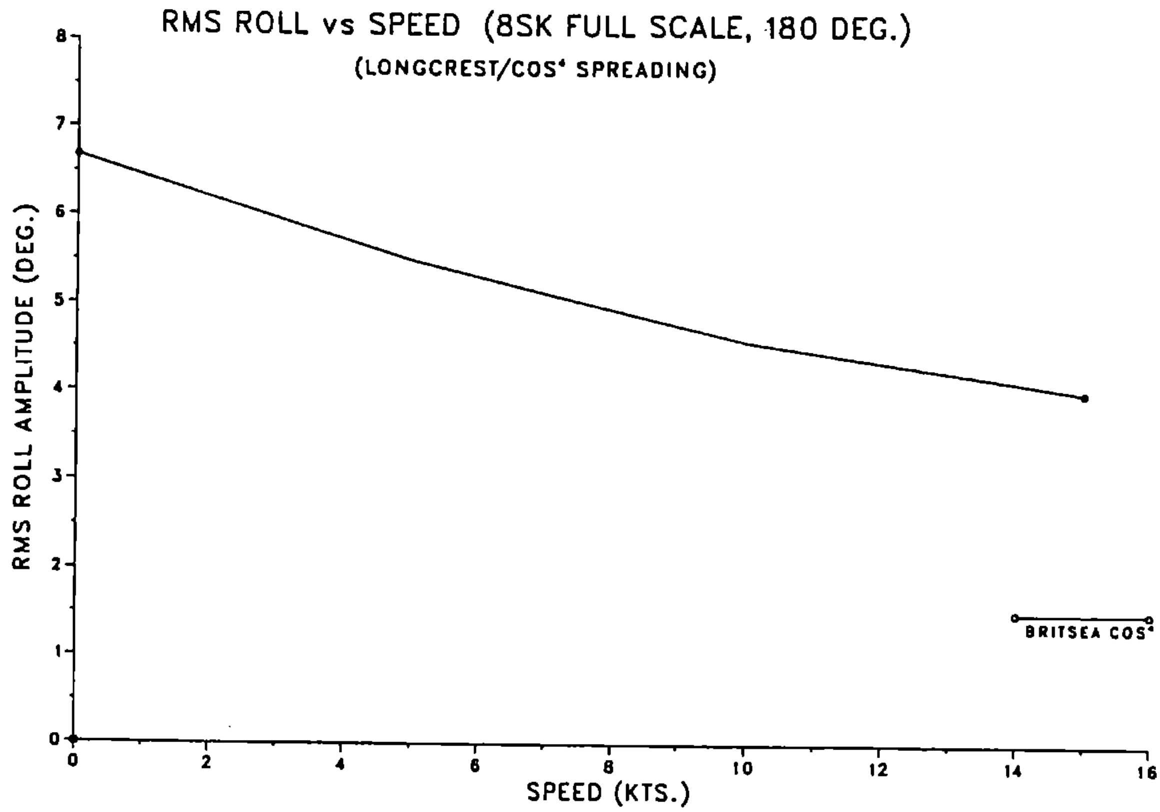

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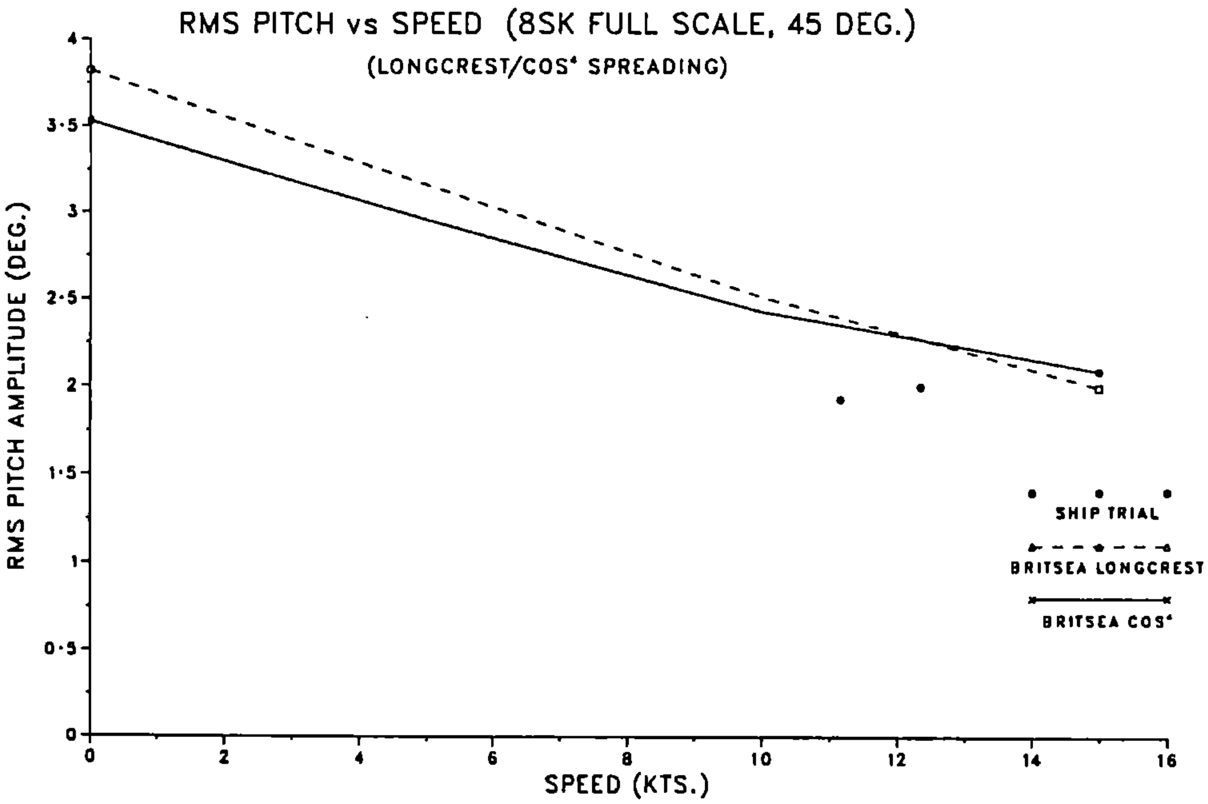

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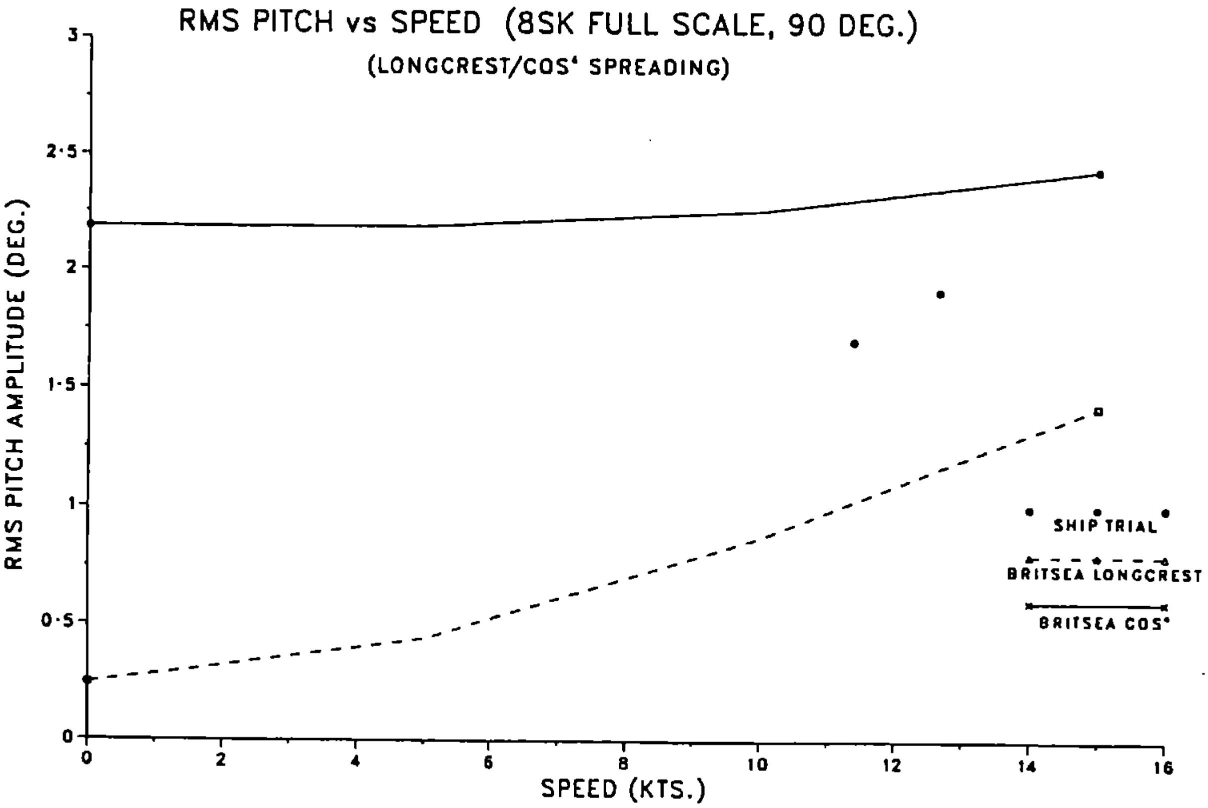

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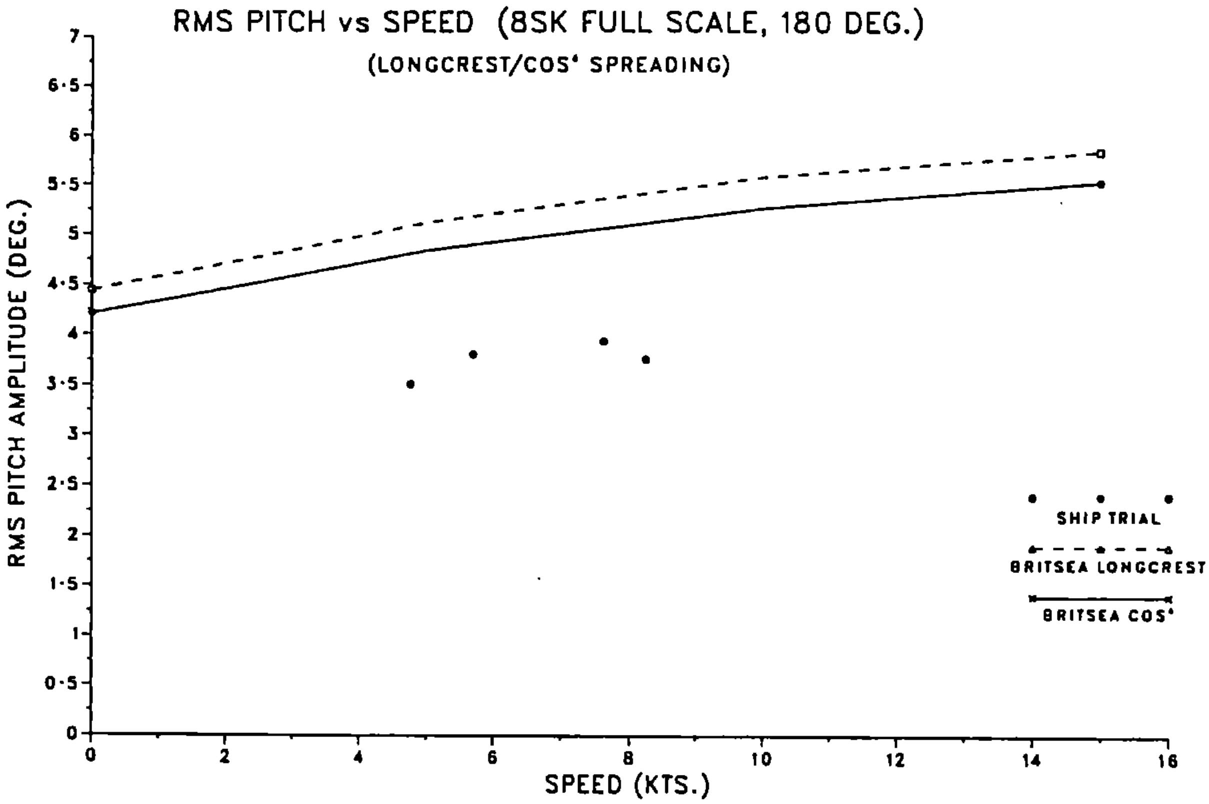
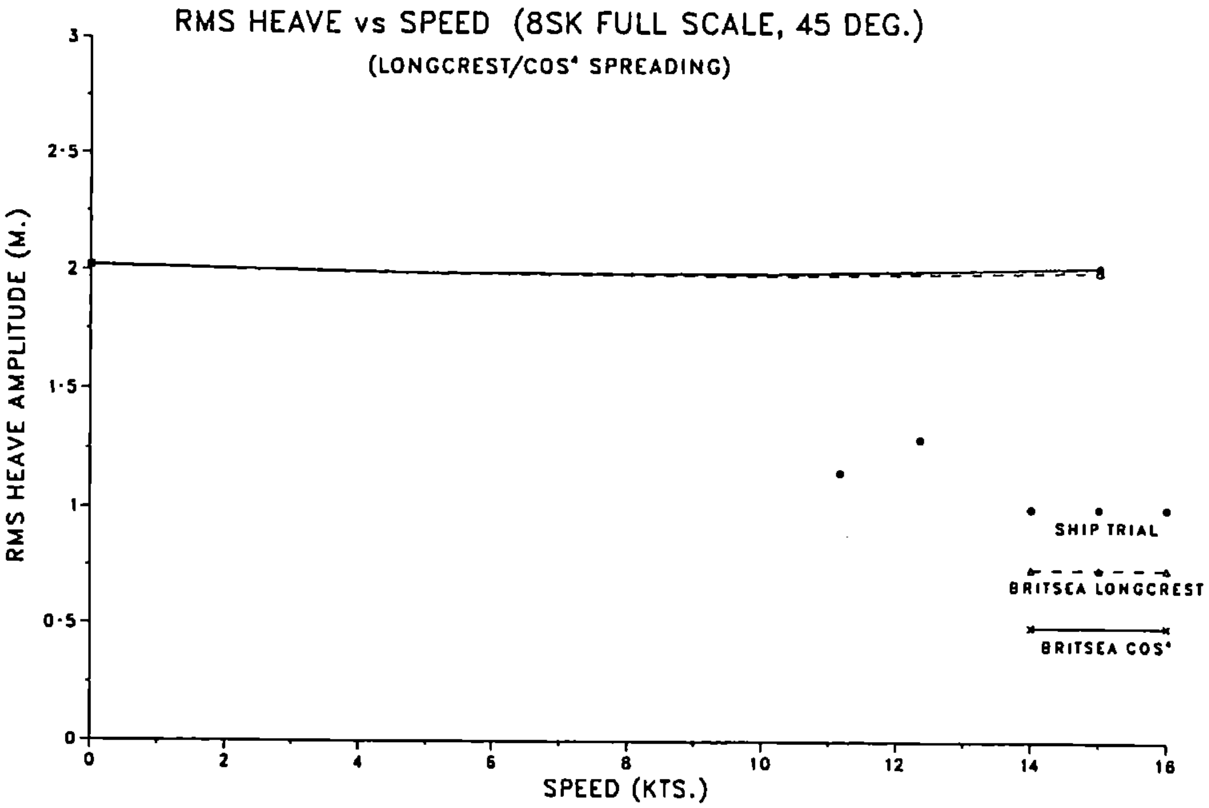


FIGURE A2.50



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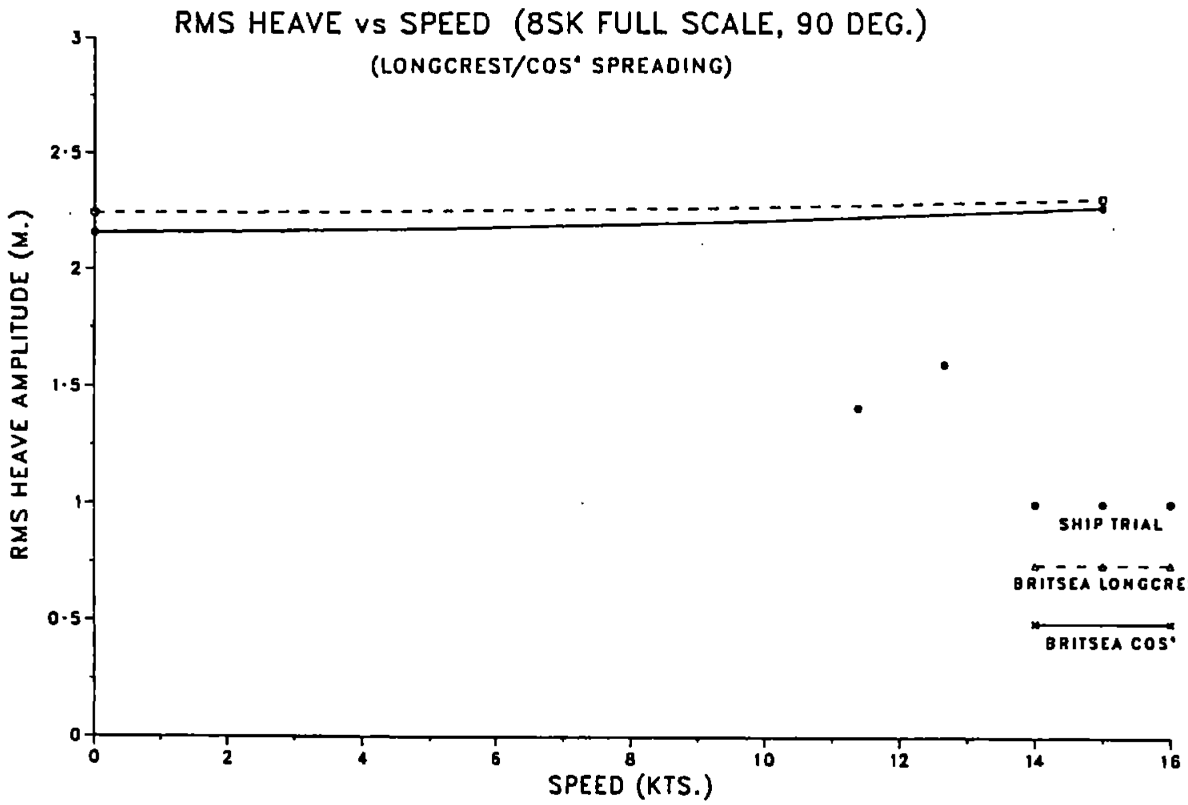

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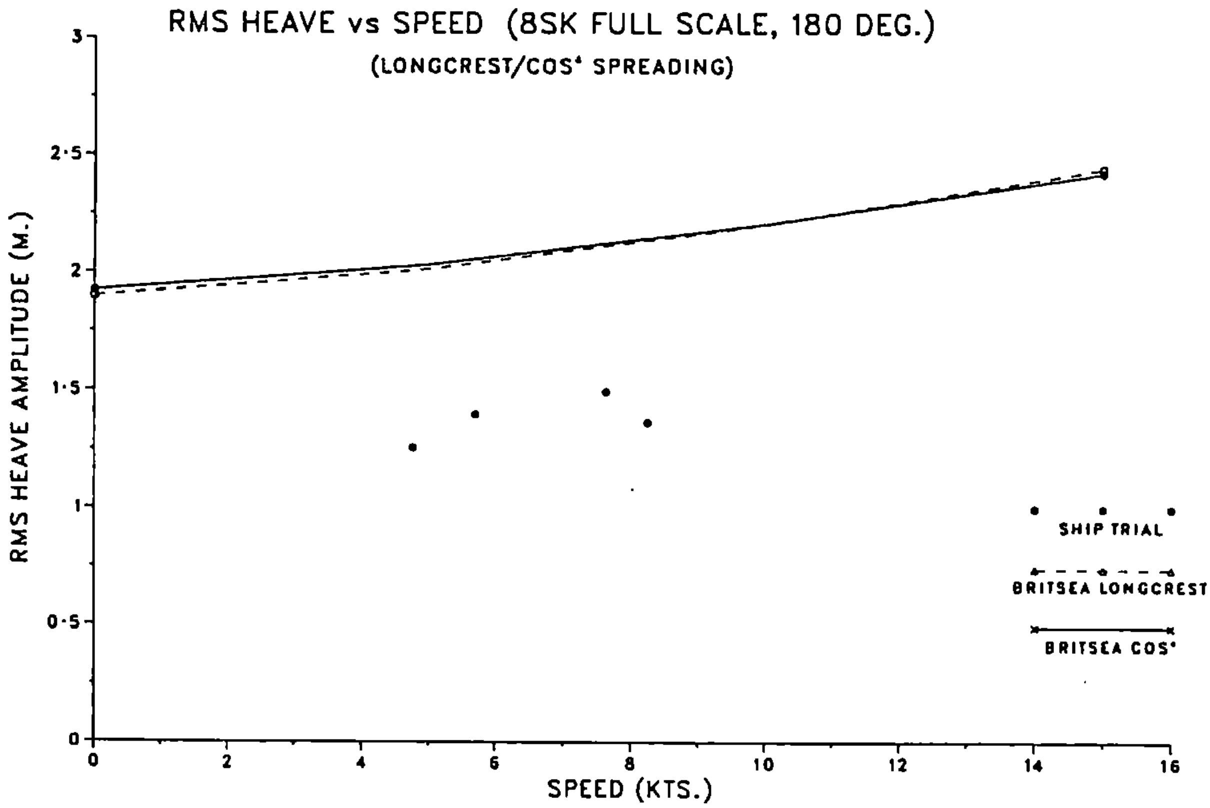

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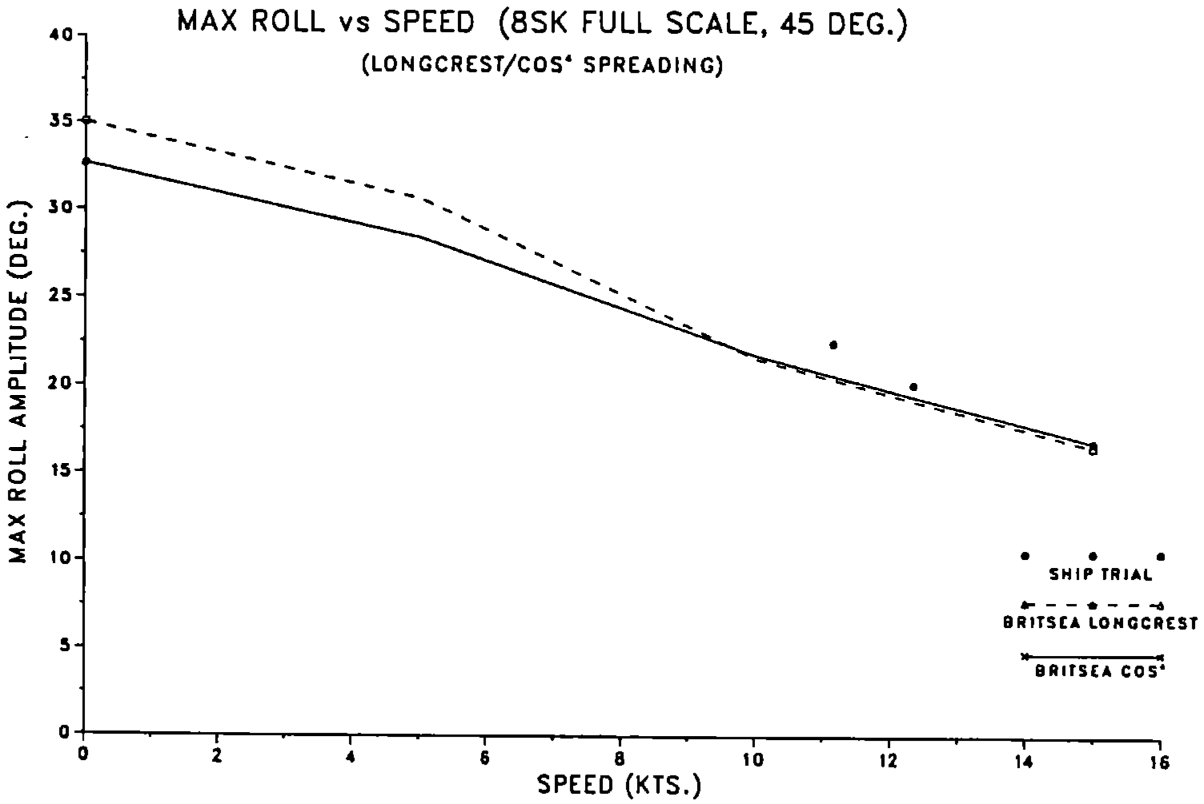
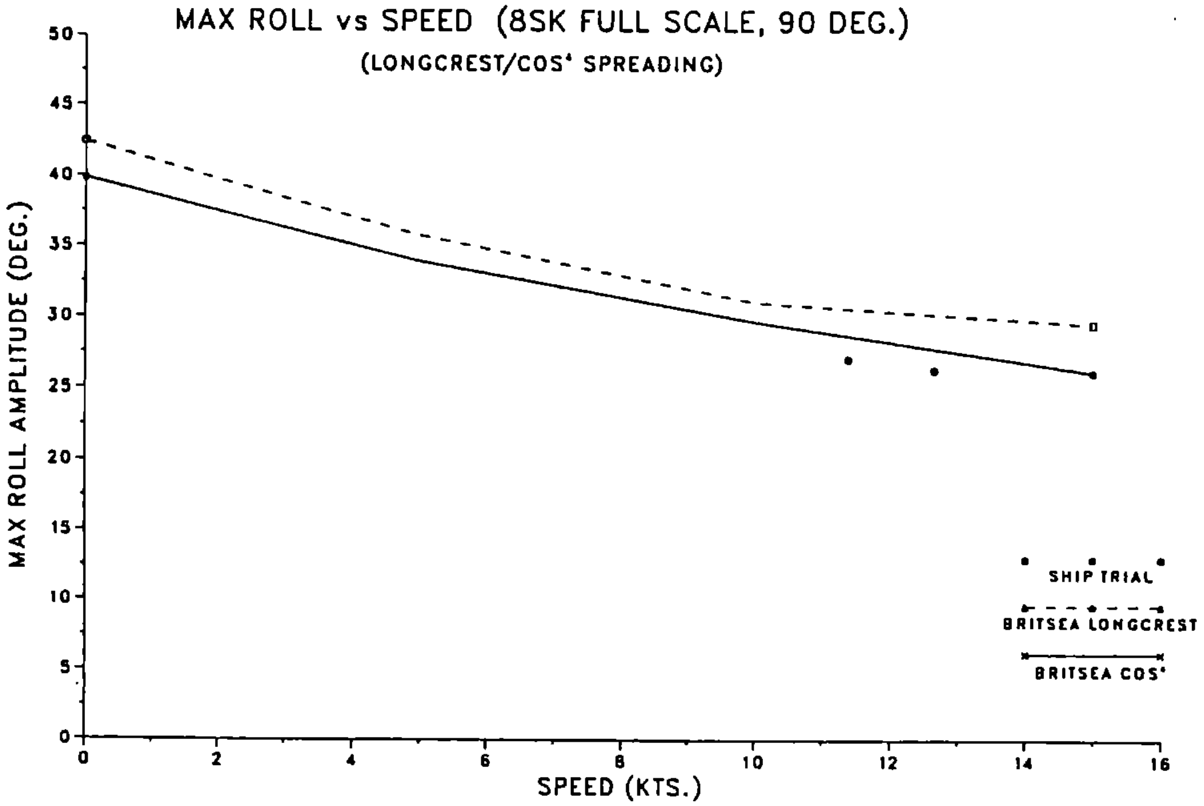


FIGURE A2.54



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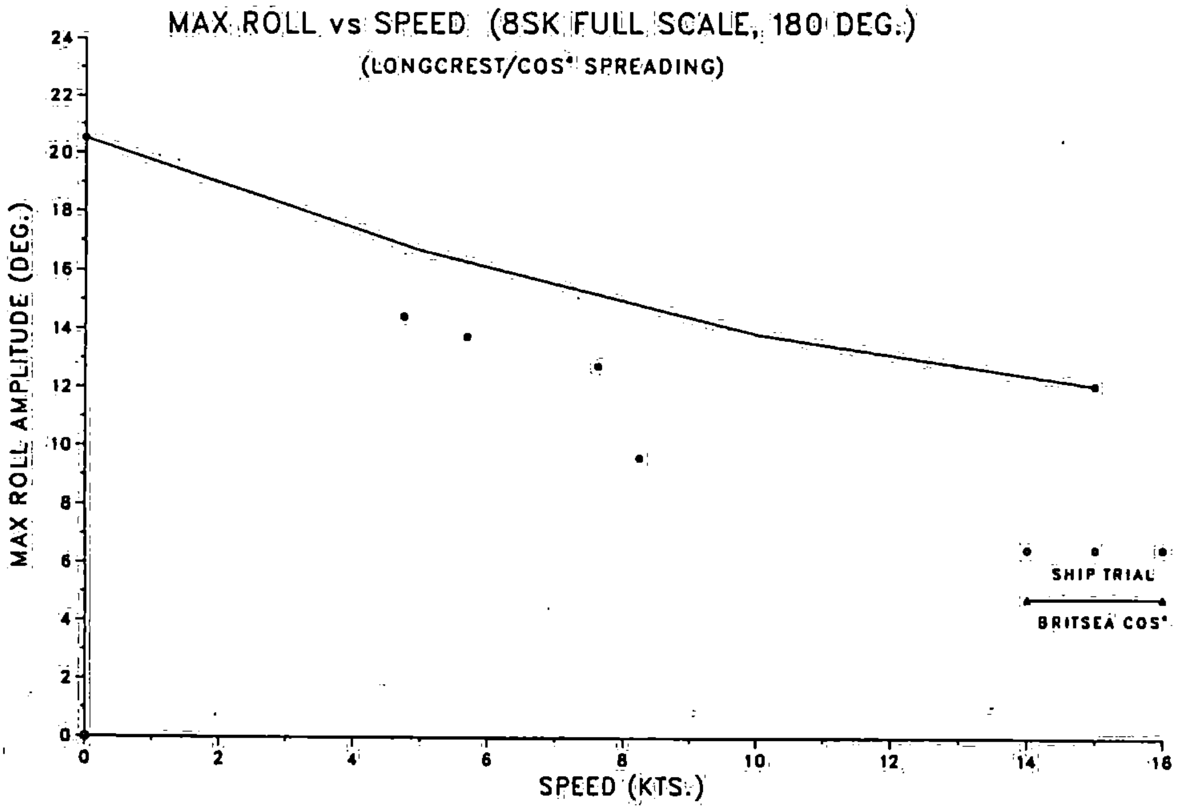

MAX ROLL vs SPEED (8SK FULL SCALE, 180 DEG.)
(LONGCREST/COS* SPREADING)
MAX ROLL AMPLITUDE (DEG.)
SPEED (KTS.)
0
2
4
6
8
10
12
14
16
18
20
22
24
SHIP TRIAL
BRITSEA COS*

Appendix A3

Computer Program Flowcharts

FIGURE A3.1 MAIN PROGRAM

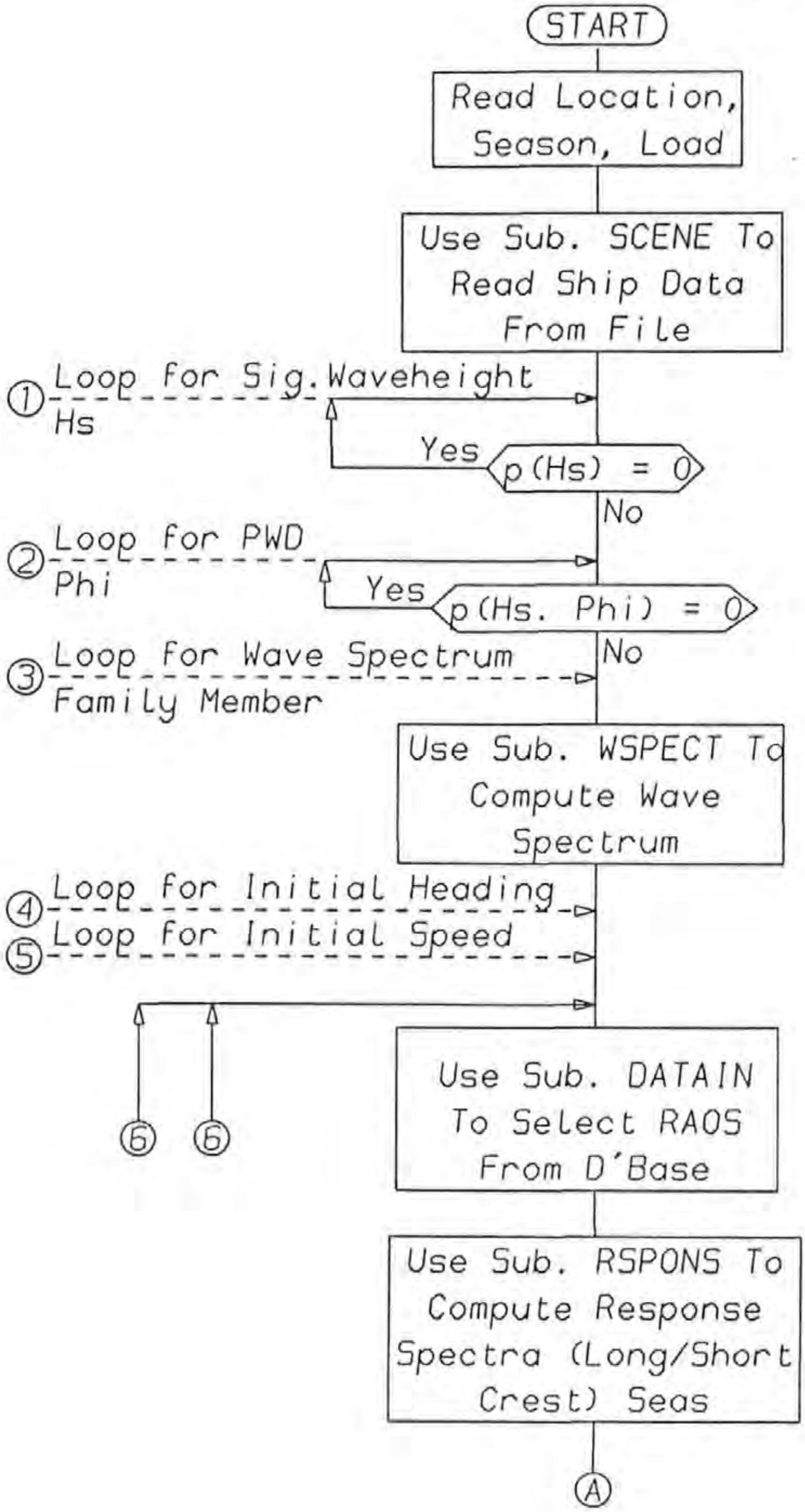
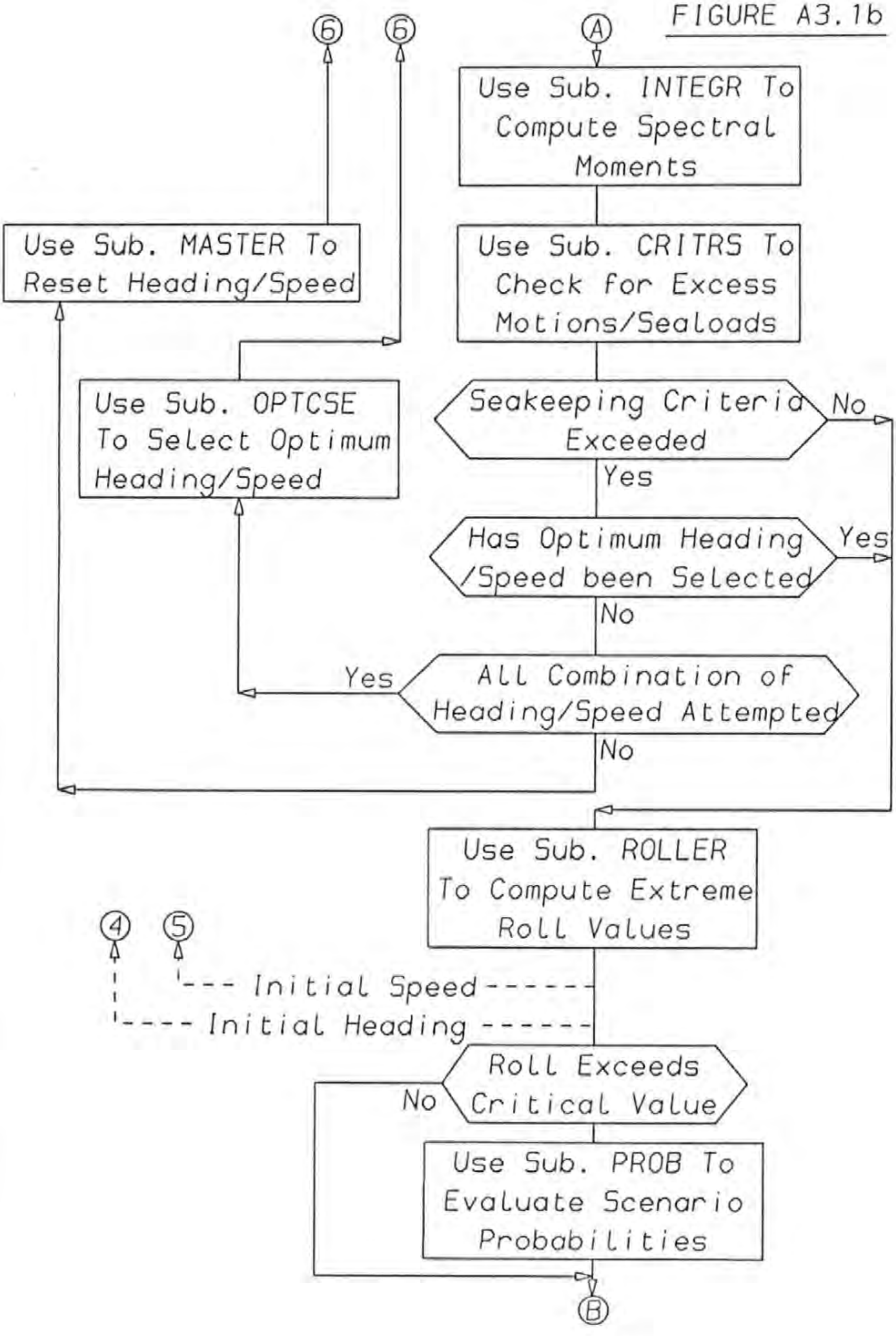
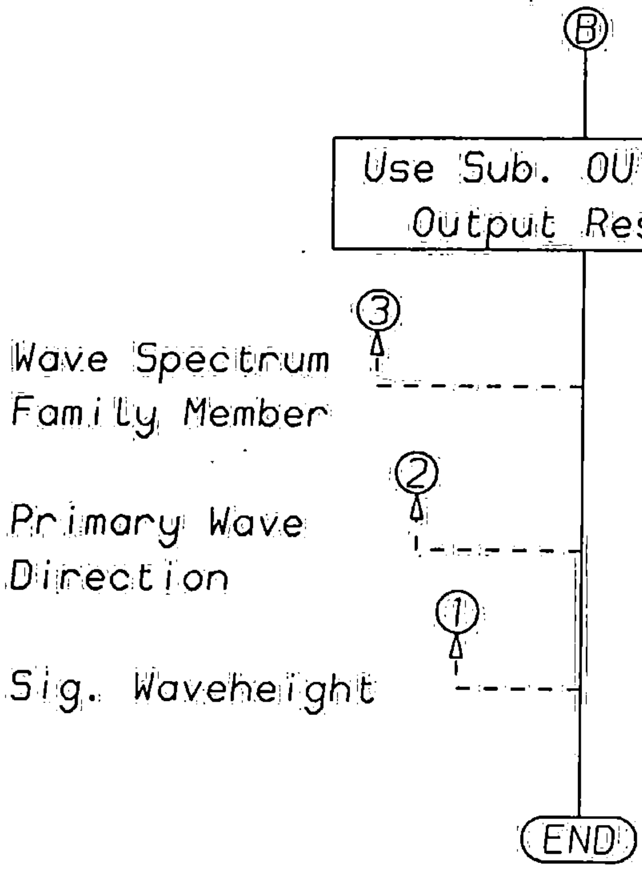


FIGURE A3.1b



6
6
A
Use Sub. INTEGR To Compute Spectral Moments
Use Sub. MASTER To Reset Heading/Speed
Use Sub. CRITRS To Check for Excess Motions/Sealoads
Use Sub. OPTCSE To Select Optimum Heading/Speed
Seakeeping Criteria Exceeded
No
Yes
Has Optimum Heading /Speed been Selected
Yes
No
Yes
All Combination of Heading/Speed Attempted
No
Use Sub. ROLLER To Compute Extreme Roll Values
4
5
Initial Speed
Initial Heading
Roll Exceeds Critical Value
No
Use Sub. PROB To Evaluate Scenario Probabilities
B

FIGURE A3.1c


B
Use Sub. OUTPUT To Output Results
3
Wave Spectrum Family Member
2
Primary Wave Direction
1
Sig. Waveheight
END

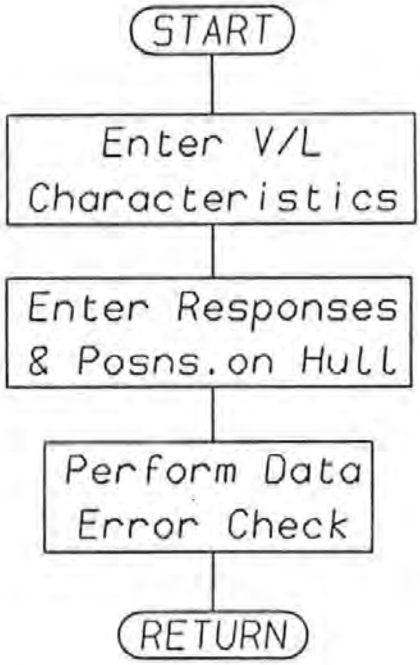


FIGURE A3.2 Subroutine SCENE

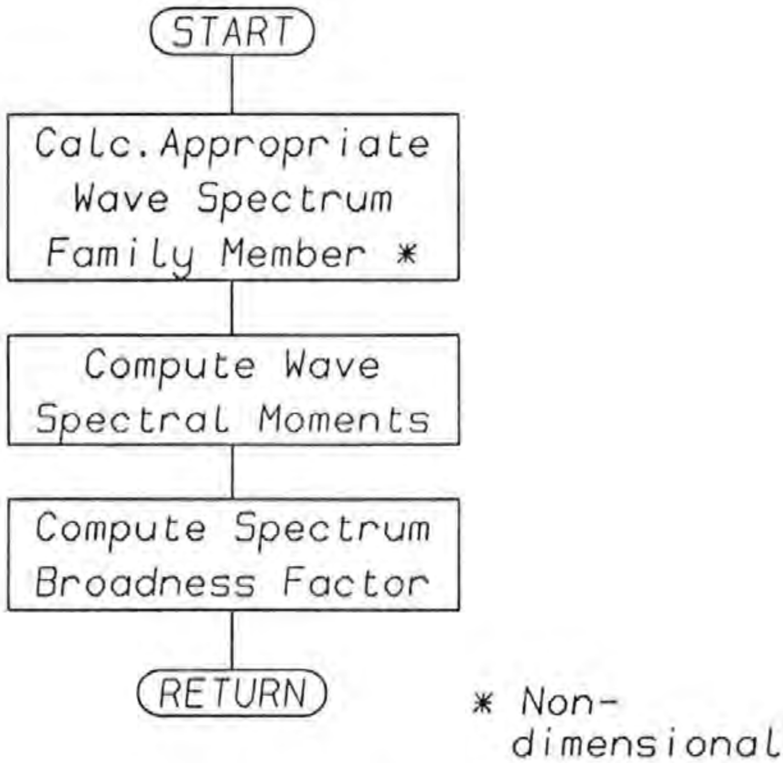


FIGURE A3.3 Subroutine WSPECT

FIGURE A3.4 Subroutine DATAIN

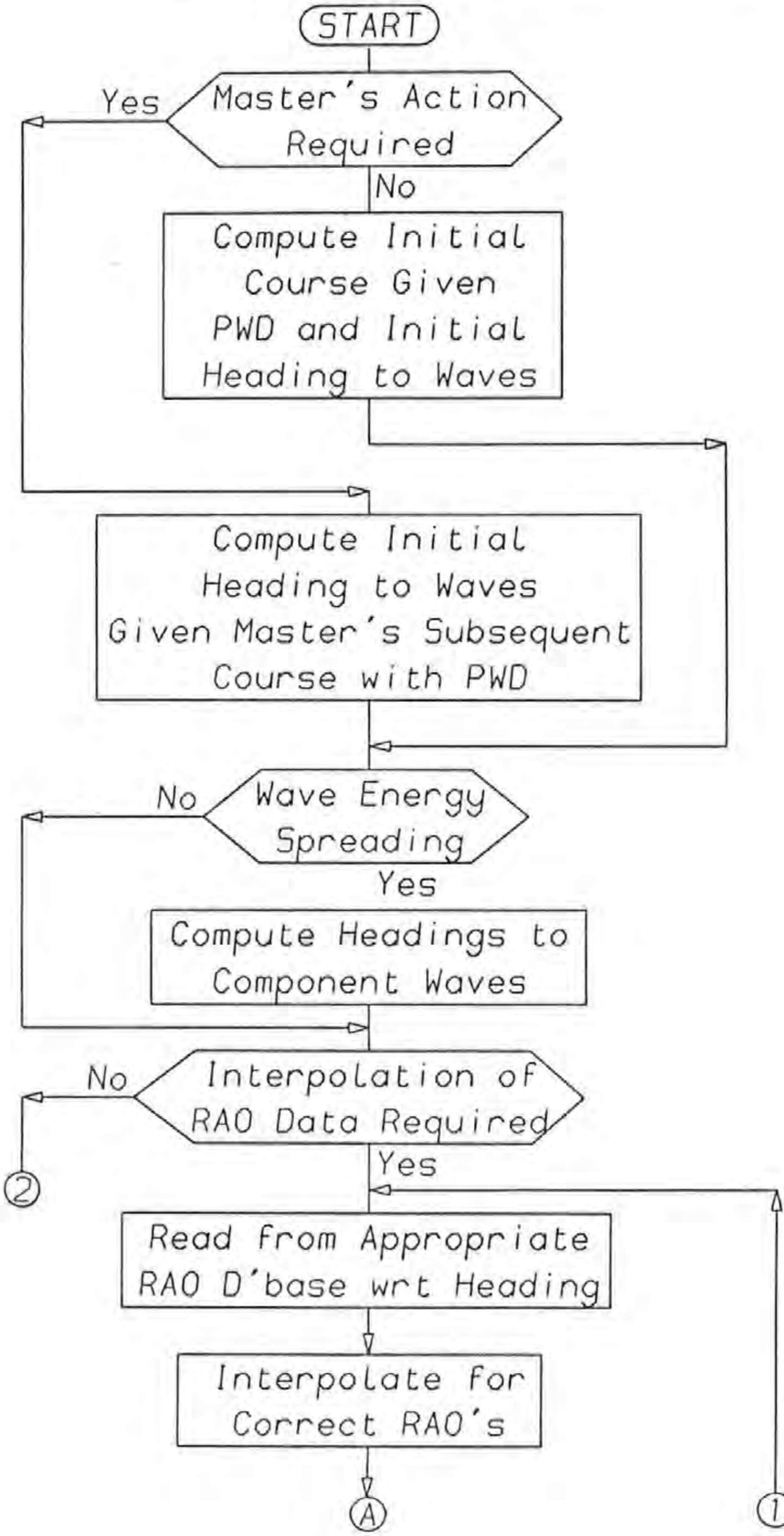


FIGURE A3.4b

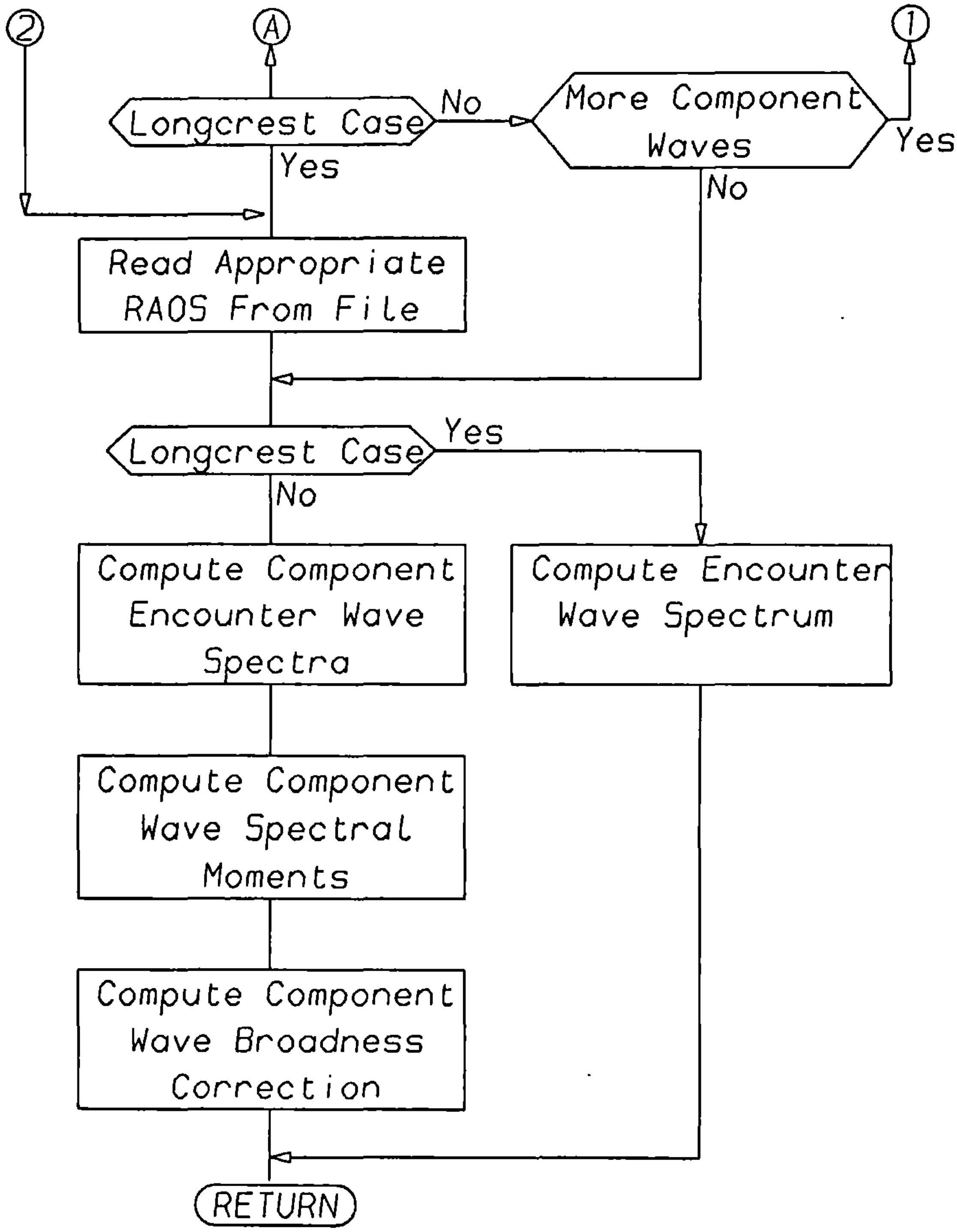

2
A
1
Longcrest Case
No
More Component Waves
Yes
Yes
No
Read Appropriate RAOS From File
Longcrest Case
Yes
No
Compute Component Encounter Wave Spectra
Compute Encounter Wave Spectrum
Compute Component Wave Spectral Moments
Compute Component Wave Broadness Correction
RETURN

FIGURE A3.5 Subroutine RSPONS

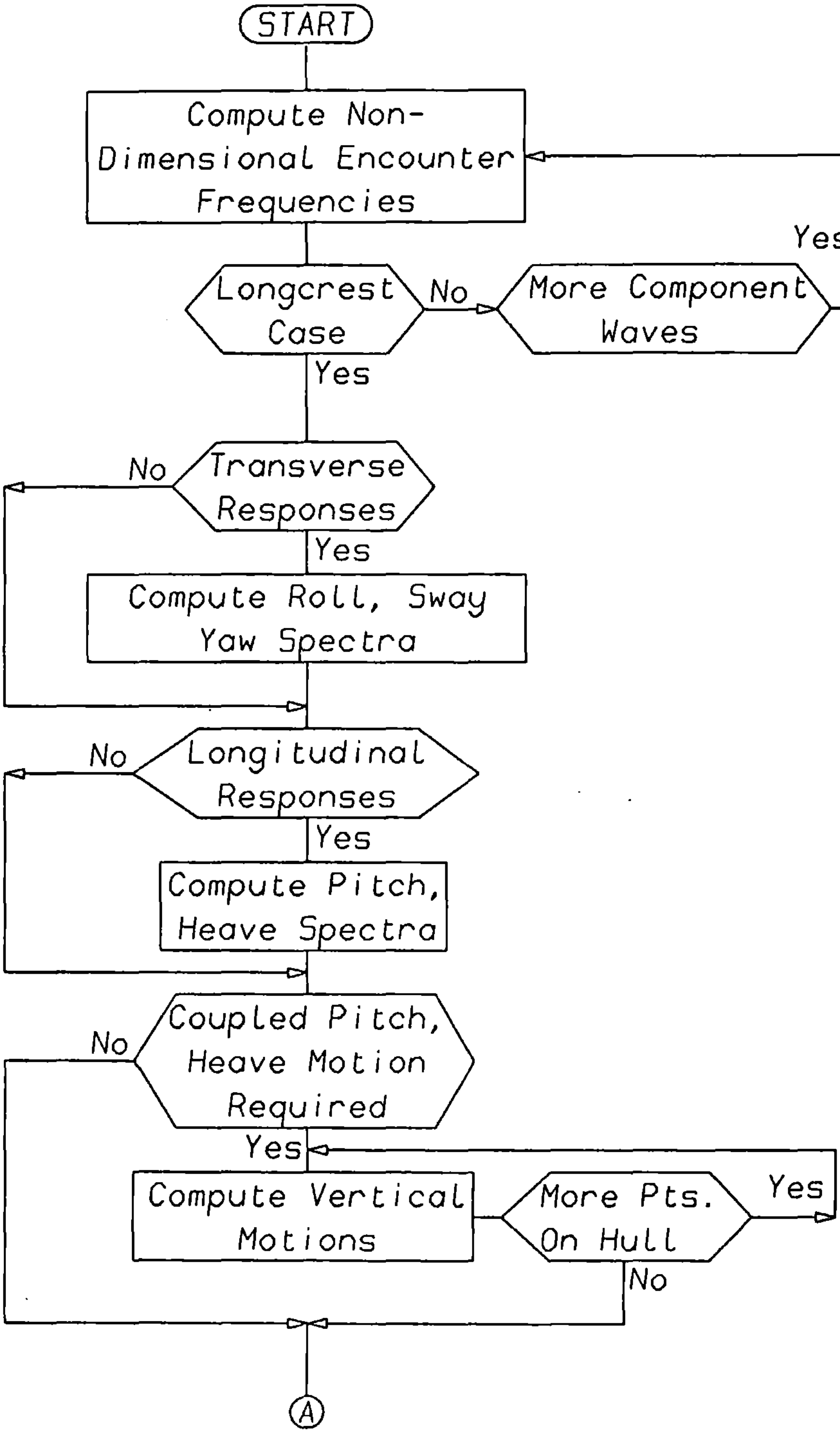


FIGURE A3.5b

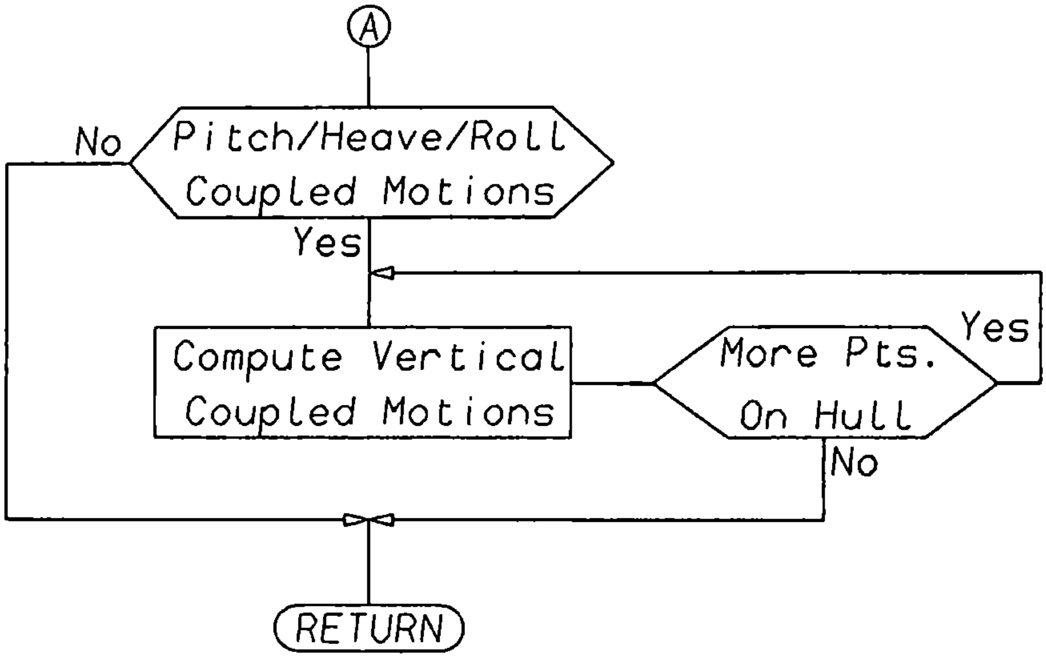

A
Pitch/Heave/Roll
Coupled Motions
No
Yes
Compute Vertical
Coupled Motions
More Pts.
On Hull
Yes
No
RETURN

FIGURE A3.6 Subroutine INTEGR

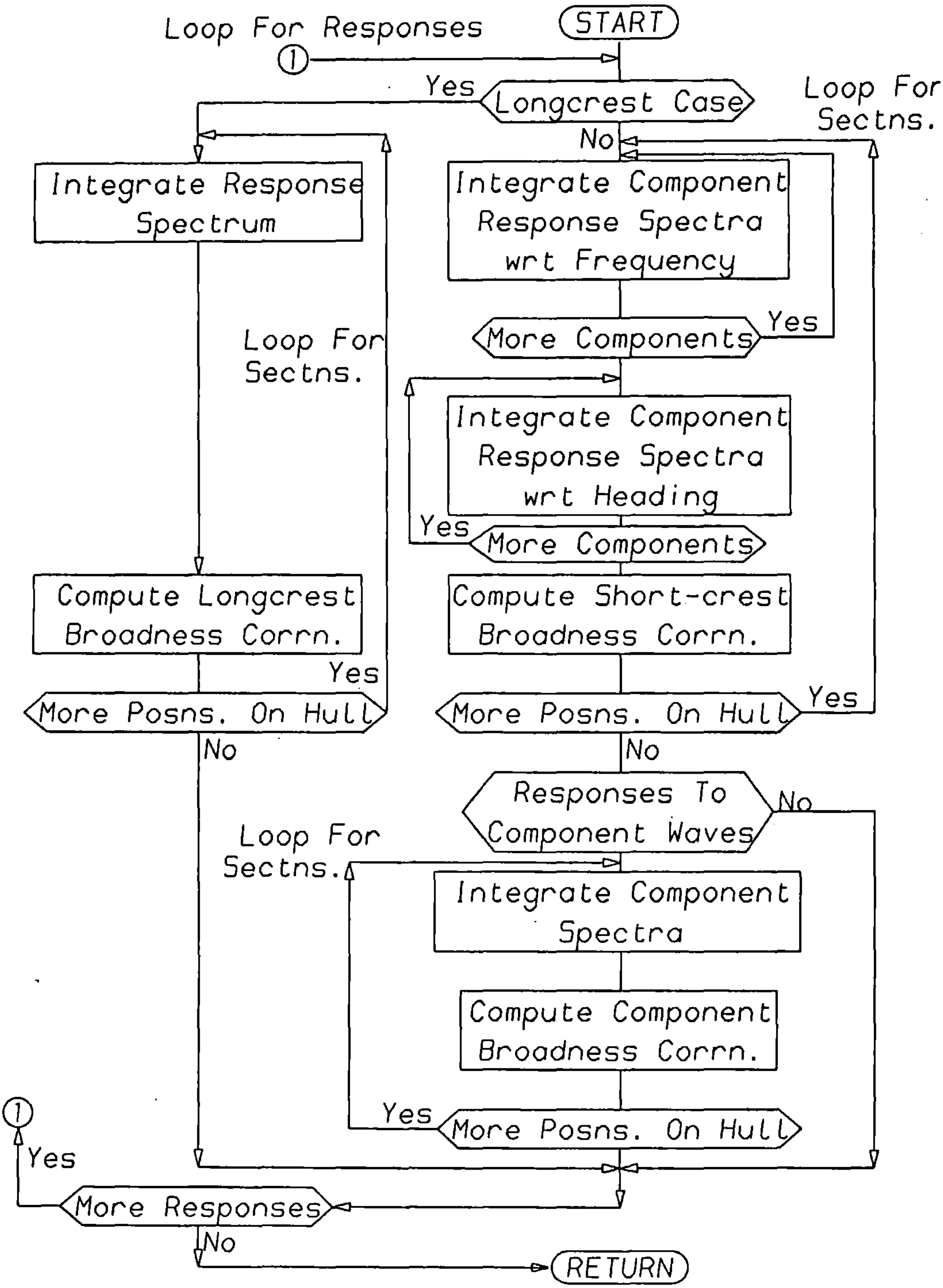
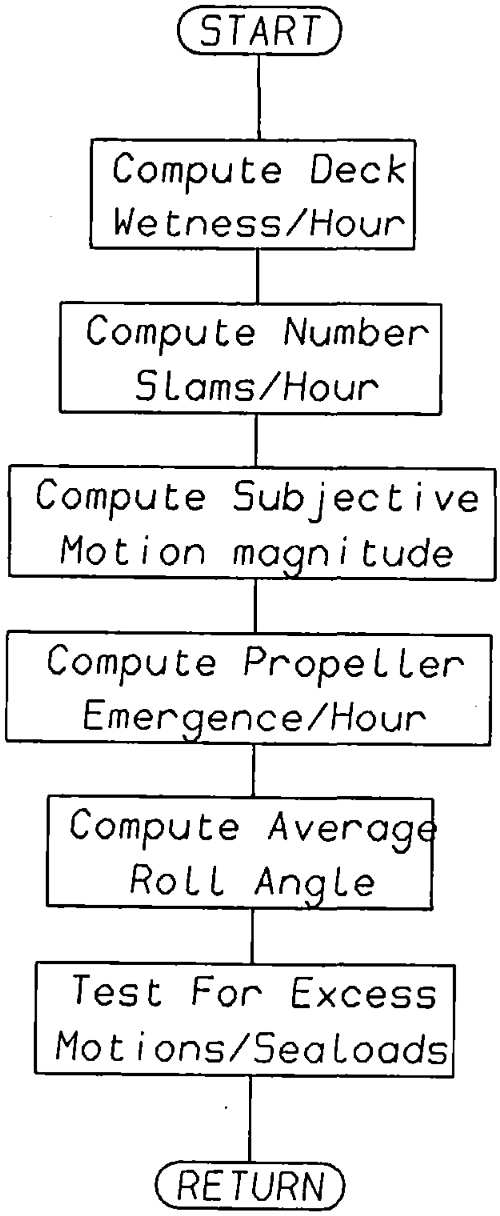


FIGURE A3.7 Subroutine CRITRS



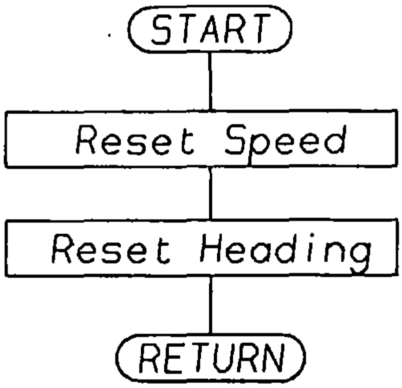


FIGURE A3.8 Subroutine MASTER

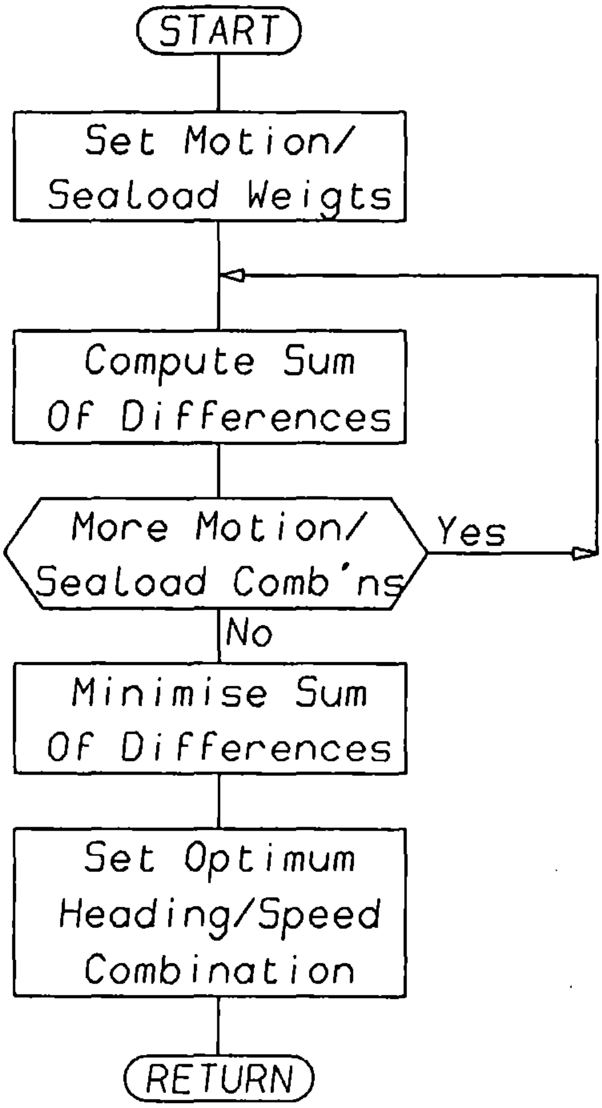


FIGURE A3.9 Subroutine OPTCSE

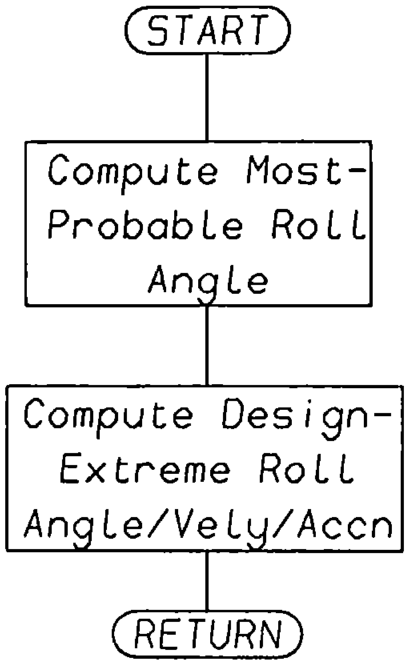


FIGURE A3.10 Subroutine ROLLER

FIGURE A3.11
Subroutine PROB

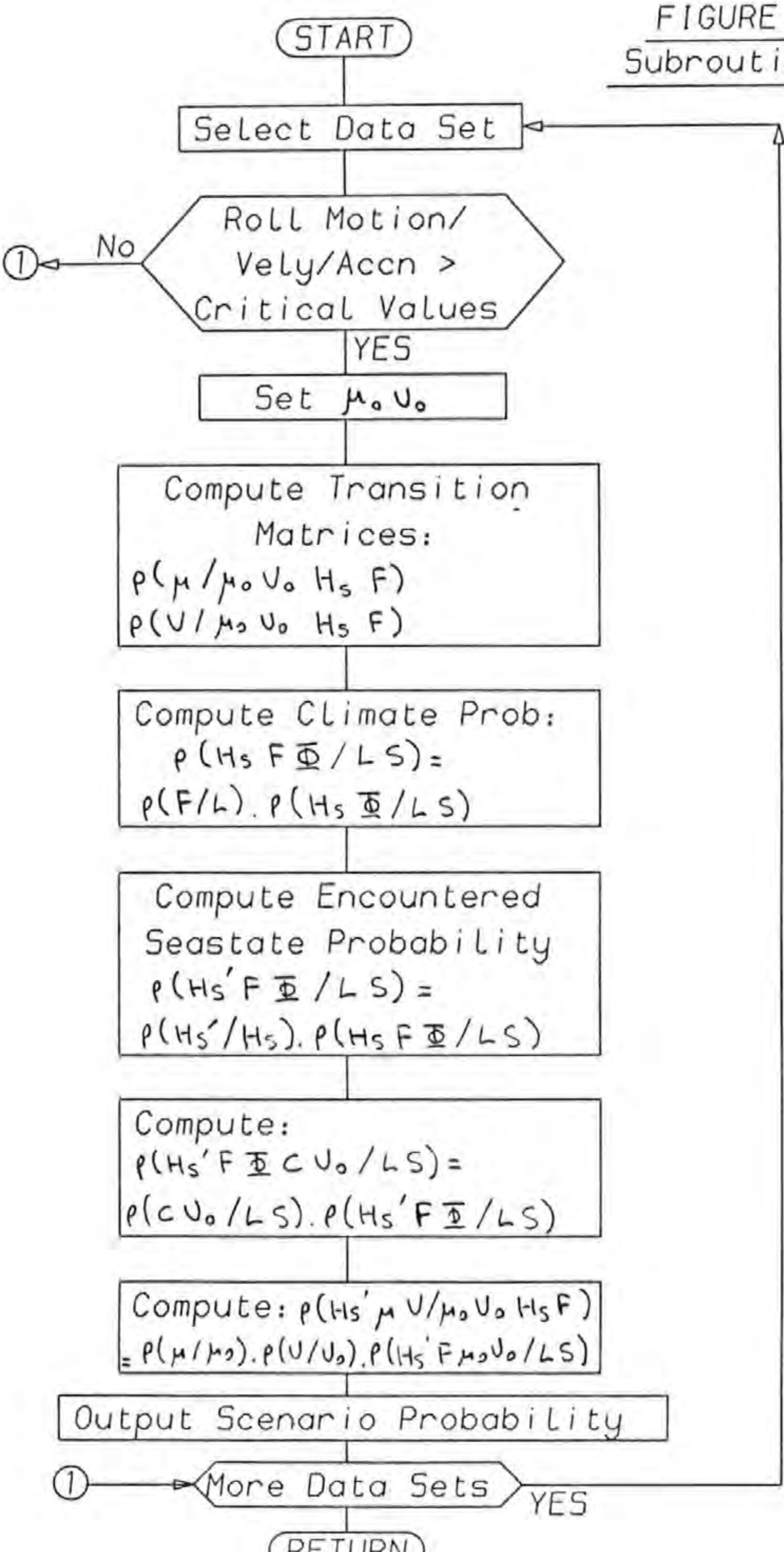
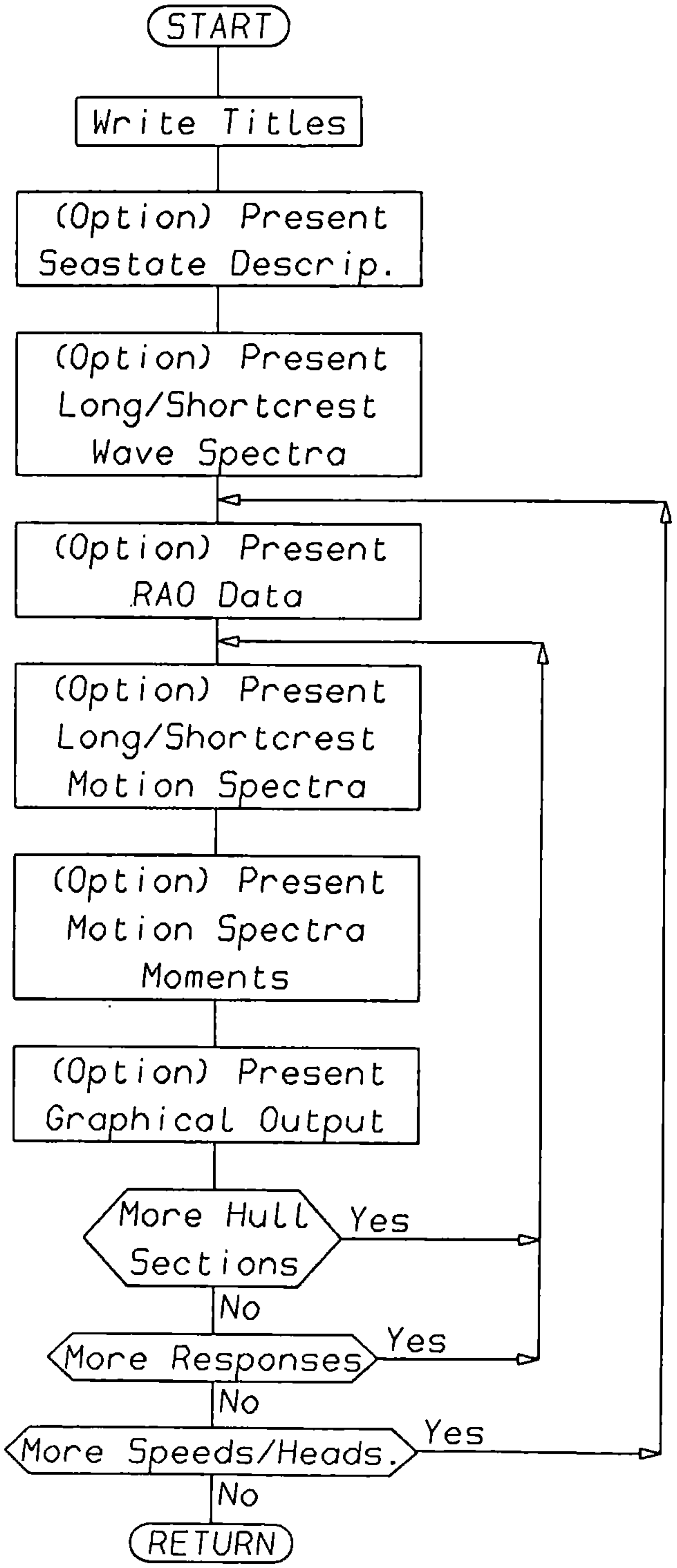


FIGURE A3.12 Subroutine OUTPUT



Appendix A4

Probability Concepts

A4.1 Random Processes

Most of the variables studied herein are defined over the positive real-number line (for example significant waveheight). They are therefore properly associated with probability density $p(x)$ such that:

$$\int_{-\infty}^{+\infty} p(x)\ dx = 1$$

and the probability $(x_1 < x < x_2)$ is given by:

$$\int_{x=1}^{x=2} p(x)\ dx$$

Thus $p(x)$ defines the probability that the variable x lies within any one of a given set of 'bands'. For example that significant waveheight (H_s) is in one of the bands 0 - 1 metre, 1 - 2 metres etc.

Also the cumulative probability is defined as the probability of observing a value less than or equal to y i.e.

$$p(x \leq y) = \int_{-\infty}^{y} p(x)\ dx$$

Certain variables are only discrete because there is insufficient data to provide continuously variable probabilities, one example of this being the load condition which is necessarily discretised into "departure condition" and "ballast condition" etc. Other variables such as the spatial domain and the season are conceptually discrete as they are used within this theory.

Thus where the variable under consideration is continuously defined on the real numbers it is presented as continuous or discrete whichever is most appropriate.

Integration is the preferred form of presentation within the text, while all the probabilities are made discrete in the numerical analysis within the computer program.

A4.2 Independent (Bernoulli) Trial Concepts

a) Independence of samples or random processes is an important concept in this study. Independence can be defined as existing if either of the following two conditions are satisfied, Chatfield (1981):

$$p(x/y)=p(x) \quad \text{and} \quad p(y/x)=p(y)$$

i.e. the conditional probability of x occurring given that y has already occurred is the same as the probability of x occurring regardless of whether y has occurred.

$$p(x,y)=p(x)\,.\,p(y)$$

i.e. the joint probability of x and y occurring is the product of the probabilities of x and y occurring separately.

An alternative consideration for this last expression is that for an independent trials process the sampling process does not alter the underlying probability for the next individual trial. Thus knowledge that an event has occurred has no bearing on the next event to occur. This is achieved in this study by the use of the independence period T_* in order to calculate N, the number of independent trial samples from;:

$$N=\frac{R}{VT_*}$$

where R is the distance along the course track and V is the vessel speed (strictly) relative to the advancing weather conditions.

b) In general, the probability of at least one event ($\in$) in N independent trials is:

$$p^N(\in)=1-(p^1(\notin))^N$$

where

$p^N(\in)$ is the probability of at least one event $\in$ in N independent trials.

$p^1(\notin)$ is the probability of <u>not</u> obtaining event $\in$ on a single independent trial.

The value of $p^N(\in)$ varies not quite linearly with N, Hutchison(1981). Specifically, when considering the probability of roll motion (σ) <u>exceeding</u> a critical roll value (σ_c) in N independent trials:

$$p^N(\sigma_c<\sigma)=1-\{p^1(\sigma_c>\sigma)\}^N$$
$$=1-\{1-p^1(\sigma_c<\sigma)\}^N$$

Previously Published Material

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Proceedings of the 1987 Summer Computer Simulation conference, pages 55 - 60;
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Critical motion simulation in the random marine environment

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Plymouth, Devon, England

ABSTRACT

Traditionally the measure of a seagoing vessel's capsize safety has been based on various properties of a still-water righting lever curve. However, in recent years it has been argued that any new and improved stability criteria should seek to take account of the variability of the environmental conditions encountered and the vessel's design features, as well as the variation in vessel load conditions and masters action.

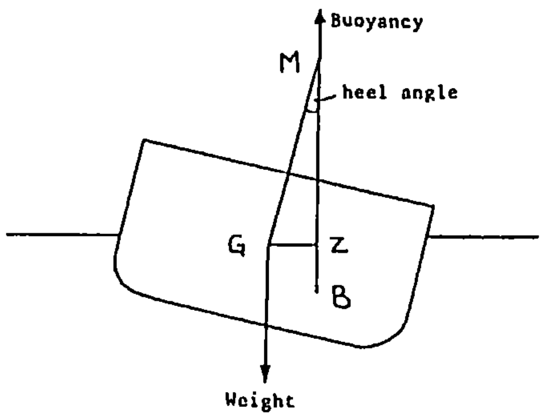
We have adopted this type of approach in order to predict the probability that a critical roll motion will be exceeded at least once during the vessel's operational lifetime. This involves computer simulation to assess motion performance in various critical scenarios, which have been identified as being potentially hazardous with respect to capsize, since it is not feasible to consider every cycle of response over many years of operation. Thus, in essence, the vessel is required to negotiate successfully a series of "test-tracks", each comprising several scenarios with their associated probabilities of occurrence. Independent (Bernoulli) trial procedures are then used in the evaluation of the final required probabilities. The vessel speed and its heading to waves fall under the control of the master. He may manoeuvre to avoid a storm if possible, but in all cases he will seek to reduce the resulting motions and sealoads to acceptable levels. The simulation takes account of these in order to derive the most likely response to a given scenario.

The assurance of a seagoing vessel's safety against capsize requires the synthesis of many variables, which affect the response obtained, and is the subject of much ongoing work. It is envisaged that the type of simulation being proposed will eventually lead to improved stability criteria and in the short-term will highlight areas for further research.

1. INTRODUCTION

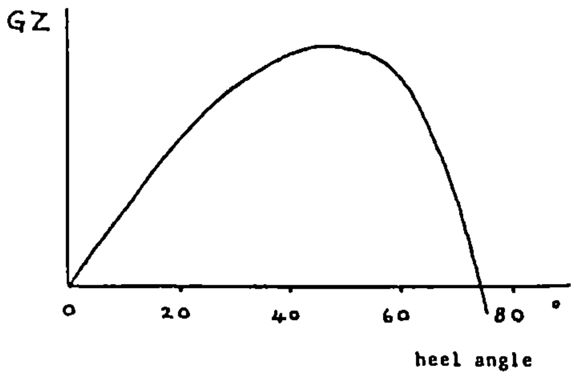
In considering safety at sea, ship stability itself is of prime importance. Ship stability is taken to mean "safety from capsizing", in which a vessel rolls from a stable upright position into an inverted position, which although also stable is highly undesirable in view of the damage and loss of life sustained. The current I.M.O. (1968) international stability criteria can be regarded as being directly derived from the work of Rahola (1939) on the properties of the still-water righting lever (GZ) curves, fig. 1.

This work however, based as it is on classical mechanical criteria in still-water, is inadequate as a predictor of the possible fate of vessels encountering rough weather in a sea-way (Bird et al. 1975). It is now generally agreed that improved criteria should take account of the variability of the environmental conditions, the vessel's design, as well as variations in load and the master's actions (Kastner 1982). A probabilistic approach is now being taken in the structural design of ships in which it is recognized that structural elements will have to withstand loads of different magnitude and frequency within their life-time. An overall strategy for probabilistic stability assessment based on these modern design methods is shown in fig. 2.



M=metacentric height
G=centre of gravity
B=centre of buoyancy
GZ=righting lever

fig. 1



The concept of risk is not new. In many instances where there is a large body of historical information an appropriate interrogation of the database can assign the risk of death, injury or other loss involved in a particular activity, table 1. However no such database exists which is capable of providing sufficient detail to assign the probability of any individual vessel's risk of capsize. This is hardly suprising given the nature of capsizal, which is usually rapid and gives no time for noting the environmental factors involved.

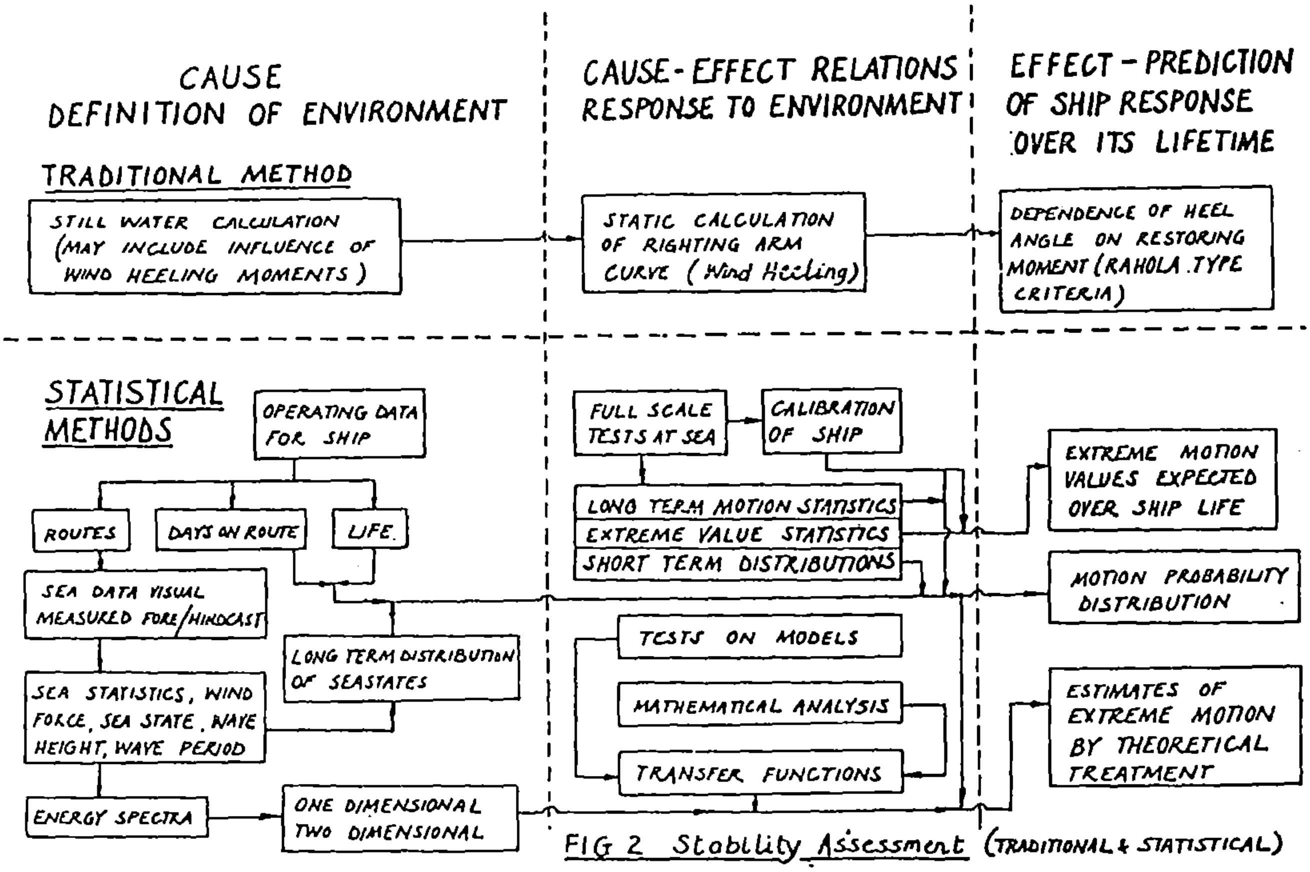


FIG 2 Stability Assessment (TRADITIONAL & STATISTICAL)

Risk source	FAFR
Average for British industry	4
Chemical industry	3.5
Steel industry	8
Fishing	35
Coal mining	40
Construction	67
Air crew	250
Staying at home	3
Driving a car	60
Rock climbing	4000

FAFR=Fatal accident frequency rate or Number of deaths per 10^8 hours of risk exposure (Jenssen 1976)

Table 1

The purpose of the present work is to explore the feasibility of developing and applying such a probability analysis model as a basis for ship safety from capsize, which may lead to improved stability, design and regulation criteria.

2. THE COMPUTER SIMULATION

The probability of exceeding a "potentially dangerous" roll motion may be estimated using independent (Bernoulli) trial concepts. That is, in general, the probability of at least one event (σ) in N independent trials is

$$P^N(\sigma) = 1 - \left[P^1(\phi)\right]^N$$

where $P^N(\sigma)$ is the probability of at least one event σ in N independent trials. $P^N(\sigma)$ varies not quite linearly with the value of N, (Hutchison 1981); also $P^1(\phi)$ is the probability of not obtaining the event ϕ on a single independent trial. Specifically, when considering the probability of roll motion (ϕ) exceeding a critical value (ϕ_c) in N independent trials

$$P^N(\sigma_c < \sigma) = 1 - \left[P^1(\sigma_c > \sigma)\right]^N$$
$$= 1 - \left[1 - P^1(\sigma_c < \sigma)\right]^N.$$

It is proposed that to assess the risk of capsize a vessel be subjected to a set of (mostly) analytical test-tracks which together comprise the proving ground appropriate in nature to the vessel being considered.

3. THE TEST-TRACK CONCEPT

3.1 Problem outline.

When applying probability concepts to the problem of vessel capsizing, it is appropriate to consider the probability of a critical roll response being exceeded. In an attempt to "trap" the worst-case scenarios, the proposed method consists essentially of a subject vessel being required to negotiate successfully (ie, without capsizing) a series of test-tracks which have been designed to represent the range of critical (potentially causing capsize) scenarios that it will encounter over its lifetime. It is envisaged that at first the test-tracks could be largely analytical in nature with some experimental back-up for certain difficult aspects until the theory improves.

For this preliminary investigation and for illustration of the overall "package" a wholly analytical frequency domain analysis will be used.

Obviously this means that certain physical capsize phenomena which may be best suited to time domain analysis (such as the broaching-to phenomenon) will not be modelled and thus the test-tracks will not be fully activated initially.

3.2 Choice of Test-Track.

The vessel type and intended zones of operation dictate the nature of the proving ground. Thus, for example, a vessel which is intended for operation in a sea-area which is well sheltered or has shelter to hand will not have to negotiate the more stringent test-tracks required of a vessel intended for extended operation in high icing latitudes.

A vessel which is intended for international operation would be subjected to the worst possible weather conditions.

By considering individual test-track performance the effect on the performance of design and operational features can be considered in detail whilst overall proving ground performance will allow comparison of total performance and safety levels across a fleet of vessels for example though this "average" value should be treated with caution.

A typical subject vessel can be expected to operate, over its lifetime, in a wide range of environmental and displacement conditions and to be subject to different masters' action. It is computationally desirable that the proving ground should only encompass all of the possible scenarios which could cause capsize, it is obviously not possible to pre-define them, and it is thus necessary initially to consider that all scenarios are potentially capsize causing. However, if an initial assumption is made that only the severest seastates cause the severest responses, the amount of computation for any scenario may be reduced. The order of severity of seastates to which the vessel is subjected (everything else remaining unchanged) is progressively reduced from the most severe possible in the operating zone under consideration. Once the predicted response level falls below the limiting safe value the computer simulation program moves on to consider the next scenario and so on.

4. APPLICATION

4.1 Managing the Lifetime of Risk.

The method of handling all the scenarios comprising a lifetime of risk is best illustrated with the aid of a simulation example. The subject vessel being used for the present study is a fisheries protection vessel which has an operational area encompassing the Northern North Sea and North Eastern Atlantic in the region of the 100 fathom line around North West Scotland. There are also occasional sorties of up to 200 miles into the open North Atlantic.

The prediction method aims to calculate $P(\phi_c<\phi)$, the cumulative probability of a 'critical roll motion' (ϕ_c) being exceeded, at least once, during the vessels lifetime of operation. This value is of course represented by the proving ground result.

The 'critical roll motion, ϕ_c' is defined, in the first instance, as the value of roll angle beyond which there is increasing concern that the vessel will be in danger of capsizing. This is referred to as the potentially dangerous roll angle, though it may subsequently be defined to include velocity or acceleration terms.

A preliminary analysis is necessary to determine the vessel's intended missions (operating practices and operating areas). For ease of illustration it is assumed that our subject vessel will only ever operate in the sea areas labelled 2 and 4 in Fig 3.

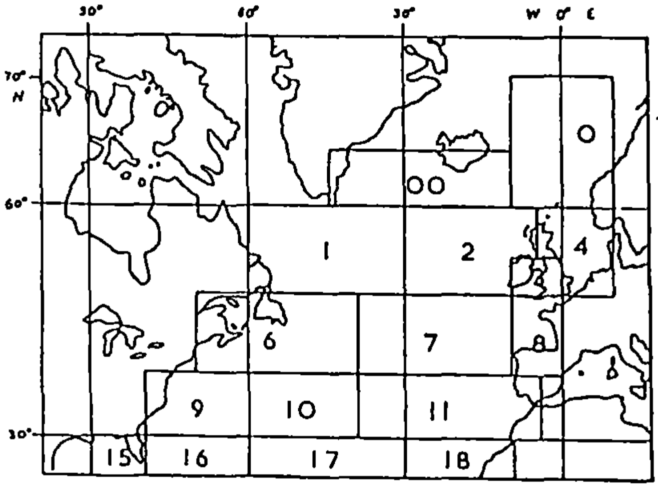


Fig. 3 North Atlantic Basin Climatology Regions

This indicates the boundaries of the sea-areas in the North Atlantic Basin into which the climatology data is divided (Bales et al 1981).

It is assumed that each sea-area has its own distinct climatology and that this is homogenous (uniform) within the area boundaries shown.

Thus the sea-areas 2 and 4 together comprise the proving ground for the subject vessel.

Typical missions identify routes within the proving ground which form the individual test-tracks. One of these is shown in Fig 4.

A typical mission is involved in proceeding from the home port (Position A in the Figure) to the patrol area at position C where time is spent on station before returning to A by the same route. It can be seen that the intended track is ABB'C which crosses the domain boundary at B'.

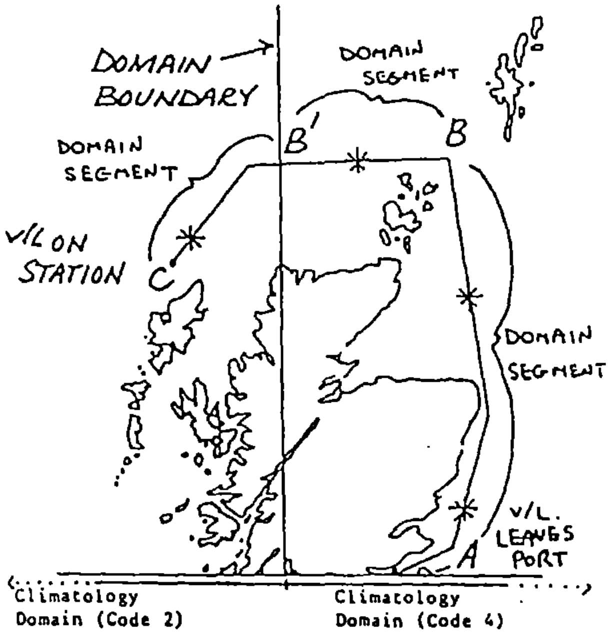
4.2 Route.

The route embodies consideration of geographical location (L), season (S), initial or intended course (C) and initial speed (V_o). The problem of determining the route is to determine the joint probability distribution of the location, season, initial course and initial speed ie, $P(L,S,C,V_o)$.

Consideration of the test-track segment being used will govern the joint probability of location and season, $P(L,S)$ where L is actually representing a distance along the vessels intended track for which the displacement condition $(\Delta,k_{xx},k_{yy},k_{zz})$ can be assumed constant. The test-track segment also governs the conditional probability distribution of initial course and speed given the location and season, $P(C,V_o,/L,S)$.

Then the required probability

$P(L,S,C,V_o) = P(C,V_o/L,S).P(L,S).$



Key: Test-Track = ABB'C

Assumption: Displacement is constant between legs AB and BC. Leg BC crosses the domain boundary at B'. * indicates independent trial sampling points.

Fig. 4

Application of the Method

4.3 Climatology

This aspect is of vital importance in the analysis and, despite increased effort, is still far from resolved. It is required to determine the conditional probability of significant waveheight (H_s), mean wave period (T_m), wave spectrum family member (F) and predominant wave direction (ϕ) given a location (L) and season (S) ie,

$$P(H_s,T_m,F,\phi/L,S) = P(F/L,S).P(H_s,T_m,\phi/L,S).$$

The necessary climatological data, $P(H_s,T_m,\phi/L,S)$ are to be found in many formats and in many sources.(Bales et al. 1981) provide an extensive database which is convenient and has been chosen for use in the present study.

A further consideration is how realistic are the predicted responses if we use the commonly available simple spectral formulations such as Pierson-Moskowitz, Bretschneider's two-parameter, Darbyshire's fetch-limited etc, which have been developed for some idealised conditions? In reality the shape of wave spectra observed in the ocean varies considerably (for the same waveheight) depending upon the geographical location, duration and fetch of wind, stage of growth and decay of a storm, and existence of swell.

In order to cover a variety of spectral shapes which a vessel may encounter in her lifetime two families of wave spectra are used in the present work. One of the families consists of 11 members for an arbitrarily specified sea severity and is called the Ochi-6 parameter wave spectral family.

$$S_\zeta(\omega) = \frac{1}{4}\sum_j \frac{\left(\frac{4\lambda_j+1}{4}\cdot\omega_{mj}^4\right)^{\lambda_j}}{\Gamma(\lambda_j)}\cdot\frac{H_{sj}^2}{\omega^{4\lambda_j+1}}\cdot e^{-\left(4\lambda_j+\frac{1}{4}\right)\left(\omega_{mj}/\omega\right)^4}$$

where j = 1,2 stands for the lower and higher frequency components respectively.

4.4 Seamanship.

This factor can have a large influence on both the motion probabilities obtained and the motions themselves once the severe seastates have been encountered. Firstly by manoeuvring to avoid a storm area (or in the case of certain particularly small vessels by not sailing at all until the storm has passed) the vessel is using avoidance seamanship. This is a function of the accuracy of weather forecasts and the skill of the ship's officers. Secondly a vessel experiencing excessive motions and sea loads may be manoeuvred to reduce these to perceived acceptable levels. The vessel is using what might be termed pacifying seamanship which is a function of the motion/sea loads information available to the ship's officers and their skill in reducing these motions and sea loads.

Pacifying seamanship consists primarily in changes of speed and/or heading once a severe seastate has been encountered. These can be represented as conditional properties of speed, V and relative heading to waves, given the seastate actually encountered after appropriate avoidance (H_s',T_m,F) and unaltered speed V and relative heading μ_o ie, $P(V,\mu/H_s',T_m,F,V_o,\mu_o)$ where μ, μ_o are functions of ship course C and wave direction ϕ.

Ship speed in a seaway comprises the involuntary speed reduction due to the added resistance and reduced propulsive efficiency in waves together with the voluntary speed reduction due to the master's action to reduce excessive motions and sea loads.

Although the present study is primarily concerned with the higher seastates where master's voluntary action overrides any consideration of natural speed reduction, nevertheless the approximate increase in added resistance is accounted for by using a conveniently available method due to Maruo (1957), to estimate the initial attained speed of the vessel on any heading. This is an area requiring further work but recourse can be made to experimental results if necessary.

For the purposes of the present study, it has been necessary to assign a set of criteria which it will be assumed the master will adhere to in order that his vessel will be rendered more seakindly. The master is likely to take action to avoid damage to his vessel's structure, engines, or cargo and to avoid undue discomfort to his passengers and crew.

4.5 Responses.

A "potentially dangerous" roll angle is taken to be a pre-assigned roll angle (30 degrees in the present case) beyond which it can be assumed that the vessel will be considered potentially unsafe from a capsize point of view. Before the required probability of exceedance of the potentially dangerous roll motion ϕ_c can be ascertained $P(\phi > \phi_c)$ an appropriate response statistic ϕ is required. For operability studies this ϕ- response is likely to be an average-type process such as the significant roll response, whereas when considering survivability some measure of the expected maximum is required.

A useful development by Ochi (1973) is the extreme response value which will be exceeded with a pre-assigned small probability the 'design-extreme value'. This is necessary because the most probable extreme value $\bar{\sigma}_n$, which can be used for comparison with the observed extreme value, has a high probability (0.632) of being exceeded for a large number of observations n, if the process is narrow band, where the most probable extreme value:-

$$\bar{\sigma}_n = \sqrt{2\ln\left[\frac{2\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\, n\right]}\;\sqrt{m_0} \qquad \text{for } \epsilon \leq 0.9$$

and ϵ is the spectral bandwith parameter of the σ process.

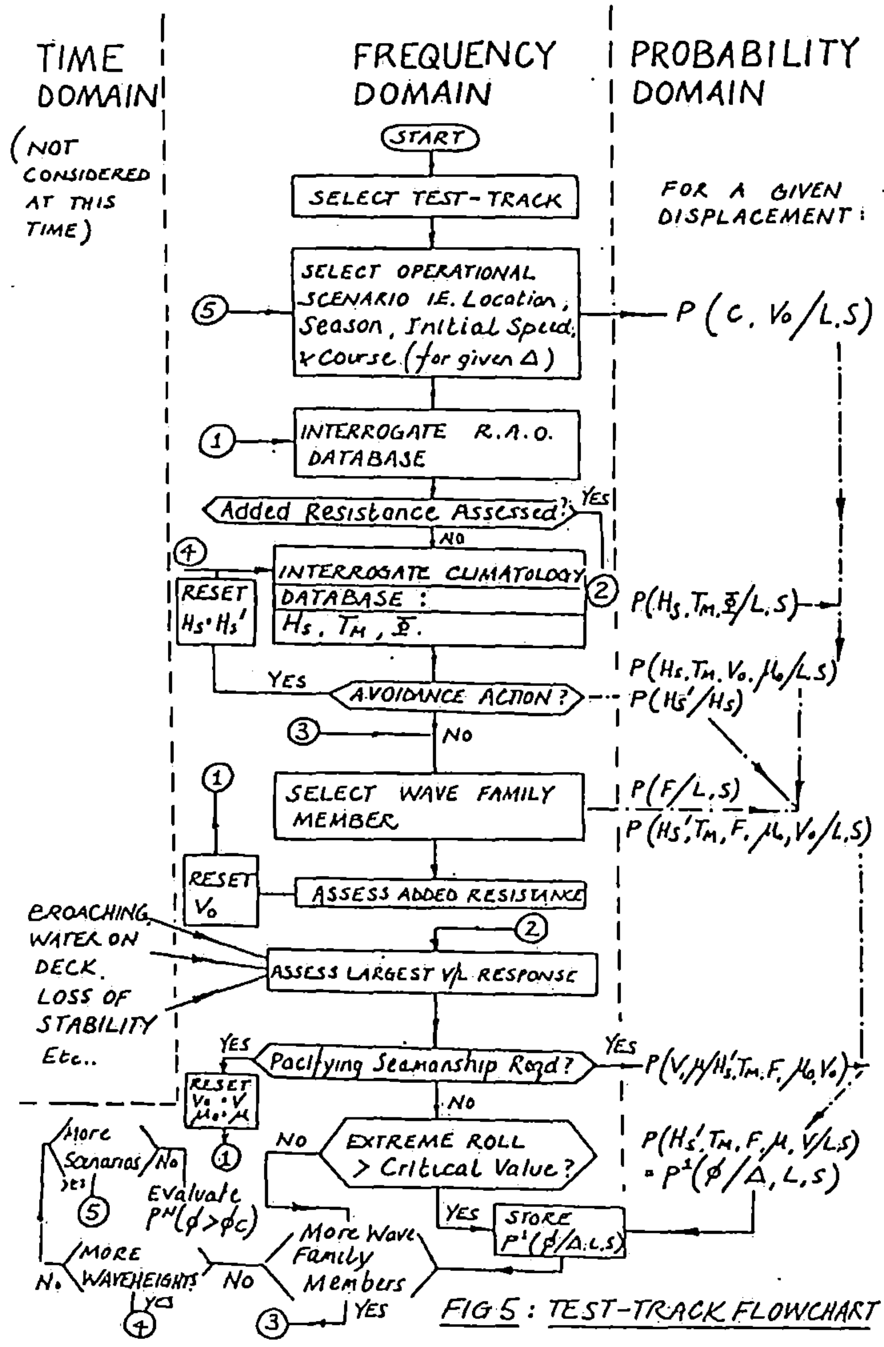


FIG 5 : TEST-TRACK FLOWCHART

GLOSSARY

C	Vessel (true) course
D	Domain
F	Wave spectrum family member
H_s, H_s'	Significant Waveheight before/after avoidance seamanship
k_{xx}, k_{yy}, k_{zz}	Radius of gyration with respect to axes
L	Geographical location
L_*	Independence distance
N, N_*	Number of independent trial samples
Q	Identical test-track number
R	Domain segment length
S	Season
T, T_*	Independence period
T_m	Mean wave period
V_o, V	Ship speed before/after pacifying seamanship
γ_ϕ, γ_ϕ''	Counting functional with respect to roll angle/acceleration
Δ	Displacement
μ_o, μ	Relative heading to waves before/after pacifying seamanship
σ	Random variable
σ_c	'Critical' random variable
ϕ, ϕ', ϕ''	Roll angle/velocity/acceleration
ϕ_c, $'\phi_c$, $''\phi_c$	Critical (potentially dangerous) roll angle/velocity/acceleration
Φ	Predominant wave direction
$P(\sigma)$	Probability density
$P^1(\sigma)$	Single independent trial probability
$P^N(\sigma)$	Multiple independent trial probability
$P^1(\sigma_c < \sigma)$	Cumulative single trial probability of $(\sigma_c < \sigma)$
$P^N(\sigma_c < \sigma)$	Cumulative multiple trial probability of $(\sigma_c < \sigma)$

$$\epsilon = \sqrt{\frac{m_0 m_4 - m_2^2}{m_0 m_4}}$$

where m_0, m_2, m_4 are the zeroth, second and fourth moments of the response process.

In terms of exposure time the most probable extreme value σ_T is given by:

$$\bar{\sigma}_T = \sqrt{2\ln\left\{\frac{60^2 T}{2\pi}\sqrt{\frac{m_2}{m_0}}\right\}}\sqrt{m_0}$$

where T is the exposure time in hours; Hutchison (1981) argued that T should be the independence period T^*. The design extreme value $\hat{\sigma}$ is similarly given in terms of number of observations and exposure time:

$$\hat{\sigma}_n = \sqrt{2\ln\left[\frac{2\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\cdot\frac{n}{\alpha}\right]}\sqrt{m_0}$$

$$\hat{\sigma}_T = \sqrt{2\ln\left\{\frac{60^2 T}{2\pi\alpha}\sqrt{\frac{m_2}{m_0}}\right\}}\sqrt{m_0}$$

Fig. 5 illustrates how a complete study would seek to encompass the time, frequency and probability domains; though only the frequency and probability aspects are being considered in the present study. Essentially the computer simulation reduces to the manipulation of the three databases containing climatology, component probability and complex functioned response amplitude operator information respectively. An important feature of the database is that it reflects the sensitivity of motion response to internal ship parameters, such as hull form and load conditions, as well as to external parameters such as encountered wave conditions.

The right hand side of fig. 5 indicates how the component probabilities combine to yield the independent single-trial probability of a particular scenario. This is equal to the independent single-trial probability of obtaining the resulting roll response provided that the response sampling interval is not less than the independence period.

To simulate responses realistically, roll motion is evaluated assuming that the master will seek to maintain "best progress" towards his destination or voyage way point. The chosen criteria for master's voluntary action are:

- number of slams per hour < 60;
- number of propeller emergences per hour < 120;
- subjective motion magnitude < 12;
- average roll angle < 15°.

These limiting criteria are used because they represent motions and sealoads actually perceived by the master at his bridge conning position (Lloyd 1977). Thus the simulation considers a response mapping of up to 50 course/speed combinations in its attempt to bring vertical motions and sea loads is below the maxima allowed by the above criteria. If it does this successfully it is assumed that the master has chosen this new course and speed and the design-extreme roll motion is then evaluated. Otherwise a heave-to position to the waves is adopted based on the "best" response-mapping value of the course and speed, found by a simple minimization technique.

For example, the following extract from the computer output file, table 2, relates to the vessel operating in a typical very severe, short and steep coastal seaway.

```
PROGRAM ENTERED
SPEED=15.0  SHIPHD=30
NUMBER OF DECK WETNESSES PER HOUR=44
SLAMMING CRITERION OF 60 PER HOUR EXCEEDED (216)
SM CRITERION OF 12 HAS BEEN EXCEEDED (15)
PROP.EMERGENCE CRITERION OF 120 HAS BEEN EXCEEDED (253)
AVERAGE ROLL ANGLE=2

SPEED=18.0  SHIPHD=15
NUMBER OF DECK WETNESSES PER HOUR=0
SLAMMING CRITERION OF 60 PER HOUR EXCEEDED (93)
SM CRITERION OF 12 HAS BEEN EXCEEDED (14)
PROP.EMERGENCE CRITERION OF 120 HAS BEEN EXCEEDED (202)
AVERAGE ROLL ANGLE=5

SPEED=12.0  SHIPHD=15
NUMBER OF DECK WETNESSES PER HOUR=0
NUMBER OF SLAMS PER HOUR=2
SM VALUE AT BRIDGE=2
NO. OF PROP.EMERGENCES PER HOUR=11
AVERAGE ROLL ANGLE=8

PROBABLE EXTREME ROLL ANGLE=30.16

DESIGN EXTREME ROLL ANGLE=37.14

SULISKER PATROL - LEG 1
LOAD CONDITION INDEX        : 1
SHIP SPEED                  : 12.00 KNOTS (FN: 0.2466)

WAVE SPECTRUM               : JONSWAP (OCHI DATA)
SIGNIFICANT WAVE HEIGHT     : 15.0 METRES
FETCH LENGTH                : 1500.0 NAUTICAL MILES
SPREADING FUNCTION          : NONE
```

Table 2

5. REFERENCES

Bales, S.L., W.T. Lee and J.M. Voelker. 1981 "Standardized Wave and Wind Environments for NATO Operational Areas", David Taylor Naval Ship Research and Development Centre Report SPD 0919-01

Bird, H. and A.Y. Octabasi. 1975 "State of Art: Past, Present and Future", Proceedings of the International Conference on Stability of Ships and Ocean Vehicles, Glasgow, 1-24

Hutchison, B.L. 1981 "Risk and Operability Analysis in the Marine Environment", Society of Naval Architects and Marine Engineers Transactions, Vol. 89: 127-154.

Jenssen, T.K. 1976 "Risk Criteria for Marine and Related Activities", Der Norske Veritas Technical Report 76-240, Oslo.

Kastner, S. 1982 "Simulation and Assessment of Roll Motion Stability", Proceedings of the 2nd International Stability Conference, Tokyo, 171-184.

Lloyd, A.R.J.M. and R.N. Andrew 1977 "Criteria for Ship Speed in Rough Weather", Proceedings of the 18th American Towing Tank Conference, Vol 2, Annapolis, Maryland.

Maruo, H. 1957 "The Excess Resistance of a Ship in a Rough Sea", Int.Shipbuilding Progress, Vol.4, 35.

Ochi, M.K. 1973 "On Prediction of Extreme Values", Journal of Ship Research, Vol. 17, 1.

Rahola, J. 1939 "The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability", PhD Thesis, Helsinki.

Previously Published Material

Capsize Prediction Using a Test-Track Concept;

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CAPSIZE PREDICTION USING A TEST-TRACK CONCEPT

E. Deakins, N.R. Cheesley

G.R. Crooker, C.T. Stockel

ABSTRACT

This interim report describes the ongoing work since 1982, at Plymouth Polytechnic, into the probabilistic assessment of vessel safety against capsize in a representative range of likely to be encountered environmental and operating conditions.

The proposed risk framework utilises probabilistic procedures which have recently been applied to operability studies. The method is capable of accounting for variations in seastate, vessel design features and load condition as well as vessel speed and heading subject to master's intervention.

The concept of a test-track is introduced as a means of standardising, particularly for regulatory purposes, the operating scenarios which should be included in any analysis which seeks to predict, in a realistic manner, vessel capsize safety.

The preliminary analysis described utilises a linear superposition technique to predict vessel response and the concept of a "potentially dangerous" roll motion is introduced to avoid the necessity to predict large non-linear capsize roll angles.

This work is affiliated to the United Kingdom Safeship project.

1. INTRODUCTION

Ship stability is a property which is not amenable to simple definition. To naval architects stability means "safety against capsizing" in a very general sense and the development of the underlying theory has had a long period of evolution which is still far from complete. Current international stability criteria can be traced directly to the work, in 1939, of Rahola [34] who proposed that a ship's measure of safety be related to certain properties of still-water righting lever (GZ) curves. However, in recent years it has been argued that these criteria, which neglect the action of the seaway, cannot be a sufficient indicator of vessel capsize resistance in the seaway [9]. Furthermore, it is generally agreed that any new and improved criteria should seek to take account of the variability of the environmental conditions encountered, the vessel's design features as well as the variation in load conditions and master's action [22].

It is in the area of structural design, especially, that there has been a movement away from the deterministic approaches, where satisfactory rules are gradually evolved by a process of trial and error, to one where the variability in the demands made on and the capability of a structural element to resist the load actions imposed is taken into account [12, 38]. In such a probabilistic approach it is recognised that a structural element will have to withstand loads of different magnitude and frequency during its lifetime and similarly that its capability to resist these loads will not have a single deterministic value, Fig 1.

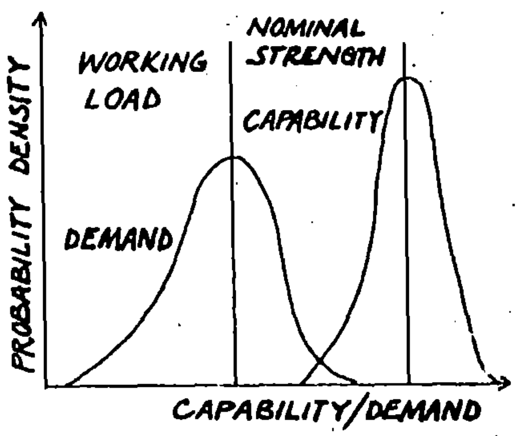


Fig 1
Variation of Demand and Capability of a Structural Element

The problem to overcome in such an approach is to ascertain the nature of the tails of the demand and capability distributions since it is in the overlap region that the comparatively rare high demand and low capability may occur simultaneously to cause failure.

An overall strategy for probabilistic stability assessment, based on modern structural design methods [12] is shown in Fig 1a and this can be compared with the traditional (current) stability assessment.

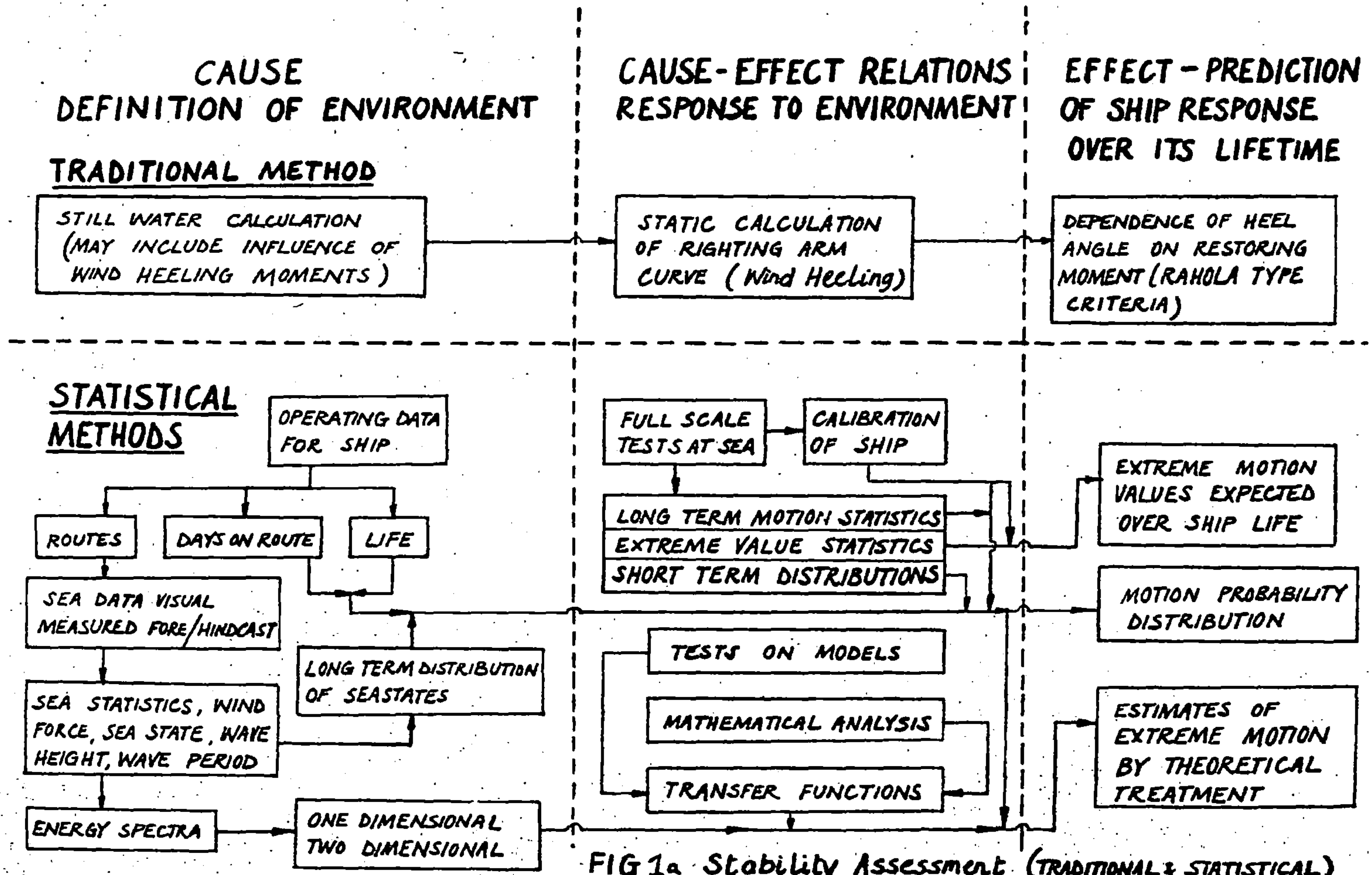


FIG 1a Stability Assessment (TRADITIONAL & STATISTICAL)

As well as being much more extensive, the modern approach features experimental and analytical models backed up by full scale trials where appropriate.

The main purpose of the work at Plymouth is to explore the feasibility of developing and applying such a probability analysis framework as a basis for ship safety from capsize which may lead to improved stability, design and regulation criteria. It is also hoped that the framework will help mesh together the different and often highly individual analytical techniques for modelling the various capsize phenomena, in a concise and efficient manner.

1.1 Assessment of Risk in the Marine Environment

The concept of risk is not new. In many instances where a large body of information exists, based on accident history, an appropriate interrogation of the database can assign the risk of death, injury or other loss involved in partaking of a particular activity, eg, Table 1.

Risk Source	FAFR	
Average for British Industry	4	
Chemical Industry	3.5	FAFR=Fatal
Steel Industry	8	Accident
Fishing	35	Frequency
Coal Mining	40	Rate
Construction Workers	67	= No of
Air crew	250	deaths
Staying at home	3	per 10^8
Driving a car	60	hours of
Rock climbing	4000	risk
		exposure
		[21]

Table 1
Risk levels by Activity

Unfortunately no database currently exists which is capable of providing sufficient detail to assign the probability of an individual vessel's risk of capsize. This is hardly surprising given the nature of a capsizal which is frequently rapid with little resulting casualty wreckage to provide evidence of the likely causes. Whilst some useful information can be obtained from the casualty records, such as the general nature of the capsize and the surrounding circumstances, no suitably detailed information can be obtained regarding the sequence or the probability of causal events which would be particularly useful for a more traditional risk analysis such as "fault-tree" [3].

Even if this information was available it would not be appropriate to extrapolate it to cover many of the unique projects which are undertaken in the marine environment today.

The alternative is to develop an appropriate prediction technique which aims to incorporate that information which is available from casualty records (where it exists) as well as catering for those casualties which nearly occurred ie, the "near misses". Fortunately probability methods have recently been developed [20] which have direct application to the problem of assessing the risk of a vessel capsizing in a seaway. These will now be discussed within the context of application to capsize assessment.

2. THE TEST-TRACK CONCEPT

2.1 Problem Outline

Risk prediction can be generally stated as determining the probability that a pre-assigned event will occur in a number of trials (or over a period of time). This definition is particularly suited to games of chance, to assess the likelihood of obtaining a particular face value of a die, for example, in so many trial throws.

When applying probability concepts to the problem of vessel capsizing, it is more appropriate to consider the probability of a critical roll response being exceeded since this will determine the area of the overlapping tails in Fig 1 ie, the probability that the operational and environmental demands exceed the vessel capability to resist the demands.

In operability-type studies such as fatigue analysis it is necessary to consider every cycle of vessel response during its lifetime since all cycles contribute to fatigue failure. In (survivability) risk-type studies this is not the case since quite often only the severest seastates will cause the severest motions, and, provided that the relatively rare catastrophic responses in mild seas can be accounted for, this suggests that the amount of computation can be reduced in some way. Obviously, it is not sufficient to seek the 'worst cases' on an ad hoc basis and some ordered approach is desirable.

2.2 Test Tracks and Proving Ground

In an attempt to 'trap' the worst-case scenarios, the proposed method consists essentially of a subject vessel being required to successfully (ie, without capsizing) negotiate a series of "test-tracks" which have been designed to represent the range of critical (potentially capsize causing) scenarios that it will encounter over its lifetime.

In the automobile industry, in particular, this type of procedure is common. A road vehicle is made to perform a series of manoeuvres over varying terrain in a variety of conditions (environmental, load, speed etc) where each test-track represents one such set of conditions. For example there will exist a handling and stability test-track, a steep gradient test-track and so on. The total test-track set is termed the "proving-ground" and its overall nature reflects the vehicle's intended use and type. Thus a sports car will have a different set of test-tracks to negotiate than an articulated lorry, though some will be identical. See Fig 2.

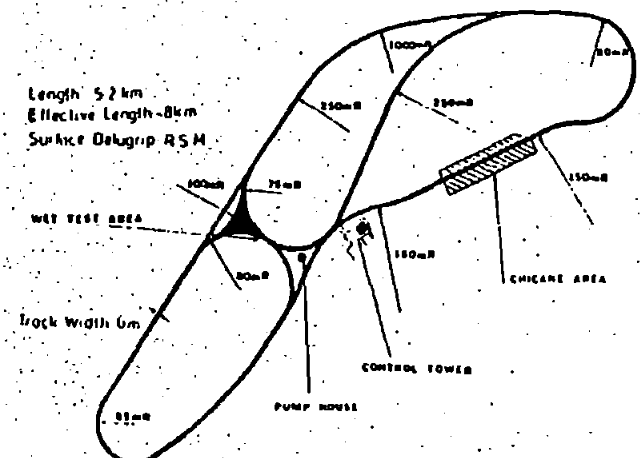


Fig 2

Handling and Stability Circuit at MIRA [40]

The main advantages to the vehicle designer of using this approach are:-

a) The full range of operating conditions, including the very important severe conditions, can be produced in a manner difficult to achieve on the open road, for example, (also making repeatability of results possible).

b) Vehicles are tested under tightly controlled conditions where individual characteristics such as handling can be assessed, in isolation if necessary, and compared against previous and other vehicles' results.

c) Attention is focused on individual elements eg, vehicle suspension settings so that if a poor performance characteristic manifests itself on one particular test-track the design can be precisely retested after suitable modification.

The authors believe that these are valuable procedures which can be used to assess the capability of a seagoing vessel to perform its duty in safety. However, leaving aside the immense difficulty of physical modelling of severe sea conditions, sheer expense would preclude the use of a purely physical marine proving ground for every single vessel. Thus it is envisaged that at first the test-tracks will be largely analytical in nature with some experimental back-up for certain difficult aspects until, as the theory improves, eventually no physical experimentation would be required (?)

For this preliminary investigation and for illustration of the overall 'package' a wholly analytical frequency domain analysis will be used. Obviously this means that certain physical capsize phenomena which may be best suited to time domain analysis (such as the broaching-to phenomenon) will not be modelled and thus the test-tracks will not be fully activated initially. Section 4 addresses the basis for using a linear frequency domain analysis for what are essentially non-linear large angle capsize phenomena.

2.3 Choice of Test-Track

As with the road vehicle case, the vessel type and intended zone or zones of operation dictate the nature of the proving ground, and thus the individual test-tracks, that the seagoing vessel will be required to negotiate successfully. Thus, for example, a vessel which is intended for operation in a sea-area which is well sheltered or has shelter to hand will not have to negotiate the more stringent test-tracks required of a vessel intended for extended operation in high icing latitudes. Indeed, some form of licensing might be desirable for individual operational zones since this would assist in avoiding the potential overdesign or underdesign of vessels which the current 'blanket' regulations may encourage.

A vessel which is intended for international operation would be subjected to the worst possible weather conditions (Appendix 2.2).

By considering individual test-track performance the effect on the performance of design and operational features can be considered in detail whilst overall proving ground performance will allow comparison of total performance and safety levels across a fleet of vessels for example though this "average" value should be treated with caution.

A typical subject vessel can be expected to operate, over its lifetime, in a wide range of environmental and displacement conditions and to be subject to different masters' action. The correct choice of test-tracks to isolate the potential capsize scenarios from amongst all possible operating scenarios encountered by the vessel during its lifetime is vital if certain critical operations are not to be overlooked along the way. Whereas it is computationally desirable that the proving ground should only encompass all of the possible scenarios which could cause capsize, it is obviously not possible to pre-define them, and it is thus necessary to initially consider that all scenarios are potentially capsize causing. However, if an initial assumption is made that only the severest seastates cause the severest responses the amount of computation for any scenario is reduced if the order of severity of seastates to which the vessel is subjected (everything else remaining unchanged) is progressively reduced from the most severe possible in the operating zone under consideration. Once the predicted response level falls below the limiting safe value the computer program moves on to consider the next scenario and so on. (Section 5) The results of Multi-variate (pattern recognition) analysis of casualty date (for the broad vessel type and size) is also used to ensure that no proven (frequently recurring) capsize scenarios have been missed, particularly in mild seas. These positively identified "capsize nuclei" (each one representing a distillation of many similar casualties) form critical scenarios for consideration and are embedded in the test-tracks with respect to time and location. Fig 3.

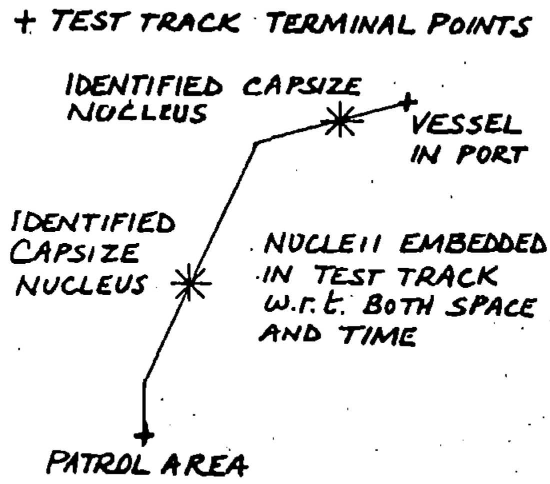


Fig 3
Vessel Steaming to Patrol Area
Test-Track containing 2 identified capsize nuclei

3. APPLICATION OF THE METHOD

3.1 Managing the Lifetime of Risk

The method of handling all the scenarios comprising a lifetime of risk is best illustrated with the aid of an example. The subject vessel being used for the present study is a fisheries protection vessel which has an operational area encompassing the Northern North Sea and North Eastern Atlantic in the region of the 100 fathom line around North West Scotland. There are also occasional sorties of up to

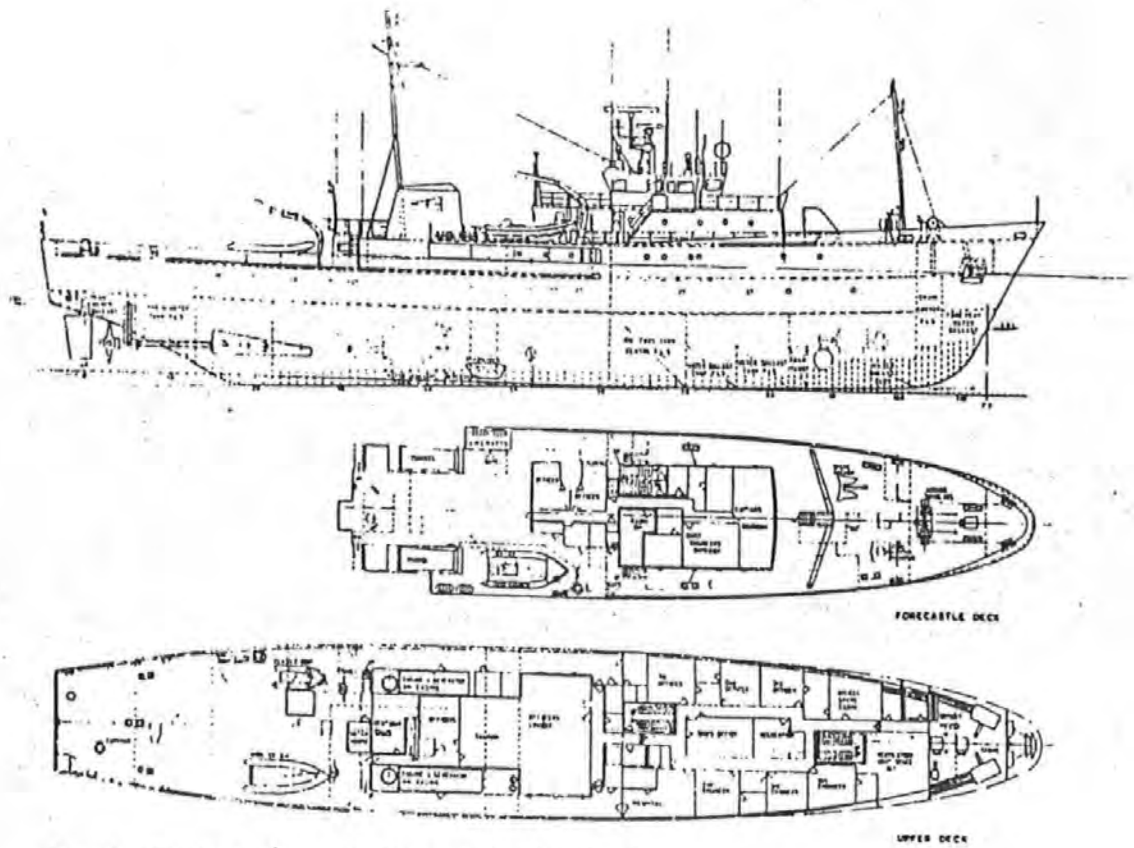


Fig. 4. General Arrangement: Fishery Protection Vessel.

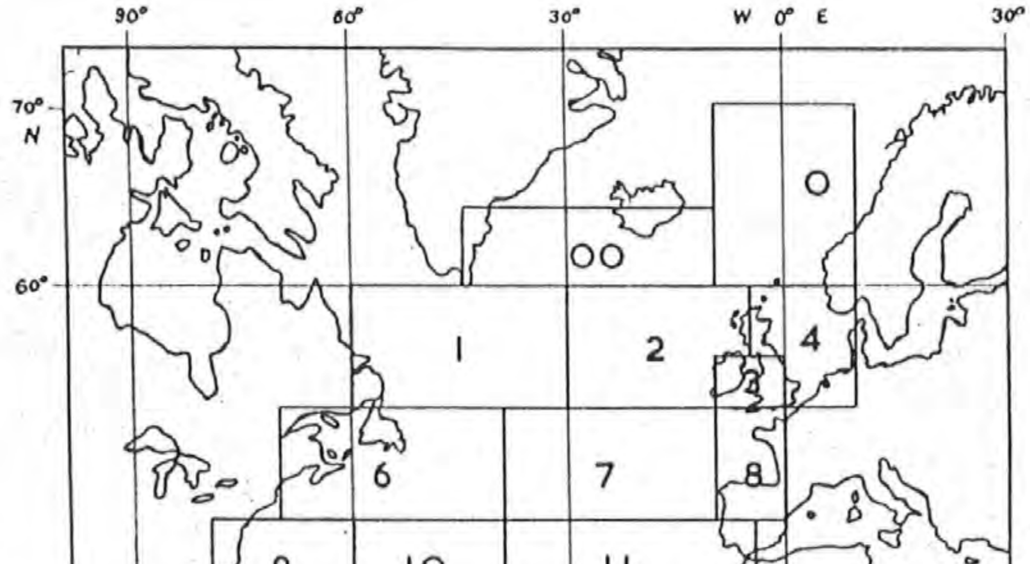


Fig. 5. North Atlantic Basin Climatology Regions [8].

200 miles into the open North Atlantic.

Principal vessel particulars are given in Table 2 and Figure 4 shows the general arrangement.

Length Overall	71.33 m
Length b.p.	64.00 m
Beam mld.	11.60 m
Design Displacement	1532 tonnes

Table 2 - Principal Particulars

The prediction method aims to calculate $P(\phi_c < \phi)$, the cumulative probability of a 'critical roll motion' (ϕ_c) being exceeded, at least once, during the vessels lifetime of operation. This value is of course represented by the proving ground result. Additionally the probabilities of exceedance during certain individual vessel operations, represented by individual test-track results, is being sought.

The 'critical roll motion, ϕ_c' is defined, in the first instance, as the value of roll angle beyond which there is increasing concern that the vessel will be in danger of capsizing. This is referred to as the potentially dangerous roll angle, though it may subsequently be defined to include velocity or acceleration terms. (These aspects are discussed in Section 4).

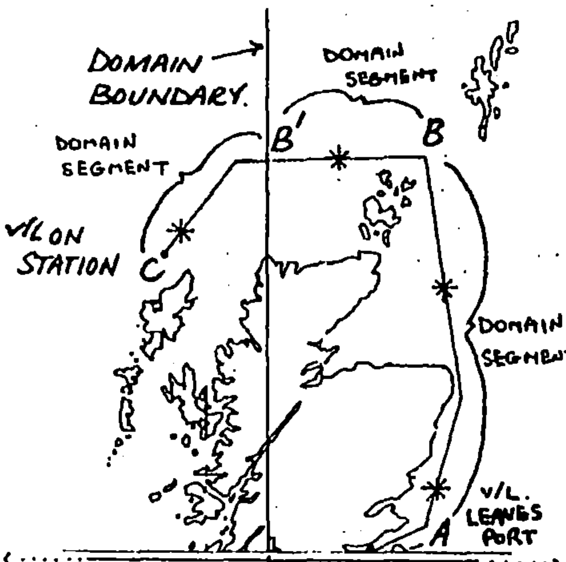
The cumulative probability $P(\phi_c < \phi)$ can be obtained from a knowledge of the underlying lifetime response probability density function $P(\phi)$. This in turn can be found by taking (ie, computer-predicting) independent trial samples of roll response over the vessels lifetime together with the independent single trial probabilities of occurrence. These independent trial results are then combined using Bernoulli trial procedures, (Appendix 1).

A preliminary analysis is necessary to determine the vessel's intended missions (operating practices and operating areas). For ease of illustration it is assumed that our subject vessel will only ever operate in the sea areas labelled 2 and 4 in Fig 5.

This indicates the boundaries of the sea-areas in the North Atlantic Basin into which the climatology data is divided in Ref [8]. It is assumed that each sea-area has its own distinct climatology and that this is homogenous (uniform) within the area boundaries shown.

Thus the sea-areas 2 and 4 together comprise the proving ground for the subject vessel.

Typical missions identify routes within the proving ground which form the individual test-tracks. One of these is shown in Fig 6.



Key: Test-Track = ABB'C

Assumption: Displacement is constant between legs AB and BC. Leg BC crosses the domain boundary at B'. * indicates independent trial sampling points.

Fig 6

Application of the Method

A typical mission is involved in proceeding from the home port (Position A in the Figure) to the patrol area at position C where time is spent on station before returning to A by the same route. It can be seen that the intended track is ABB'C which crosses the domain boundary at B'. Thus the test-track is subdivided into 2 separate spatial domains where the climatology is assumed homogeneous. Each spatial domain is further subdivided into domain segments which are segments along the intended track where the vessel's displacement condition ($\Delta, k_{xx}, k_{yy}, k_{zz}$) can be assumed constant. Thus in Figure 6, between AB and BC the displacement conditions are assumed constant and different. (For convenience, and to facilitate comparison of performance with the existing stability criteria, the actual load conditions which are used are taken from the vessel's stability booklet to represent the complete range of vessel capability).

3.2 Independent Trial Samples

In order to be able to use the simple procedures, for manipulating probabilities which are given in Appendix 1, for risk and operability studies, it is necessary to ensure that all the predicted responses (trial samples of the underlying lifetime response probability density function) are independent. This necessitates that the response obtained from one scenario shall not have been influenced by any previous responses obtained along a domain segment ie, the response obtained should have no 'memory'.

Thus it is required to know how many independent trial samples of the underlying response distribution can be taken in each domain segment since this has an important bearing on the probabilities obtained (Appendix 1). For this purpose an independence interval was introduced by Hutchison [20]. This 'interval' represents the minimum distance in time and/or space that a vessel must travel before the seastates (and by inference the resulting responses) can be considered independent trial samples of the underlying seastate probability density function. This is an important concept since conditional information concerning the seastate (and thus the responses obtained) at one instant strongly alters the probability distribution for seastates (responses) at nearby times or locations but the influence of the conditional data diminishes as one moves further away in time or space until eventually the underlying seastate (response) probability distribution is again dominant.

Hutchison proposed a simple form of metric for the number of independent ship exposure cycles, N_* where

$$N_* = \sqrt{\left(\frac{T}{T_*}\right)^2 + \left(\frac{VT}{L_*}\right)^2} \qquad [20]$$

where T_* = independence period, Hours
L_* = independence distance, nautical miles
T = exposure time, hours
V = average vessel speed

The independence period/distance is the time/distance required between two observations to be independent. See Fig 6. Further work is required in this area but values for the independence period of between 13 and 26 hours have been quoted based on some available seastate process sampling rates on a scale significant to ship routeing [20].

In fact a simpler measure

$$N = \frac{\text{Exposure distance R}}{VT_*}$$

is more appropriate if vessel speed relative to the advancing weather conditions is used.

3.3 Applied Probability Concepts

A particular design which is operating in a domain segment (ie, of a particular load condition) will have a motion response dependent upon the combination of broad factors route, climatology and seamanship. These factors are considered in detail in Appendix 2.

It is apparent that the single trial probability of obtaining a roll response level (ϕ) is equal to the single trial probability of encountering the particular load condition, route, climatology and seamanship giving rise to the response.

Thus the single trial probability of obtaining the predicted roll response ϕ, given the load condition Δ, location L and season S .

$P^1(\phi/\Delta,L,S)$, where P^1 indicates the single trial probability, is equal to the single trial probability of encountered seastate (H_s',T_m,F), relative heading to waves (μ) and speed (V) given load condition (Δ), location (L) and season (S). Thus

$$P^1(\phi/\Delta,L,S) = P^1(H_s',T_m,F,\mu,V/\Delta,L,S)$$

The value of $P^1(H_s',T_m,F,\mu,V/\Delta,L,S)$ is obtained by manipulation of the component probabilities given in Table 3 from Appendix 2. There are several ways of combining these probabilities but in the present study the adopted procedure is as follows:

(a) For a given domain segment ($\Delta,k_{xx},k_{yy},k_{zz}$ constant), the relative heading to waves, before any modifying seamanship, is given by [$\mu_o = C - \phi$] where C is the course and ϕ the predominant wave direction.

Now, the joint probability of seastate, heading, wave spectrum and speed (prior to seamanship) given the location and season is

$$P(H_s,T_m,F,\mu_o,V_o/L,S) = P(C,V_o/L,S).P(H_s,T_m,F,\phi/L,S) = P(C,V_o/L,S).P(H_sT_m,F,[C-\mu_o]/L,S)$$

(b) Incorporating the avoidance type seamanship $P(H_s'/H_s)$ gives after avoidance:

$$P(H_s',T_m,F,\mu_o,V_o/L,S) = P(H_s'/H_s).P(H_s,T_m,F,\mu_o,V_o/L,S)$$

(c) Incorporating the pacifying type seamanship, $P(V,\mu/H_s',T_m,F,V_o,\mu_o)$ yields the required joint probability of seastate, heading and speed (after seamanship action) given the location and season is,

$$P(H_s',T_m,F,\mu,V/L,S) = P(V,\mu/H_s',T_m,F,V_o,\mu_o).P(H_s',T_m,F,V_o,\mu_o/L,S) \text{ or}$$

$$P(H_s',T_m,F,\mu,V/L,S) = P(V,\mu/H_s',T_m,F,V_o,\mu_o).\ P(H_s'/H_s).P(C,V_o/L,S).P(H_s,T_m,F,[C-\mu_o]/L,S)$$

This is the single independent trial probability of obtaining the predicted roll response ϕ resulting from this scenario in a given domain segment for 1. set of conditions. There are many such sets or combinations of conditions which must be considered.

Probability	Description
$P(L,S)$	Joint Probability of V/L location and season
$P(C,V_o/L,S)$	Joint Probability of intended course and speed given the location and season
$P(H_s',T_m,F,\phi/L,S)$	Joint Probability of encountered significant waveheight and mean wave period, wave family spectrum and predominant wave direction given location and season.
$P(H_s'/H_s)$	Probability of encountering a seastate of severity H_s'after taking avoidance action given that H_s would have been encountered if no bad weather avoidance had been attempted
$P(V,\mu/H_s',T_m,F,V_o,\mu_o)$	Joint Probability of new speed and new heading to waves after master's alteration in response to excessive motions caused by seastate severity and original speed and heading

Table 3
Component Probabilities used in the Analysis (Appendix 2)

At this stage of combining all the possible combinations, the opportunity is taken to obtain directly the single trial probability of roll angle ϕ exceeding the critical value ϕ_c, $P^1(\phi_c<\phi)$. To every scenario a response level ϕ is predicted, such as the expected maximum roll angle which has a value dependent on the duration of exposure to each seastate, (ultimately the independence period - Appendix A2.4).

If a counting functional is constructed from:-

$$\gamma_\phi = \begin{bmatrix} 1 \text{ for } \phi_c < \phi \\ 0 \text{ otherwise} \end{bmatrix}$$

the cumulative single trial probability of exceeding the critical roll ϕ_c in the domain segment (for a given load condition, location and season) is given by

$$P^1(\phi_c<\phi/L,S) =$$

$$\int_0^{2\pi}\int_0^{\infty}\int_0^{2\pi}\int_{F=1}^{F=f} P(V,\mu/H_s',T_m F,V_o,\mu_o).P(H_s'/H_s).$$

$$P(C,V_o/L,S).P(H_s,T_m,F,[C-\mu_o]/L,S).\gamma\phi$$

$$d\mu_o,dH_s,dC,dF$$

If required, further counting functionals can be added to this equation, eg:

$$\gamma_{\ddot\phi}'' = \left|\begin{array}{l} 1 \text{ for } \ddot\phi_c < \ddot\phi \\ 0 \text{ otherwise}\end{array}\right|$$

would give the cumulative single trial probability of roll angle ϕ exceeding ϕ_c with ϕ roll acceleration $\ddot\phi$ exceeding $\ddot\phi_c$.

$$P^1(\phi_c<\phi,\ddot\phi_c<\ddot\phi).$$

The number of independent trials in the domain segment is found from

$$N = \frac{R}{VT_*}$$

where R is the distance along the course track between entrance and exit boundaries of a domain segment eg, distances AB,BB',B'C in Figure 6

V = vessel speed relative to weather speed of advance

T_* = independence period.

Then the probability of $(\phi_c < \phi)$ in N independent trials in the domain segment is given by (Appendix 1):

$$P^N(\phi_c<\phi/L,S) = 1 - [1-P^1(\phi_c<\phi/L,S)]^N$$

Since the $P^N(\phi_c < \phi)$ processes are independent processes in each domain segment L, domain D and season S the probability that ϕ exceeds ϕ_c at least once on a single independent test-track is given by

$$P^1(\phi_c<\phi) = 1 - \left\{\prod_{LDS}\prod\prod [1-P^N(\phi_c<\phi/L,S)]\right\}$$

this is the <u>required single test-track result</u>.

For <u>Q</u> repeated identical test-tracks in a lifetime of operation

$$P^Q(\phi_c<\phi) = 1 - [1-P^1(\phi_c<\phi)]^Q$$

Since the proving ground involves several <u>distinct types</u> of test-track

$$P^{\Sigma Q_i}(\phi_c<\phi) = 1 - \Pi[1-P^1(\phi_c<\phi)]^{Q_i}$$

where Q_i = number of test-tracks of type i gives the <u>proving ground</u> result ie, the overall risk that ϕ exceeds ϕ_c for a lifetime of operation.

Thus $P^{\Sigma Q_i}(\phi_c<\phi) =$

$$1 - \Pi\left[1-\left(1-\left\{\prod_{LDS}\prod\prod[1-P^N(\phi_c<\phi/L,S)]\right\}\right)\right]^{Q_i}$$

$$= 1 - \Pi\left[1-\left(1-\left\{\prod_{LDS}\prod\prod[1-(1-(1-P^1(\phi_c<\phi/L,S))^N)]\right\}\right)\right]^{Q_i}$$

where $P^1(\phi_c<\phi/L,S) =$

$$\int_0^{2\pi}\int_0^{\infty}\int_0^{2\pi}\int_{F=1}^{F=f} P(V,\mu/H_s',T_m,F,V_o,\mu_o).P(H_s'/H_s).$$

$$P(C,V_o/L,S).P(H_s,T_m,F,[C-\mu_o]/L,S).\gamma\phi\ d\mu_o,dH_s,dC,dF$$

4. SCOPE OF THE PRESENT WORK

The previous section has outlined the method of manipulating probabilities of independent response samples so that the probability of exceeding, at least once, a critical roll motion can be found for each of the test-tracks and the proving ground.

Of equal importance is the prediction of the motions themselves in what is essentially a large angle non-linear phenomenon.

Poor stability (operational or icing effects)
Wave amidships causing stability loss
Mathieu effect (periodic resonance with waves)
Broaching-to (directional instability in following waves)
Heavy seas from one side
Breaking Waves
Cargo Shift
Water on Deck

<u>Table 4 [39] Capsize Phenomena</u>

Investigations of casualty data and experiments with scale models has led to the categories of capsize shown in Table 4. Especially for smaller vessels physical wave effects can be critical, especially in some local conditions which may be encountered off the Norwegian coast for example [39].

It follows that every test-track segment should be analysed to take account of <u>all</u> possible capsize phenomena, especially when smaller vessels are under investigation. Consideration should also be given to the possibility of one phenomenon giving rise to another eg, heavy seas from one side causing cargo shift. This would lead to the ideal demand/capability assessment of Figure 7 which is necessarily a mix of analytical techniques (time domain and frequency domain) and experimental techniques at this time. The largest roll motion obtained from all these procedures would be carried forward in the calculation. However in these early stages, for illustration, only certain of the capsize phenomena are being investigated, through the use of the linear superposition theory. The basis for this choice is now explained.

4.1 The Potentially Dangerous Roll Angle

When a vessel capsizes, from whatever cause, it assumes a large angle of inclination from which it cannot recover. It follows that the measure of the vessel's overall capsize safety should be its capability to resist this ultimate roll motion during its lifetime. This requires a reliable method for predicting the large roll angles which can properly handle the non-linear nature of the roll damping and restoring moments as well as the important coupling of roll, sway, yaw motions giving rise to considerable roll motion damping. In addition, for risk analysis purposes, the method should ideally be capable of taking account of the key parameters such as the environment, speed and heading to waves as well as changes in hull form and load condition. A method which could also simultaneously predict pitch and heave motions would be particularly useful in a computer simulation because the magnitude of the vertical motion and acceleration together with associated physical phenomena such as slamming may cause the master to change speed/heading to seek acceptable motion limits.

Unfortunately such a general theory for non-linear system response to stochastic processes which is suitable for a risk analysis does not currently exist. Methods which are available tend to either give accurate prediction of uncoupled large roll angles for an intact vessel stopped in beam seas, for example [35] or else to have the scope for a risk analysis study but not the capability to predict the large roll angles. The linear superposition principle of St Denis and Pierson [16] falls under the latter category. Whilst it can give reasonably good results for coupled pitch and heave motions the prediction of large amplitude coupled lateral motions is less satisfactory because of the inherent motion non-linearities.

Thus a further important feature of the present analysis is that the prediction of the actual large angle capsize is not attempted per se. Instead a lesser roll angle termed the "potentially dangerous roll angle" is chosen beyond which it is assumed that a capsize is likely. Thus the potential for disaster is being predicted rather than the disaster itself. This novel approach can be justified for the following reasons:-

a) Long before the vessel reaches its capsize angle there is often great likelihood of cargo shifting.

b) Simultaneously there is great likelihood of water downflooding as well as water trapped on deck.

This would necessitate the accurate prediction of large angle damage stability and roll taking account of possible cargo shifting effects and water on deck and further complicated by large changes in hydrodynamic coefficients as the deck edge is immersed. Until such methodologies become available, it is proposed that the linear theory be stretched to the limit of its capabilities in order to estimate the occurrence of a roll motion judged "potentially dangerous".

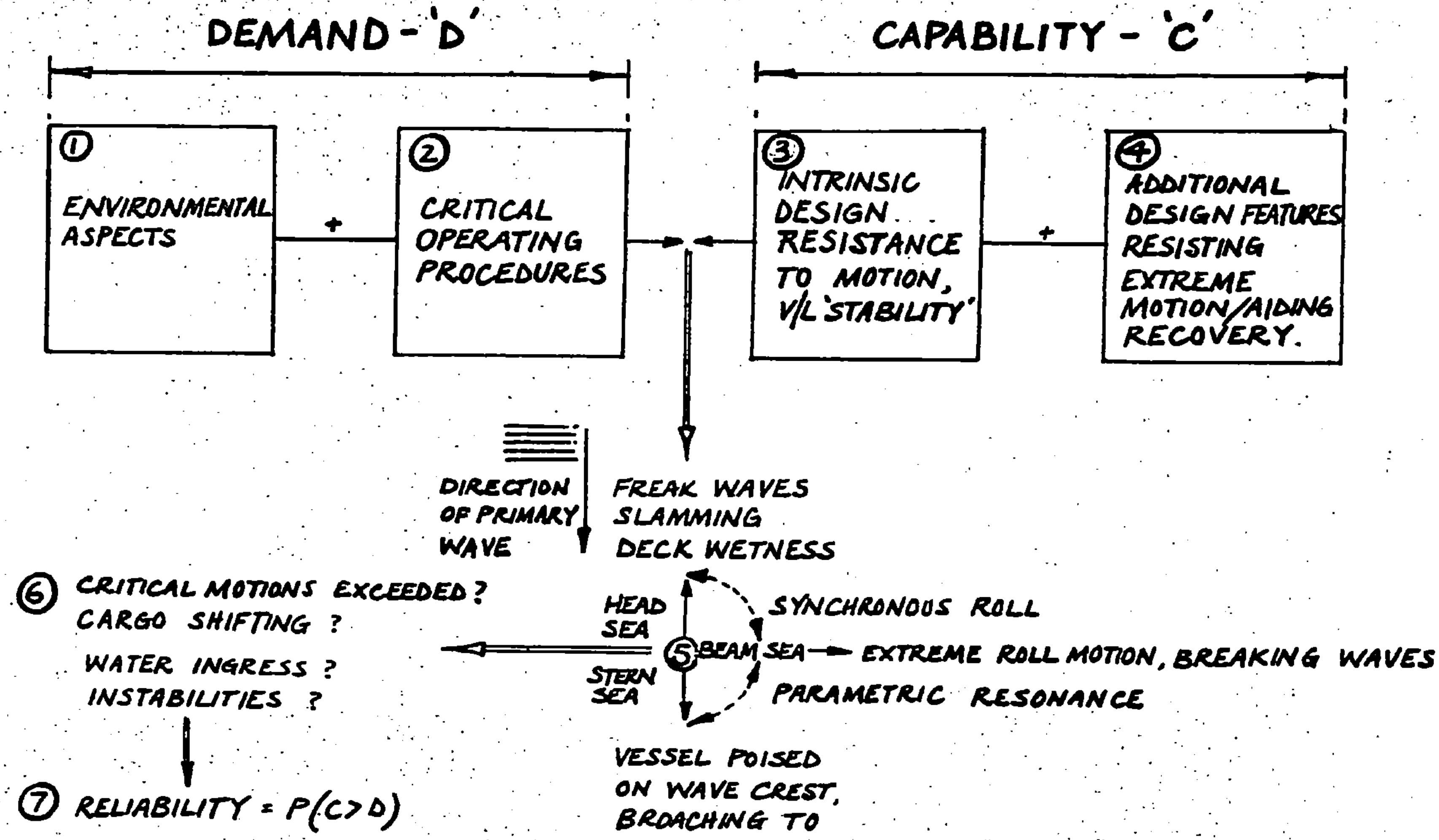


FIG 7 : VESSEL DEMAND & CAPABILITY

Based on discussions and correspondence with fleet operators and serving commanding officers [33] an angle from the upright of 30 degrees has been selected for the subject vessel (length of 60 m) as the potentially dangerous roll angle. This does not imply that when a vessel rolls to 30 degrees it will capsize. It does, however, reflect the view that beyond this angle there is increasing cause for concern by the vessel operators and that a vessel "regularly" rolling to 30 degrees and beyond should be considered suspect. This would be reflected in a high probability of 30 degrees being exceeded in a particular operational scenario. Through the SAFESHIP project Brook [11] has demonstrated that, provided the righting lever curve is approximately linear to the angle in question it is more important, for roll prediction, to include coupled motions through linear theory rather than to use an uncoupled non-linear prediction method. He also demonstrated that in some cases the coupled-linear roll angles were greater than the coupled non-linear roll angles and sometimes less. (See Table 5)

Wave Direction	30 degrees		
Ship	1	2	3
	ϕ max 2 hrs		
Coupled, Non-linear	18.1	11.7	9.9
Coupled linear	14.6	9.1	7.2
Uncoupled Non-linear	-	-	-

Wave Direction	90 degrees		
Ship	1	2	3
	ϕ max 2 hrs		
Coupled, Non-linear	34.3	19.0	21.7
Coupled linear	40.5	16.2	26.0
Uncoupled Non-linear	25.2	54.2	5.2

Ship 1 = Offshore Supply V/L (53 m)
Ship 2 = Stern Trawler (60 m)
Ship 3 = Coastal Tanker (67 m)

Table 5 from Ref [11]

The linear nature of the subject vessel's GZ curve is illustrated in Fig 8 for angles up to well in excess of 30 degrees.

It is envisaged that in due course better motion prediction methods, having the required scope for risk studies, will become available and the linear spectral analysis used in this work will be superseded. This argument will not be pursued here any further since the primary aim of this work is to synthesise the components of demands made on the vessel and the capability of the vessel itself, where the demand and capability is constantly changing over the vessel's lifetime.

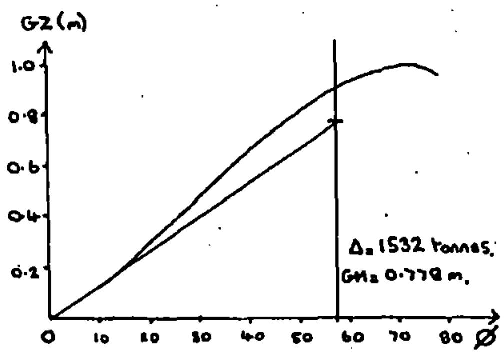


Fig 8

GZ curve - Fisheries Protection Vessel

5. THE COMPUTER SIMULATION

The foregoing sections have outlined how the probability of exceeding a "potentially dangerous" roll motion can be estimated, making use of independent (Bernoulli) trial concepts. It has also been proposed that every vessel be subjected to a set of (mostly) analytical test-tracks which together comprise the proving ground appropriate in nature to the vessel being considered. This aspect is particularly suited to regulatory purposes where vessels are subject to standard procedures and assumptions.

Work is continuing on the computer program which is required for implementation of the method; however Figure 9 indicates the overall extensive nature of the program as far as it can be envisaged at this time. The figure

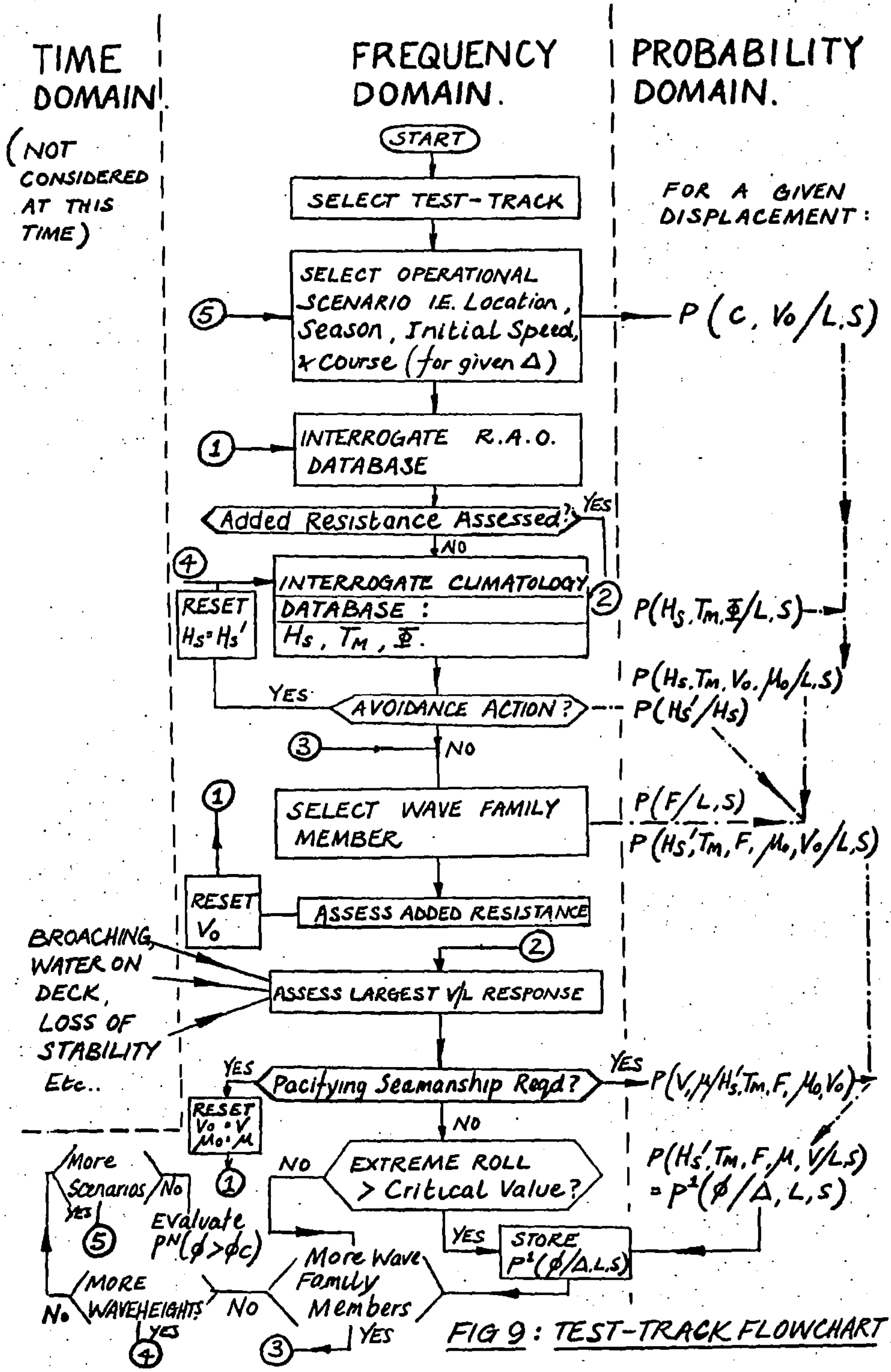


FIG 9: TEST-TRACK FLOWCHART

illustrates how a complete study would seek to encompass the time, frequency and probability domains though only the frequency and probability aspects are being considered in the present study.

The figure also indicates to which stages in the frequency domain calculation the component probabilities relate. Essentially the computer simulation reduces to the manipulation of 3 databases containing climatology, component probability and complex functioned response amplitude operator information respectively. An important feature of the RAO database is that it reflects the sensitivity of motion response to internal ship parameters such as hull form and load condition as well as to external parameters such as encountered wave conditions [36] for example.

Once a particular scenario has been established ie, the load condition and intended speed and heading for a particular location and season, the appropriate climatology and RAO information is combined to assess the degree of added resistance in waves once any avoidance seamanship (Appendix A2.3) has been carried out. With new vessel speed as argument the vessel's vertical responses are predicted and scrutinised for resulting severe motions and sealoads which are likely to cause the master to alter speed or heading (Appendix A2.3).

If these motions perceived by the master are acceptable the extreme roll response is then evaluated (Appendix 2.4). However, in the event that critical motions are exceeded the heading and/or speed is varied (conducive with best progress in the desired direction) until the perceived motions are again within acceptable limits. The vessel may have to assume a hove-to attitude at this time but in any event the roll response is still evaluated, taking account of the exposure time to each scenario through the use of the independence period (Appendix 2.2).

Provided that the roll motion is larger than the potentially dangerous value the scenario probability is carried forward for inclusion in the calculation to find the cumulative probability of critical motion exceedance, as outlined in Section 3.3. Thus the prediction method proceeds through all possible combinations of:-

a) Wave spectrum family members (max. 11)
b) Courses } Heading (7)
c) Wave primary heading } to waves
d) Significant waveheight (10)
e) Modal period (10)
f) Speeds (10)

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for a given single load condition, location and season.

It is apparent that the amount of computation for the several required load conditions, locations and seasons is potentially enormous, and while this can be reduced (from 77,000 to about 8,000) by excluding certain physically impossible seastates and by assuming that responses vary linearly with significant waveheight for the same modal period, on the other hand these aspects also introduce their own data handling difficulties.

At the present time the main calculation has not been carried out, thus it is difficult to make estimates of the eventual computing requirements. However, a recent roughly equivalent operability study [5] used about 2 hours of mainframe computer time for around 1,300 calculations the cost of which can be expected to fall as the processing capabilities of computers continue to increase. It should be emphasised that this is a once-only survivability calculation which it is being proposed should be carried out in the design stages before a vessel is even launched. No further assessment would be required unless the vessel is subsequently required to operate in different geographical zones or it undergoes alterations which materially affect its response to waves.

6. SUMMARY AND REQUIRED FURTHER WORK

In any engineering enterprise, particularly where human life is exposed to dangerous conditions, it is the responsibility of the designer as well as the statutory authorities concerned to ensure that the vehicle, structure etc, is safe, judged by the scientific knowledge of the day.

In this interim report a procedure has been outlined, which is intended as a once-only calculation, to evaluate by using independent (Bernoulli) trial concepts the probability that a "potentially dangerous" roll motion will be exceeded at least once in a series of typical missions (test-tracks) which have been identified as being representative of a vessel's operating lifetime.

In the present pilot study the interpretation of the term 'test-track' is that it represents an identified typical mission of the subject vessel. This is necessary because it is not known à priori which scenarios could cause capsizing and thus the marine equivalent of the automobile test-tracks, where individual characteristics are exclusively tested, are not derivable (until, possibly, experience has been gained with the method). However, while this causes difficulty at present for novel vessel types, the proposed present analysis is able to incorporate specific scenarios which historic casualty data have indicated as frequently recurring and potentially capsize causing. (using pattern recognition analysis)

It is felt that, while the results obtained are not likely to be mathematically rigorous, the proposed overall framework is of vital importance since:-

a) The problem of vessel capsizing is a pressing one which cannot wait until every aspect of every analytical technique has been perfected.

b) There exists a patchwork of analytical and experimental techniques for predicting the various capsize phenomena and these ultimately need to be fitted into an overall risk framework.

c) Lack of mathematical rigour does not prevent the results generated being used in a comparative manner in these early stages.

d) It will highlight areas for further research.

Thus the proposed method is primarily a framework for evaluating, in a realistic manner, the effects of the variation in demand and capability which will enable the comparative risk of a critical roll motion being exceeded while accounting for likely operational scenarios. There are 6 basic elements to consider:-

(i) Identify the critical scenarios which give rise to large roll motion and possible capsize.

(ii) Assign the probability of encountering each of the critical scenarios which have been identified in (i).

(iii) Predict the 6 degrees of freedom motion response for each operational scenario.

(iv) Manipulate scenario responses and associated probabilities using independent (Bernoulli) trial procedures to find the probability that a critical roll response will be exceeded at least once during an individual typical mission as well as during a lifetime of operation.

(v) Compare the probabilities obtained against an accepted risk level.

(vi) Adjust the operational procedures and/or the design to improve the risk levels (if necessary).

Unfortunately the procedure raises more questions than it answers. Given that a full treatment, as proposed, would reflect the risk of a large roll motion being exceeded by all of the mechanisms which have been identified eg, broaching-to, Mathien effect etc, etc, there still remain some fundamental unanswered questions which would form research projects in their own right, eg:

(i) Is roll angle alone a sufficient description of the capsize potential?

(ii) What assurance against capsize risk is acceptable to the industry since perfect safety is not possible?

(iii) How may the risks be reduced to the acceptable standard?

(iv) Can the method yield a set of stability criteria as simple to enforce as those currently in use?

A large angle prediction method to incorporate all of the non-linearities and to take account of the associated dynamic effects will probably be a long time coming. Thus, it is particularly important that a method which seeks to predict the onset of capsize has a proper measure of potentially dangerous motion which may contain velocity and/or acceleration terms. The illustration of such a joint probability process is shown in Fig 10. (By assuming narrow bandedness of the response the roll angle, velocity and acceleration can be shown to be independent processes and the probability of a critical angle/velocity combination being exceeded can thus be deduced. This is represented by the shaded portion in Fig 10).

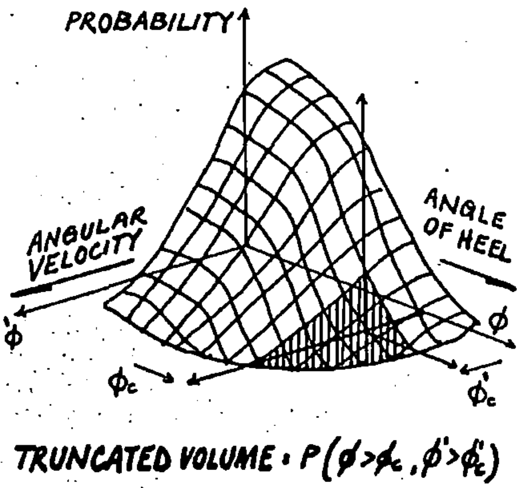

Fig 10

Unfortunately little is known about what the critical values of velocity/ acceleration should be. Whilst it is reasonably possible to set limiting acceleration values, for example on the cargo lashings, it is no simple matter to do the same for bulk cargoes let alone to consider sliding 'liquefaction' instability of damp fine grained minerals for example [17].

Assuming that the capsize phenomenon can be quantified the issue of acceptable risk levels is a vexing one. Essentially the analysis of costs versus benefits, such a measure of acceptable risk seeks to incorporate the 'value' of a human life [21] and to assess how an individual accepts risk whether consciously or unconsciously. It seems reasonable that a starting point is to demonstrate that an individual's risk of fatality has been reduced by appropriate measures which arise from the type of analysis proposed, without involving oneself in absolute values of risk (provided that they are comparable with the majority of current 'equivalent' industrial risks). In any event absolute safety cannot ever be guaranteed and an appropriate acceptable risk level is needed as the measure of survivability.

Ultimately, through refinement of the method it may be possible to formulate a set of stability criteria which take realistic account of the environmental and operational variations and yet are as simple to apply as the current regulations. However, simplicity of application is no longer a strict necessity given the potential speed and capacity of the new generation of parallel-processor computers, and thus a standard agreed procedure would seem most appropriate for future stability requirements (with an appropriate risk of capsize as the desirable aim). Indeed it is more important that one builds into the procedure the experience of serving ship's officers and crews.

The proposed method is very much a first attempt and contains many areas for further research. In addition to the obvious uncertainties inherent within the motions prediction there is also uncertainty regarding the value of the independence period T_* which determines the number of independent trials, N_* in a domain segment and thus the probabilities obtained.

Finally, although the method is initially being applied to a 64 m fisheries protection vessel it is actually suitable for any fixed or moving ocean vehicle or structure. Perhaps one day these might even individually be licensed to operate in specific areas with known risk levels from both an operability and survivability point of view.

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NOMENCLATURE

C	Vessel (true) course
D	Domain
F	Wave spectrum family member
H_s, H_s'	Significant Waveheight before/after avoidance seamanship
k_{xx}, k_{yy}, k_{zz}	Radius of gyration with respect to axes
L	Geographical location
L_*	Independence distance
N, N_*	Number of independent trial samples
Q	Identical test-track number
R	Domain segment length
S	Season
T, T_*	Independence period
T_m	Mean wave period
V_o, V	Ship speed before/after pacifying seamanship
$\gamma_\phi, \gamma''_\phi$	Counting functional with respect to roll angle/acceleration
Δ	Displacement
μ_o, μ	Relative heading to waves before/after pacifying seamanship
σ	Random variable
σ_c	'Critical' random variable
ϕ, ϕ', ϕ''	Roll angle/velocity/acceleration
$\phi_c, \phi'_c, \phi''_c$	Critical (potentially dangerous) roll angle/velocity/acceleration
Φ	Predominant wave direction
$P(\sigma)$	Probability density
$P^1(\sigma)$	Single independent trial probability
$P^N(\sigma)$	Multiple independent trial probability
$P^1(\sigma_c<\sigma)$	Cumulative single trial probability of $(\sigma_c<\sigma)$
$P^N(\sigma_c<\sigma)$	Cumulative multiple trial probability of $(\sigma_c<\sigma)$

REFERENCES

(1) Aerttsen, G et al; "Service Performance and Seakeeping Trials on Two Conventional Trawlers". Trans NEC 1965.

(2) Aerttsen, G; "Service Performance and Seakeeping Trials of MV Jordaens". Tran RINA Vol 108, 1966.

(3) Aldwinckle, D S et al; "Reliability and Safety Assessment Methods for Ships and Other Installations", Lloyds Register of Shipping Report No 82, 1983.

(4) Andrew, R N et al; "Full Scale Comparative Measurements of the Behaviour of Two Frigates in Severe Head Seas", Trans RINA, Vol 123, 1981.

(5) Andrew, R N et al; "The Assessment of Ship Seakeeping Performance in Likely to be Encountered Wind and Wave Conditions", Intl Symp on Wave and Wind Climate Worldwide, RINA 1984.

(6) Andrews, K S et al; "Wave Climate Synthesis", NMI Report R149, January 1983.

(7) Baitis, A E et al; "Human Factors Considerations Applied to Operations of the FFG8 and Lamps Mk III, ASNE Day 1984.

(8) Bales, S et al; "Standardized Wave and Wind Environments for NATO operational areas", DTNSRDC Report SPD 0919-01 July 1981.

(9) Bird, H et al; "State of Art; Past, Present and Future", Intl Conf on Stability of Ships and Ocean Vehicles, Glasgow 1975.

(10) Bledsoe, M D et al; "Seakeeping Trials on Three Dutch Destroyers", Trans SNAME, Vol 68, 1960.

(11) Brook, A K; "A practical assessment of the rolling behaviour of ships at the design stage and in service", BSRA Contract Report W1067 (Confidential).

(12) Caldwell, J B; "The Theory and Synthesis of Thin-Shell Ship Structures".

(13) Chatfield, C; "Statistics for technology", Chapman and Hall (publ) 1981.

(14) Chazal, E A; "Status Report on the Application of Stress and Motion Monitoring in Merchant Vessels", SNAME STAR Symp 1980.

(15) Conolly, J E; Standards of Good Seakeeping for Destroyers and Frigates in Head Seas", Intl Symp Dynamics of Marine Vehicles in Waves, Inst Mech Eng, 1975.

(16) St Denis, M et al; "On the Motions of Ships in Confused Seas" Trans SNAME 1953.

(17) Green, P V et al; "Behaviour of Damp Fine-grained Bulk Mineral Cargoes", Trans (TM) Inst Marine Engineers, 1981.

(18) Hogben, N et al; "Ocean Wave Statistics", HMSO, London 1967.

(19) Hosodo, R et al; "A Method for Evaluation of Seakeeping Performance in Ship Design Based on Mission Effectiveness Concept".

(20) Hutchison, B. L; "Risk and Operability Analysis in the Marine Environment", SNAME (Trans) Vol 89, 1981.

(21) Jenssen, T K; "Risk Criteria for marine and related activities", Det Norske Veritas Technical Report 76-240, 1976.

(22) Kastner, S; "Simulation and Assessment of Roll Motion Stability", 2nd Intl Stability Conference, Tokyo, 1982.

(23) Kehoe, J W; "Destroyer Seakeeping - Ours and Theirs", Proc US Naval Inst 1973.

(24) Lloyd, A R J M et al; "Criteria for ship speed in Rough Weather", 18th Am Towing Tk Conf Vol 2, 1977.

(25) Lloyd, A R J M; "Ship Motions, Wind and the Helicopter", Symp on Helicopters and the Marine Environment, Royal Aeronautical Society. June 1982.

(26) Maruo, H; "The Excess Resistance of a ship in a rough sea" Intl Shipbuilding Progress, Vol 4, No 35, 1957.

(27) Ochi, M K; "On Prediction of Extreme Value", Jnl of Ship Research, Vol 17, 1973.

(28) Ochi, M K; "Prediction of Slamming Characteristics and Hull Responses for Ship Design", Trans SNAME, Vol 81, 1973.

(29) Ochi, M K; "Wave Statistics for the Design of Ships and Ocean Structures", Trans SNAME, Vol 86, 1978.

(30) Ochi, M K et al; "Effect of Various Spectral Formulations in Predicting Responses of Marine Vehicles and Ocean Structures", 9th OTC, Houston, 1977.

(31) Ochi, M K; "A Series of Jonswap Wave Spectra for Offshore Structure Design", 2nd Intl Conf on Behaviour of Offshore Structures, London, 1979.

(32) Ochi, M K; "On 6-parameter wave spectra", Proc 15th Conf on Coastal Engineering, 1976.

(33) Personal Correspondence;

(34) Rahola, J;
"The Judging of the Stability of Ships" and the Determination of the Minimum Amount of Stability PhD Thesis, Helsinki, 1939.

(35) Roberts, J B et al;
"A Probabilistic Model of Ship Roll Motions for Stability Assessment", Intl Conf on the Safeship Project, RINA June 1986.

(36) Schmitke, R T;
"The Influence of Displacement, Hull Form, Appendages, Metacentric Height and Stabilization on Frigate Rolling in Irregular Seas" SNAME STAR Symp, June 1980.

(37) Schoenberger, R W;
"Subjective Response to Very Low Frequency Vibration", Aviation, Space and Environmental Medicine. June 1975.

(38) Stiansen, S G et al;
"Reliability Methods in Ship Structures", RINA 1979 Spring Papers.

(39) Varheim, R et al;
"Small Cargo Vessels which have capsized in Heavy Weather", Seminar on Norwegian "Ships in Rough Seas" (SIS) Project, RINA (publ) 1982.

(40) Williams, A R et al;
"The Design and Use of the Dunlop/MIRA handling and stability circuit" Conference on Road Vehicle Handling, Nuneaton 1983.

APPENDIX 1: INDEPENDENT (BERNOULLI) TRIAL CONCEPTS

a) Independence of samples or random processes is an important concept. Independence can be defined as existing if either of the following two conditions are satisfied [13]:-

i) $P(A/B) = P(A)$ [and $P(B/A) = P(B)$]

is the probability of A given that B has already occurred is the same as the probability of A regardless of whether B has occurred.

ii) $P(A,B) = P(A).P(B)$

ie, the joint probability of A and B occurring is the product of the probabilities of A and B occurring separately.

Another way of looking at (i) is that for an independent trials process the sampling process does not alter the underlying probability for the next individual trial, thus knowing that an event has occurred has no bearing on the next event to occur.

b) In general, the probability of at least one event (σ) in N independent trials is

$$P^N(\sigma) = 1 - [P^1(\bar{\sigma})]^N$$

where $P^N(\sigma)$ = probability of at least one event σ in N independent trials. $P^N(\sigma)$ varies not quite linearly with the value of N [20].

$P^1(\bar{\sigma})$ = probability of not obtaining the event σ on a single independent trial.

Specifically, when considering the probability of roll motion (ϕ) exceeding a critical value (ϕ_c) in N independent trials.

$$P^N(\sigma_c<\sigma) = 1 - [P^1(\sigma_c>\sigma)]^N$$

$$= 1 - [1-P^1(\sigma_c<\sigma)]^N.$$

APPENDIX 2: FACTORS FOR CONSIDERATION

Fundamentally each test-track reduces into the four considerations of Route, Climatology, Seamanship and Response. A full treatment of these aspects is beyond the scope of the present work. However, an underlying aim is to render them useful for regulatory purposes, through simplification without undue loss in realism.

A2.1 Route

The route embodies consideration of geographical location (L), season (S), initial or intended course (C) and initial speed (V_o). The problem of determining the route is to determine the joint probability distribution of the location, season, initial course and initial speed ie, $P(L,S,C,V_o)$.

Consideration of the test-track segment being used will govern the joint probability of location and season, P(L,S) where L is actually representing a distance along the vessels intended track for which the displacement condition ($\Delta, k_{xx}, k_{yy}, k_{zz}$) can be assumed constant. The test-track segment also governs the conditional probability distribution of initial course and speed given the location and season, $P(C,V_o/L,S)$.

Then the required probability

$$P(L,S,C,V_o) = P(C,V_o/L,S).P(L,S).$$

A2.2 Climatology

This aspect is of vital importance in the analysis and, despite increased effort, is still far from resolved. It is required to determine the conditional probability of significant waveheight (H_s), mean wave period (T_m), wave spectrum family member (F) and predominant wave direction (ϕ) given a location (L) and season (S) ie,

$$P(H_s,T_m,F,\phi/L,S) = P(F/L,S).P(H_s,T_m,\phi/L,S).$$

The necessary climatological data, $P(H_s,T_m,\phi/L,S)$ are to be found in many formats and in many sources [6, 8, 18]. Reference [8] is an extensive database which is convenient and has been chosen for use in the present study. It contains climatological data for different geographical areas and seasons of the year. An important recent development has been a method for correcting the masses of raw visual observations held in many meteorological archives [6].

A further consideration is how realistic are the predicted responses if we use the commonly available simple spectral formulations such as Pierson-Moskowitz, Bretschneider's two-parameter, Darbyshire's fetch-limited etc, which have been developed for some idealised conditions? In reality the shape of wave spectra observed in the ocean varies considerably (for the same waveheight) depending upon the geographical location, duration and fetch of wind, stage of growth and decay of a storm, and existence of swell.

Unfortunately data is very scarce regarding the occurrence and severity of severe seas and this data is particularly important in an extreme risk analysis. Ochi [29] presents a method to estimate the frequency of occurrence of seas of various severity from available data based on the underlying probability function. He also presents a method to predict the severest sea condition likely to be encountered.

In order to cover a variety of spectral shapes which a vessel may encounter in her lifetime two families of wave spectra are used in the present work. One of the familes consists of 11 members for an arbitrarily specified sea severity and is called the Ochi-6 parameter wave spectral family.

$$\Phi\zeta(\omega) = \frac{1}{4}\sum_j \frac{\left(\frac{4\lambda_j+1}{4}\cdot\omega_{mj}^{\,4}\right)^{\lambda_j}}{\Gamma(\lambda_j)} \cdot \frac{H_{sj}^{\,2}}{\omega^{4\lambda_j+1}} \cdot$$

$$e^{-\frac{(4\lambda_j+1)}{4}(\omega_{mj}/\omega)^4}$$

where j = 1,2 stands for the lower and higher frequency components respectively.

An example is given in Fig 11 for a significant waveheight of 3 m using the values, which were derived from 800 available spectra observed in the North Atlantic [32]. Consideration of the underlying spectrum parameter probability functions yields the required probability of encountering in a given location and season the particular wave spectrum family member, P(F/L,S).

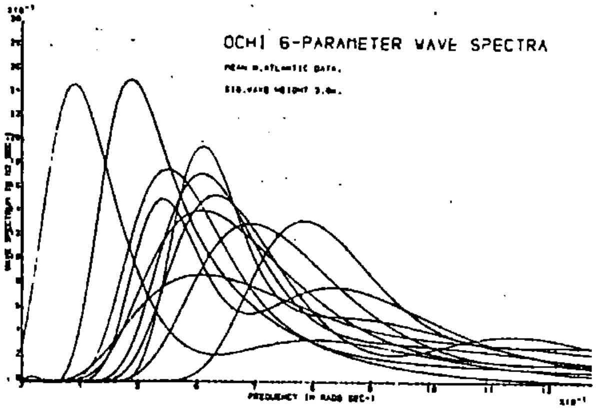

Fig 11

6-Parameter Spectrum

It should be noted that the 6-parameter wave spectrum family covers a wider variety of shapes than other commonly used spectra and that some have double peaks indicating the co-existence of swell and sea waves.

In using the Ochi-6 parameter family of wave spectra for the short-term prediction for each sea severity, one of the family members yields the largest response with confidence coefficient of 0.95 while another yields the smallest response with confidence coefficient 0.95. Hence by connecting the points obtained in each sea severity, the upper and lower response bounds can be established eg, Fig 12.

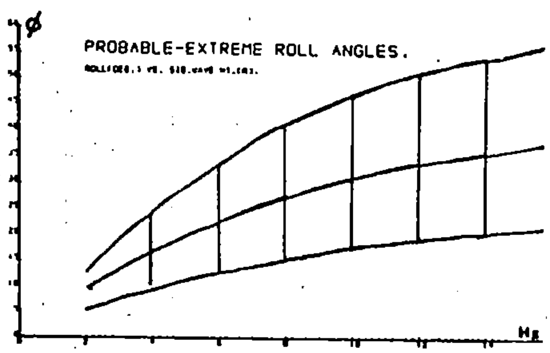

Fig 12

Probable Extreme Roll Angle

Ochi and Bales [30] have demonstrated that, for a range of vessels and offshore structures, the bounds obtained by using the 6-parameter family with N Atlantic data reasonably covers the variation of responses computed using measured spectra in various locations of the world. Fig 13.

A similar analysis has been performed for a family of Jonswap wave spectra suitable for fetch limited seas, to cover the variation in expected spectral shape [31].

The current investigation uses both 6-parameter and Jonswap spectral families for open-sea and fetch limited seas respectively.

In order to account for short-crestedness of the seaway and following the recommendation in [8] from which the wave climatology is extracted, cosine squared spreading of wave energy is assumed. This aspect requires further attention by oceanographers.

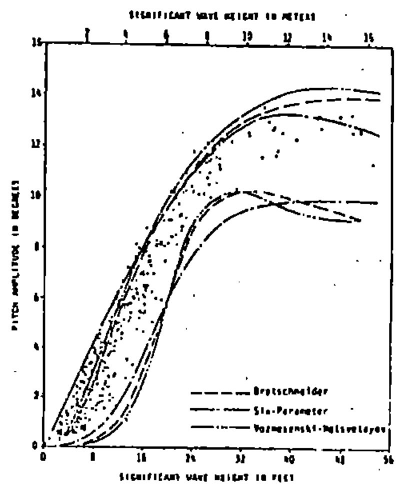

Fig 13

Mariner Probable Extreme Pitch Values (head seas)

A2.3 Seamanship

This factor can have a large influence on both the motion probabilities obtained and the motions themselves once the severe seastates have been encountered. Firstly, by manoeuvring to avoid a storm area (or in the case of certain particularly small vessels by not sailing at all until the storm has passed) the vessel is using avoidance seamanship. This is a function of the accuracy of weather forecasts and the skill of the ship's officers. Secondly a vessel experiencing excessive motions and sea loads may be manoeuvred to reduce these to perceived acceptable levels. The vessel is using what might be termed pacifying seamanship which is a function of the motion/sea loads information available to the ship's officers and their skill in reducing these motions and sea loads.

Avoidance type seamanship can be represented by a Markov mapping [20] ie, P(i/j) from the probability of encountering each seastate in the absence of avoidance seamanship to the probability of encounter with avoidance seamanship. An example transition matrix $P(H_s'/H_s)$ is given in Table 6 where H_s' is the seastate encountered after avoidance action and H_s the seastate which would have been obtained in the absence of avoidance action.

Pacifying seamanship consists primarily in changes of speed and/or heading once a severe seastate has been encountered. These can be represented as conditional properties of speed, V and relative heading to waves, given the seastate actually encountered after appropriate avoidance (H_s', T_m, F) and unaltered speed V_o and relative heading μ_o ie, $P(V, \mu / H_s', T_m, F, V_o, \mu_o)$ where μ, μ_o are functions of ship course C and wave direction ϕ.

Encountered seastate after avoidance seamanship H_s'		Seastate which would have been encountered H_s: 1	2	3	4	5
	1	1.0	0	0	0	0
	2	0	1.0	0.2	0	0
	3	0	0	0.8	0.5	0.1
	4	0	0	0	0.5	0.6
	5	0	0	0	0	0.3
		1.0	1.0	1.0	1.0	1.0

Table 6

Ship speed in a seaway comprises the involuntary speed reduction due to the added resistance and reduced propulsive efficiency in waves together with the voluntary speed reduction due to the master's action to reduce excessive motions and sea loads.

Although the present study is primarily concerned with the higher seastates where master's voluntary action overrides any consideration of natural speed reduction, nevertheless the approximate increase in added resistance is accounted for by using a conveniently available method due to Maruo [26], to estimate the initial attained speed of the vessel on any heading. This is an area requiring further work but recourse can be made to experimental results if necessary.

The problem of voluntary slowdown/ change of heading criteria to reduce motions and loads is no less difficult. It is inevitable that any proposed criteria will be subjective ie, based upon the master's previous experience, will depend upon how well the master perceives the motions and loads from his conning position, and will also be vessel dependent.

Once criteria have been agreed a more objective response from the master should be possible, if suitable instrumentation is provided, to indicate the motions and loads being imposed together with suggested critical motion/load limits and even possible optimum courses of action to reduce these to acceptable levels. [14]

In the meantime, and for the purposes of the present study, it has been necessary to assign a set of criteria which it will be assumed the master will adhere to in order that his vessel will be rendered more seakindly. The master is likely to take action to avoid damage to his vessel's structure, engines, or cargo and to avoid undue discomfort to his passengers and crew. There have been several studies with both merchant and warships eg, [1,2,10,15,23] into limiting motion criteria for different types of vessel, but several of the proposed criteria suffered from the drawback that they could not be readily assessed from the master's conning position and were also not relevant to the environment being experienced by the crew. For example Conolly proposed a criterion based upon slamming at 0.2 L bp abaft the fore perpendicular [15] and Aerttsen used the amplitude of acceleration at the fore perpendicular [2]. To address these deficiencies Lloyd and Andrew [24] proposed the following measures of ship behaviour in connection with predictions of voluntary speed loss in rough weather:-

i) Slam-induced whipping vibration acceleration at bridge not to exceed 0.05 g in a 15 minute sampling period.

ii) Subjective motion magnitude (SM) weighted according to personnel location and averaged along ship length SM = 15.

iii) Average deck wetness interval at F.P. not less than 100 secs.

iv) Average propeller emergence interval to be greater than 30 secs.

The actual estimates for the limiting conditions were based on seakeeping trials with destroyers [10] and the cargo ship JORDAENS [2].

The Slamming Criterion [1] has been subsequently amended because it is possible, by using the original criterion, to apparently improve the seakeeping performance by moving the bridge to the region of a node where there is no whipping response and thus no speed limitation. The amended slamming criterion refers to the "average whipping acceleration experienced over the entire ship" which should not exceed 0.18 g and is based on full scale trials with 2 frigates [4]. Aertssen, meanwhile in the discussion to [4] proposed a value of 0.20 g for the bridge whipping acceleration based on trials with the trawler Belgian Lady [1].

The Subjective Motion Magnitude (SM) concept [24] attempts to quantify the motion environment within the ship experienced by the crew and to relate this to human response to ship motions. The original concept was proposed by Schoenberger [37].

Whilst subsequent full scale trials and results of questionnaires have borne out the original proposed SM value of 12-15 over a 12 hour period in head seas, and it is therefore expected that higher values might be tolerable in the short term, it is generally agreed that a subjective magnitude criterion should not be based solely upon vertical accelerations in head seas but that rolling and lateral plane motions should also be accounted for in one single SM value if possible. Hosodo et al [19] proposed a method based on reliability engineering techniques by treating the human being as a series system and obtained an overall "human effectiveness" by multiplying individual effectiveness appropriate to each motion level being experienced. Baitis et al [7] also reported studies to determine criteria for limiting motions based on vertical with lateral forces.

The average deck wetness interval has been changed to 40 seconds following full scale trials [4], although this figure takes no account of sensitive equipment or men on deck. The above represents a great deal of ongoing work which, for the reasons outlined, are inconclusive except for some particular full scale trials results, mostly on 2 frigates. For this reason the following limiting motion criteria will be assumed in the present study.

Criterion	Fisheries Protection (64m)	Stern Trawler (58M)
No of slams +	60 per hour	60 per hour
SM ǂ	12	15
No of deck wetness ‡	90 per hour	90 per hour
No of propeller emergences	120 per hour	120 per hour

Table 7

[All of these values reflect the calculation assumptions and do not therefore necessarily reflect the physical situation observed].

NB + For this length of vessel slamming whipping is not considered a problem. A slam is deemed to occur when the impact velocity > 0.093 $(g/L)^{1/2}$ [28].

ǂ Especially relevant in a survivability study when the master will aim to keep the seas on the bow.

‡ Method of calculation takes no account of distortion by hull of incident waves nor static/dynamic swell-up.

If the subject vessel exceeds one or more of these motion criteria it will be caused to alter heading/speed conducive to the continued "success" of the mission, which will reduce the motions to acceptable levels, otherwise the vessel will achieve a hove-to position if motions and loads cannot be reduced to acceptable levels.

A2.4 Responses

In Section 4.1 the concept of a "potentially dangerous" roll angle was introduced. This was stated to be a pre-assigned roll angle (30 degrees in the present case) beyond which it can be assumed that the vessel will be considered potentially unsafe from a capsize point of view. Before the required probability of exceedance of the potentially dangerous roll motion ϕ_c can be ascertained, $P(\phi > \phi_c)$ an appropriate response statistic ϕ is required. For operability studies this ϕ-response is likely to be an average-type process such as the significant roll response, whereas when considering survivability some measure of the expected maximum is required.

A useful development by Ochi [27] is the extreme response value which will be exceeded with a pre-assigned small probability, the 'design-extreme value'. This is necessary because the most probable extreme value $\bar{\sigma}_n$, which can be used for comparison with the observed extreme value, has a high probability (0.632) of being exceeded for a large number of observations n, if the process is narrow band, where the <u>most probable extreme value</u>:-

$$\bar{\sigma}_n = \sqrt{2 l_n \left\{\frac{2\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\, n\right\}}\sqrt{m_o} \quad \text{for } \epsilon \leqslant 0.9$$

and ϵ is the spectral bandwith parameter of the σ process.

$$\epsilon = \sqrt{\frac{m_o m_4 - m_2^2}{m_o m_4}}$$

where m_o, m_2, m_4 are the zeroth, second and fourth moments of the response process.

In terms of exposure time. the most probable extreme value $\bar{\sigma}_T$ is given by [27].

$$\bar{\sigma}_T = \sqrt{2 \ln\left\{\frac{60^2 T}{2\pi}\sqrt{\frac{m_2}{m_o}}\right\}}\sqrt{m_o}$$

where T = exposure time in hours. (It is argued in Ref [20] that T should be the independence period T_*). The <u>design extreme value $\hat{\sigma}$</u> is similarly given in terms of number of observations and exposure time:-

$$\hat{\sigma}_n = \sqrt{2 \ln\left\{\frac{2\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\cdot\frac{n}{\alpha}\right\}}\sqrt{m_o}$$

$$\hat{\sigma}_T = \sqrt{2 \ln\left\{\frac{60^2 T}{2\pi_\alpha}\sqrt{\frac{m_2}{m_o}}\right\}}\sqrt{m_o}$$

for small α and for $\epsilon \leqslant 0.9$.

Choosing α as 0.01 for example, implies that only one vessel in 100 sister vessels operating under statistically identical environments may suffer from a response greater than the predicted value in a given period of time.