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AN ADAPTABLE MATHEMATICAL MODEL FOR INTEGRATED NAVIGATION SYSTEMS

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AN ADAPTABLE MATHEMATICAL MODEL FOR INTEGRATED NAVIGATION SYSTEMS

by

JOHN CHUDLEY

A thesis submitted to the University of Plymouth
in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

School of Computing
Faculty of Technology

In collaboration with
Kelvin Hughes Ltd

February 1994

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AN ADAPTABLE MATHEMATICAL MODEL FOR INTEGRATED NAVIGATION SYSTEMS

JOHN CHUDLEY

ABSTRACT

The project has been directed towards improving the accuracy and safety of marine navigation and ship handling, whilst contributing to reduced manning and improved fuel costs. Thus, the aim of the work was to investigate, design and develop an adaptable mathematical model that could be used in an integrated navigation system (INS) and an automatic collision avoidance system (ACAS) for use in marine vehicles.

A general overview of automatic navigation is undertaken and consideration is given to the use of microprocessors on the bridge. Many of these systems now require the use of mathematical models to predict the vessels' manoeuvring characteristics. The different types and forms of models have been investigated and the derivation of their hydrodynamic coefficients is discussed in detail. The model required for an ACAS should be both accurate and adaptable, hence, extensive simulations were undertaken to evaluate the suitability of each model type.

The modular model was found to have the most adaptable structure. All the modular components of this model were considered in detail to improve its adaptability, the number of non-linear terms in the hull module being reduced. A novel application, using the circulation theory to model the propeller forces and moments, allows the model to be more flexible compared to using traditional B-series four-quadrant propeller design charts. A new formula has been derived for predicting the sway and yaw components due to the propeller paddle wheel effect which gives a good degree of accuracy when comparing simulated and actual ship data, resulting in a mean positional error of less than 7%.

As a consequence of this work, it is now possible for an ACAS to incorporate a ship mathematical model which produces realistic manoeuvring characteristics. Thus, the study will help to contribute to safety at sea.

CONTENTS

Contents			Page No
	CONTENTS		i
	LIST OF FIGURES		vi
	LIST OF TABLES		ix
	LIST OF PLATES		x
	ACKNOWLEDGEMENTS		xi
	DECLARATION		xii
	NOMENCLATURE		xiii
1.	INTRODUCTION.		
	1.1	Prelude.	1
	1.2	System development.	2
		1.2.1 Collision avoidance.	4
	1.3	Objectives.	6
	1.4	Organisation of the thesis.	7
2.	AUTOMATIC NAVIGATION.		
	2.1	Introduction.	11
	2.2	Marine electronic navigation systems.	12
	2.3	Factors in the development of automatic navigation.	14
	2.4	The use of microprocessors on the bridge.	17
		2.4.1 Integration of navigational data.	18
	2.5	Integrated navigation systems.	21

2.6 Conclusion. 22

3. MATHEMATICAL MODELS IN SHIP MANOEUVRING.

3.1 Introduction. 24
3.2 Definition and general form of the mathematical model. 25
3.3 Types of mathematical model. 28
3.3.1 The input-output relationship model. 29
3.3.2 The holistic model. 30
3.3.3 The force mathematical model. 31
3.3.4 The modular manoeuvring model. 33
3.4 Hydrodynamic coefficients. 34
3.4.1 Derivation of hydrodynamic coefficients. 35

4. MODEL FORMULATION AND SIMULATION.

4.1 Introduction. 37
4.2 Manoeuvring simulations. 38
4.2.1 The holistic model. 38
4.2.1.1 Three degree of freedom linear model. 38
4.2.1.2 Four degree of freedom linear model. 39
4.2.1.3 Three degree of freedom non-linear model. 39
4.2.1.4 Four degree of freedom non-linear model. 39
4.2.2 Three degree of freedom non-linear modular model. 40
4.2.2.1 Hull forces and moments. 40
4.2.2.2 Propeller forces and moments. 41
4.2.2.3 Rudder forces and moments. 43
4.2.3 Simulations. 44
4.3 Discussion. 59
4.3.1 Three degree of freedom linear holistic. 59
4.3.2 Four degree of freedom linear holistic. 59
4.3.3 Three degree of freedom non-linear holistic. 59
4.3.4 Four degree of freedom non-linear holistic. 60
4.3.5 Three degree of freedom non-linear modular. 60

5. THE ADAPTABLE MODULAR MODEL.

5.1 Introduction. 61
5.1.1 Derivation of modules and their coefficients. 61
5.2 Hull forces and moments. 62
5.2.1 Sway and yaw terms. 62
5.2.2 Surge terms. 65
5.3 Total resistance. 65

5.3.1 Frictional resistance. 66
5.3.1.1 Form factor of the hull. 66
5.3.2 Appendage resistance. 67
5.3.3 Wavemaking resistance. 68
5.3.4 Additional resistance due to bulbous bow. 70
5.3.5 Additional resistance due to immersed transom. 70
5.3.6 Model-ship correlation resistance. 71
5.3.7 Resistance calculations. 71
5.4 Circulation theory applied to propeller modelling. 73
5.4.1 Basic circulation theory. 74
5.4.2 A mathematical approach to circulation. 76
5.4.3 Application to screw propellers. 78
5.4.3.1 Correction factors. 81
5.4.3.2 Screw performance calculations. 84
5.4.3.3 Application of calculations to a screw. 89
5.4.4 Wake distribution. 93
5.4.5 Validation of circulation theory. 96
5.4.5.1 Presentation of open water tests. 96
5.4.5.2 Validation of a B-series screw. 97
5.4.5.3 Validation of a non B-series screw. 100
5.5 Propeller Forces and Moments. 105
5.5.1 Surge terms. 105
5.5.2 Sway and Yaw terms. 105
5.6 Rudder forces and moments. 106
5.7 Additional model information. 106
5.8 Discussion. 107

6. THE PC BASED SIMULATOR.

6.1 Introduction. 108
6.2 Vessel trials. 113
6.2.1 Sand Skua trials. 113
6.2.2 Picket Boat 9 trials. 119
6.3 Comparison of actual and simulator results. 122
6.3.1 Sand Skua results. 122
6.3.2 Picket Boat 9 results. 130
6.3.3 Esso Osaka results. 133
6.4 Discussion. 140
6.4.1 Sand Skua. 140
6.4.2 Picket Boat 9. 141
6.4.3 Esso Osaka. 142
6.4.4 Conclusion. 142

7. **AUTOMATIC COLLISION AVOIDANCE SYSTEM (ACAS).**

7.1 Introduction. 145

7.2 An intelligent computer system for collision avoidance. 145

7.3 Previous work. 147

7.3.1 Criteria for decision making. 150

7.3.2 Inference engine and rule structure. 152

7.4 Ship Modelling in Collision Avoidance. 154

7.4.1 Modelling of hazard vessel. 155

7.4.2 Modelling of own vessel. 158

7.5 System validation. 158

7.6 Discussion. 161

8. **CONCLUSIONS AND FURTHER WORK.**

8.1 Introduction. 162

8.2 Conclusions. 163

8.2.1 The adaptable mathematical model. 163

8.2.2 The PC simulator. 164

8.2.3 External effects. 165

8.4 Concluding summary and future work. 166

REFERENCES. 168

APPENDIX A.

A.1 General vessel principal dimensions. A.1

APPENDIX B.

B.1 General vessel hydrodynamic coefficients. B.1

APPENDIX C.

C.1 Afterbody forms. C.1

APPENDIX D.

D.1 Adaptable model vessel dimensions and program input data. D.1

APPENDIX E.

E.1 Details of non B-series screw. E.1

E.2 Details of B-series screw. E.2

APPENDIX F.

F.1 Tank tests. F.1

APPENDIX G.

G.1 Turning circle. G.1
G.2 Zig zag manoeuvre. G.2
G.3 Direct spiral. G.3
G.5 Pull out manoeuvre. G.4

APPENDIX H.

H.1 Sand Skua trials data. H.1

APPENDIX I.

I.1 List of publications. I.1
I.2 Copies of published papers. I.2

LIST OF FIGURES

		Page No
1.1	Prototype System Schematic	2
1.2	Flow Diagram for Computer 1	3
1.3	Flow Diagram for Computer 2	4
1.4	The Anti Collision Loop	5
2.1	Costs of Navaids Against Benefits	15
2.2	Main Causes of Major Shipping Accidents 1987-1991	16
2.3	Automatic Navigation and Guidance	19
2.4	Integrated Information System	20
2.5	Kalman-Bucy Filter for GPS/INS Integration	20
3.1	Ship Axes Co-ordinate System	26
3.2	Schematic of a Typical Ship Manoeuvring System	27
3.3	Forces and Moments Acting on a Ship	32
4.1	Four Quadrant Propeller Operation	41
4.2	Open Water Results for the B4.70 Propeller Operating in Four Quadrants	42
4.3	Ratio of Induced Force on Ship Hull by Rudder Action to the Normal Rudder Force Against Hull Form Factor	44
4.4	Linear 3 Degree Holistic Model (Container Vessel)	45
4.5	Linear 3 Degree Holistic Model (Container Vessel)	47
4.6	Linear 4 Degree Holistic Model (Container Vessel)	49
4.7	Linear 4 Degree Holistic Model (Container Vessel)	51
4.8	Non-Linear 3 Degree Holistic Model (150m Ro/Ro Ferry)	53
4.9	Non-Linear 3 Degree Holistic Model (150m Ro/Ro Ferry)	55
4.10	Non-Linear 3 Degree Modular Model (Esso Osaka)	57
5.1	Structure of the Modular Model	62
5.2	Total Resistance Curve for the "Esso Osaka"	72
5.3	Total Resistance Curve for the "Sand Skua"	72

5.4	Total Resistance Curve for "Picket Boat 9"	73
5.5	Streamline Flow Around a Cylinder	75
5.6	Adjustment of Stagnation Points to Avoid Infinite Velocity at Trailing Edge	76
5.7	Circulation Flow in a Vortex	77
5.8	Tip and Axial Vortices	79
5.9	Vortex System	79
5.10	Vortex System Over a Finite Foil Span	80
5.11	Blade Velocity Diagram	81
5.12	Curvature Correction Chart	82
5.13	Goldstein Reduction Factors	83
5.14	Lift and Drag Characteristics of a Foil	88
5.15	Variation of Drag of Airfoil Sections with Thickness Ratio and Angle of Attack	88
5.16	Determination of the Angle of Attack of the Blade Section	90
5.17	Wake Distribution	94
5.18	Open Water Test Results of B4.70 Screw Series	98
5.19	Operating Characteristics for a B4.70 Screw	99
5.20	Theoretical Operating Characteristics for a B4.70 Screw	99
5.21	Theoretical and Actual Comparison for the B4.70 Screw	100
5.22	Operating Characteristics from Tank Tests	103
5.23	Theoretical Operating Characteristics	104
5.24	Theoretical and Tank Test Comparison for the Non B-Series Screw	104
6.1	Intel Microprocessor Development	108
6.2	Flow Diagram of *model.c*	110-112
6.3	Speed Reduction in a 20° Starboard Turning Circle for the Sand Skua	115
6.4	Speed Reduction in a 20° Port Turning Circle for the Sand Skua	115
6.5	Speed Reduction in a 10° Starboard Turning Circle for the Sand Skua	116
6.6	Speed Reduction in a 10° Port Turning Circle for the Sand Skua	116
6.7	20° Port Turning Circle for the Sand Skua	117
6.8	20° Starboard Turning Circle for the Sand Skua	117
6.9	10° Port Turning Circle for the Sand Skua	118
6.10	10° Starboard Turning Circle for the Sand Skua	118
6.11	5° Port Turning Circle for PB9	121
6.12	2.5° Starboard Turning Circle for PB9	121
6.13	10° Port Turning Circle (Simulated Sand Skua)	122-123
6.14	10° Starboard Turning Circle (Simulated Sand Skua)	124-125
6.15	20° Port Turning Circle (Simulated Sand Skua)	126-127
6.16	20° Starboard Turning Circle (Simulated Sand Skua)	128-129
6.17	0° Rudder Angle Showing "Paddle Wheel" Effect (Simulated Sand Skua)	129

6.18	2.5° Starboard Turning Circle (Simulated PB9)	130-131
6.19	5° Port Turning Circle (Simulated PB9)	132-133
6.20	35° Port Turning Circle (Simulated Esso Osaka)	134-135
6.21	35° Starboard Turning Circle (Simulated Esso Osaka)	136-137
6.22	36° Starboard Turning Circle (Simulated Esso Osaka)	138-139
6.23	0° Rudder Angle Showing "Paddle Wheel" Effect (Simulated Esso Osaka)	140
6.24	Comparison of Adaptable and Modular Models	143-144
7.1	Multiple Look Ahead Simulation	151
7.2	Collision Avoidance Decision Network	153
7.3	Effects of ACAS on a Sample of 1000 Randomly Generated Encounter Situations	159
7.4	Comparison of 'Arc' and 'Adaptable' Models in a Crossing Situation	160
7.5	Comparison of 'Arc' and 'Adaptable' Models in a Head On Situation	161
8.1	Structure of the Modular Model	163
8.2	Turning Circle for the Esso Osaka with Wind and Tide	165

LIST OF TABLES

		Page No
5.1	Signs of the Hydrodynamic Derivatives	64
5.2	Stern Shape Coefficient	67
5.3	Approximate $1+k_2$ Values	68
5.4	Determination of the Actual Angle of Attack	91
5.5	Determination of the Actual Performance Data of the Blade Element	91
5.6	Performance Calculations	92
5.7	Initial Wake Fractions for Approach Speed	95
5.8	Wake Fractions for Final Speed	96
5.9	Theoretical Prediction for the B-Series Screw	98
5.10	RNEC Open Water Test Results	101
5.11	Theoretical Prediction for the Non B-Series Screw	103
6.1	Sand Skua Turning Circle Error	141
6.2	PB9 Turning Circle Error	141
6.3	Esso Osaka Turning Circle Error	142
7.1	Value of D' for Various Ship Types	156

LIST OF PLATES

		Page No
5.1	The Underwater Housing of the Towing Carriage	102
5.2	Towing Tank at the Royal Naval Engineering College	102
6.1	The "Sand Skua"	114
6.2	"Picket Boat 9"	120
7.1	Expert System Icon Pop-up Menu	148
7.2	"Tracks" Window Pop-up Menu	148
7.3	Response to Repeated Activation of Expert System	149

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- Past and present researchers of the 'Marine Dynamics Research Group'.
- My family, for their understanding and encouragement throughout.
- Above all, my wife Judith, for her constant encouragement and support.

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 CNAA or of a university.

Publications by the author, in connection with this research, are included at the end of the thesis.

J. [signature]

6/5/94

NOMENCLATURE

A_{BT}	Transverse sectional area of the bulb
A_o	Propeller disc area
B	Beam of vessel
cp	Tangential propeller velocity
C_B	Block coefficient
C_M	Midship area coefficient
C_P	Prismatic coefficient
C_T	Thrust coefficient
C_{WP}	Waterplane area coefficient
D	Propeller Diameter
D'	Non-dimensional tactical diameter
D_T	Tactical diameter
F_n	Froude number
GM	Metacentric height
I_X	Moment of inertia about x axis
I_Z	Moment of inertia about y axis
K	Hydrodynamic roll moment
L	Ship length between perpendiculars
m	Mass of ship
n	Propeller revolution rate
N	Hydrodynamic yaw moment
N_v, N_r etc.	Yaw hydrodynamic derivatives
P	Propeller pitch
p	Roll rate
R	Propeller radius
R_n	Reynolds number
r	Yaw rate
T	Propeller thrust
T	Draught of vessel
t	Thrust deduction fraction

u	Forward velocity
up	Axial propeller velocity
v	Lateral velocity
v_a	Velocity of advance
v_s	Ship speed
v_x	Mean longitudinal velocity at x
w	Wake fraction
X	Hydrodynamic surge force
X_v, X_r etc.	Surge hydrodynamic derivatives
x_h	Hub radius coefficient
Y	Hydrodynamic sway force
Y_v, Y_r etc.	Sway hydrodynamic derivatives
δ	Rudder angle
ε	Hydrodynamic advance angle
ϕ	Angle of roll
ψ	Angle of yaw
∇	Displaced volume of vessel

The following shorthand notation has been adopted;

$$X_u = \frac{\partial X}{\partial u}, \quad \overline{X}_{uu} = \frac{1}{2}\frac{\partial^2 X}{\partial u^2}, \quad \overline{X}_{uuu} = \frac{1}{6}\frac{\partial^3 X}{\partial u^3}$$

CHAPTER 1

INTRODUCTION

1.1 Prelude

The work that has been undertaken was initiated as part of a research and development programme, involving the former Ship Control Group of Polytechnic South West (now the Marine Dynamics Research Group of the University of Plymouth), in collaboration with Kelvin Hughes Ltd. The project was directed towards improving the accuracy and safety of marine navigation and ship handling, whilst contributing to reduced manning and improved fuel costs. The aim of the work covered by the group was to investigate, design and develop an integrated navigation and automatic collision avoidance system (ACAS) for use in marine vehicles.

The purpose of the research covered in this thesis was to develop an *adaptable mathematical model* that can be used in the ACAS, or similarly, in the control software. An *adaptable mathematical model* should be able to simulate any vessel to which the proposed system is fitted, without requiring time consuming and expensive trials to formulate the hydrodynamic coefficients. The different types and form of model are investigated and the derivation of their hydrodynamic coefficients discussed. The model required should be both accurate and adaptable, hence, extensive simulations are undertaken to evaluate the suitability of each model type. The model found to have the most flexible structure will be considered in detail to improve its adaptability. The propeller forces and moments will be modelled using the circulation theory, this allows the model to be more flexible compared to using traditional B-series four-quadrant propeller design charts, as is done at present. A new formula will be derived for predicting the sway and yaw components due to the propeller paddle wheel effect. As a consequence of this work, it will be shown possible for an ACAS to incorporate a ship mathematical model which produces realistic manoeuvring characteristics. Thus, the study will help to contribute to safety at sea.

The research programme presented was initiated in 1989 and has been undertaken on a part-time basis since, the author being employed as a lecturer in marine technology. It is for this reason that during the thesis it will be seen that some of the work in the overall programme has been completed at an earlier date.

1.2 System Development

A schematic diagram of the full integrated navigation system is shown in figure 1.1. The system comprises two computers linked together by a parallel interface, the tasks of which are shown in figures 1.2 and 1.3. These diagrams show the primary functions of each computer. However, as well as performing the tasks shown, each computer will perform background computations, such as disturbance modelling, detection of errors in ship's instrumentation and user interface activities.

The filtering and initial control aspects were investigated by Miller (1990) and this work was continued by Mayo (1993). A new joint research project was instigated in 1992 involving Kelvin Hughes and three other academic institutions of which the University of Plymouth is one. Witt (1993), as a result of this project, is undertaking research into the use of neural networks for autopilot applications. The relevance in referencing these previous and ongoing projects is to highlight the purpose of the research undertaken and presented in this thesis. Figure 1.1, showing the prototype system schematic, indicates that the central element, and hence the most important aspect, is the mathematical model. This mathematical model should be adaptable and easily formulated so as the system can be fitted as an integral part of the integrated system, on any vessel, without requiring expensive sea trials or model tests.

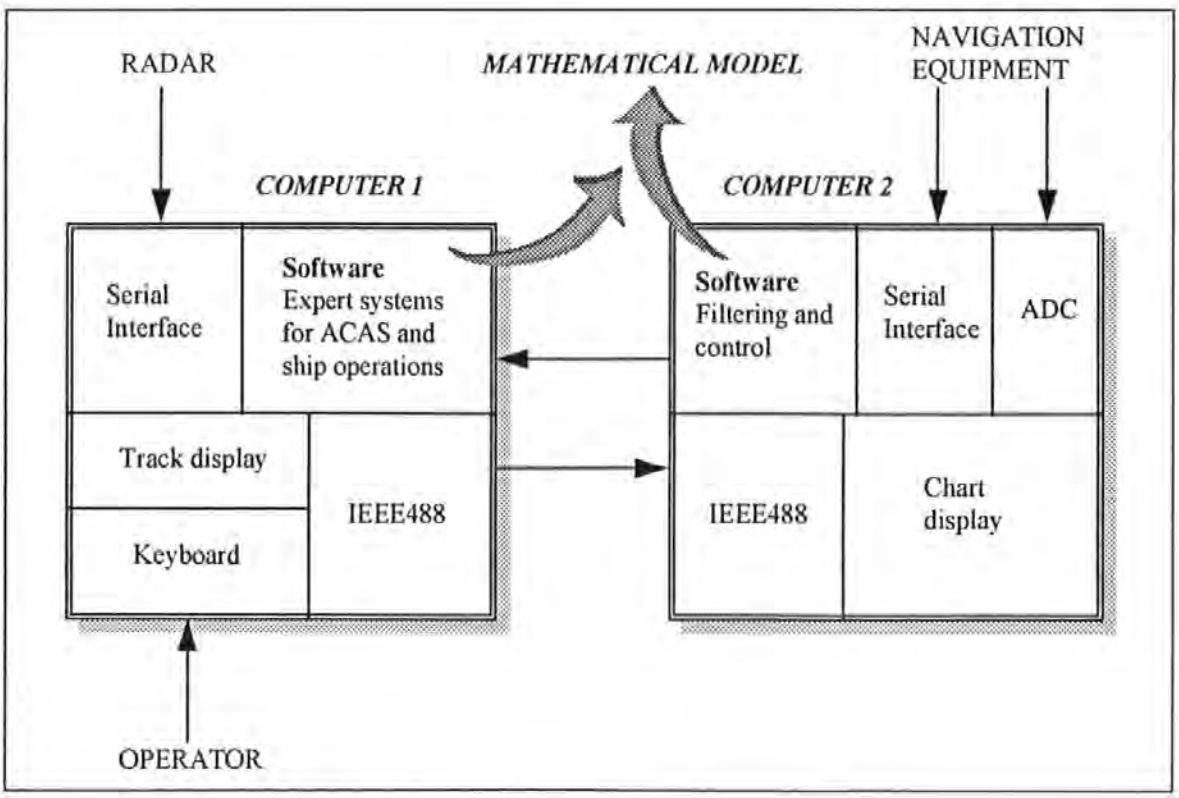


Figure 1.1. Prototype system schematic. Adapted from Miller (1990).

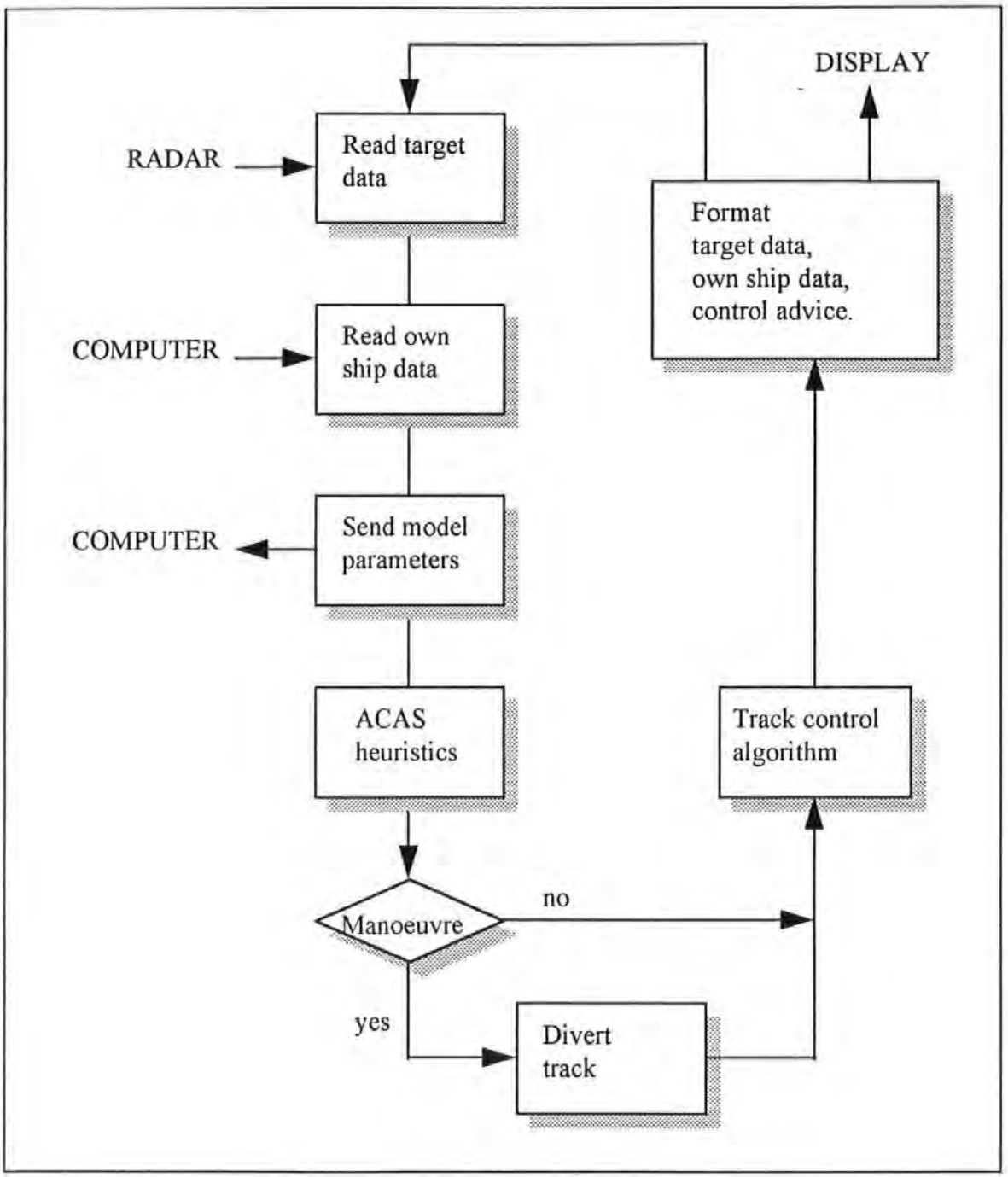


Figure 1.2. Flow diagram for computer 1.

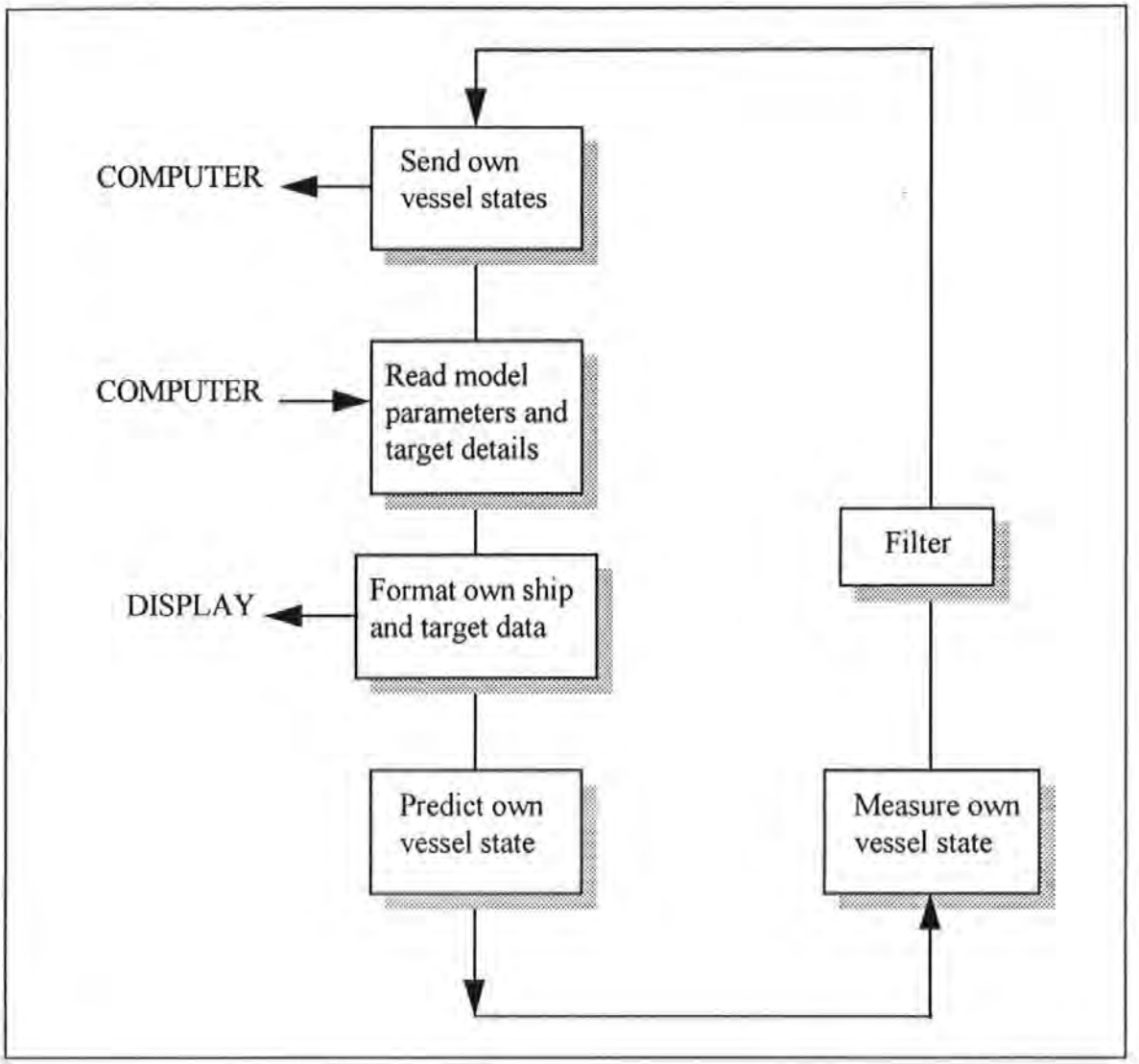


Figure 1.3. Flow diagram for computer 2.

1.2.1 Collision Avoidance

A potential encounter situation between two or more vessels requires an intelligent, reasoned response from the master of each of those vessels. A computer based expert system for marine collision avoidance must also be capable of emulating all of these functions. At present the only computational aid to the master on the bridge of a ship, for collision avoidance, is the use of the Automatic Radar Plotting Aid (ARPA).

The ARPA has long been a standard piece of equipment fitted to the ship's bridge to aid in navigation. The role of ARPA can be seen in figure 1.4, *the anti-collision loop*. As presently envisaged the system takes data from the radar sensor, stores the data in a

database, operates on the database to obtain the relevant information and then displays the data in a digestible form to the observer, Bole and Jones (1981).

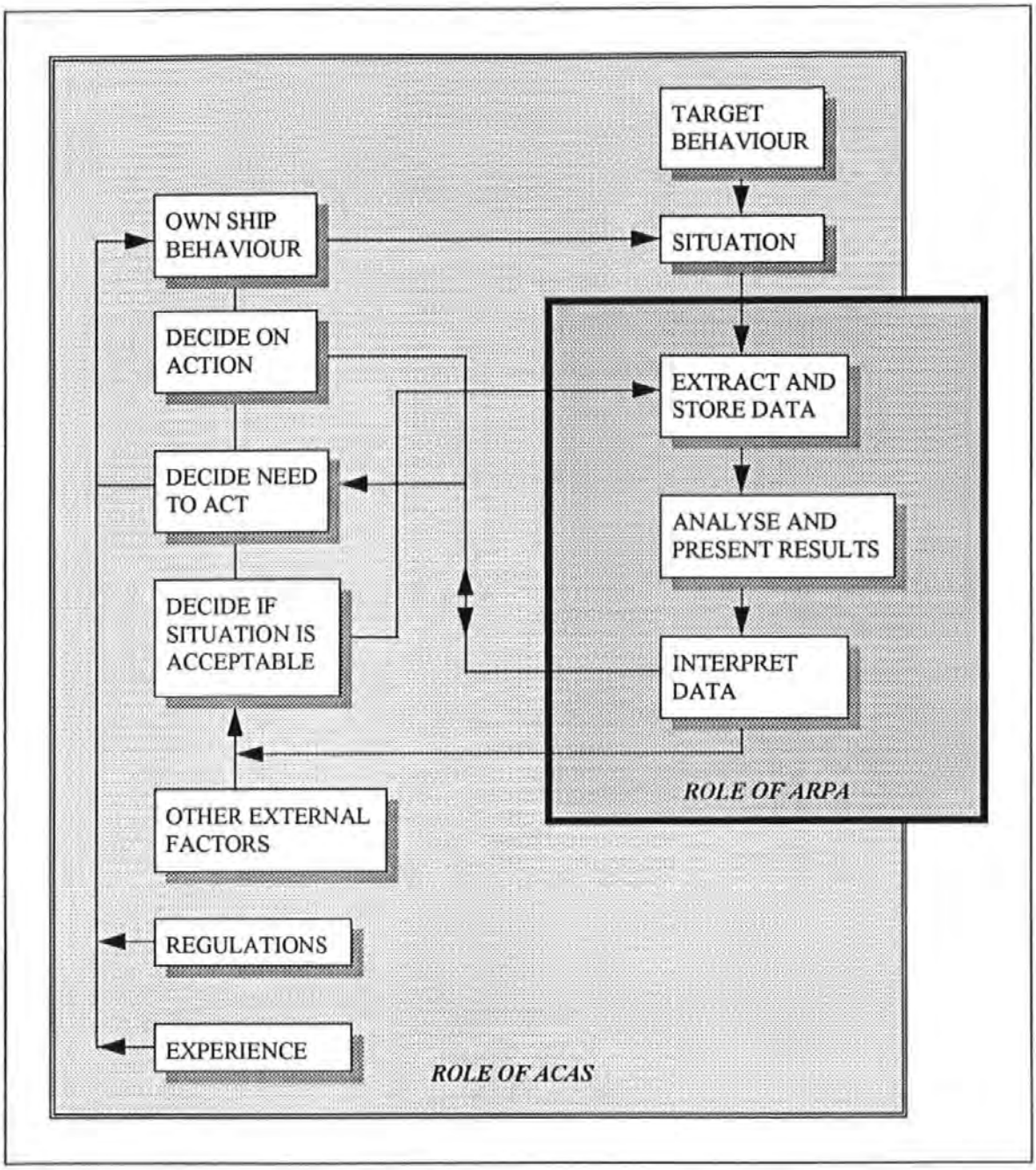


Figure 1.4. The anti collision loop.
Adapted from Bole et al (1987).

The role of ARPA is thus seen to be the extraction and analysis of data, relieving the operator of the tedious and time consuming task of vector analysis calculations. The ARPA will not, however, surpass the decision making role of the operator.

Figure 1.4 also shows the role of the ACAS, in which principally, all responsibility will be taken from the operator; whether closing the loop is a realistic option will be discussed later in the thesis. Once again the mathematical model will become the central element of this system; it obviously requiring a model of own ship behaviour. A lengthy discussion of ACAS will not be undertaken here as the diagram shows the principle components, a full description can be obtained from Blackwell (1992).

1.3 Objectives

The main objectives can be listed as shown below:

- to undertake a survey of automatic navigation and existing 'state of the art' integrated navigation systems;

- investigate all existing mathematical model types and compare, through various simulations, their accuracy and adaptability;

- to improve on the mathematical models adaptability and validate against a range of vessels differing in size;

- implement the mathematical model into a collision avoidance system.

As well as the list given there are a number of secondary objectives that should be considered.

1. Forthcoming IMO standards for manoeuvrability have highlighted the problems of predicting manoeuvring behaviour of new designs. Indeed, The Marine Technology Directorate Ltd (MTD) have recently funded the MOSES (manoeuvrability of ships and estimation schemes) programme, one of the long-term goals of which is the development of 'manoeuvring for design' software, Wilson (1992).

   It is envisaged that the model developed during this research could be used for manoeuvring predictions at the preliminary design stage. A personal computer (PC) based simulator will be produced.

2. The model is being used in other research work, undertaken by members of the Marine Dynamics Research Group, in different applications. This is expanded upon later in the thesis.

1.4 Organisation of Thesis

The contents of the succeeding chapters of this thesis are organised as described below.

- **Chapter 2:** Automatic Navigation.

  A general overview of automatic navigation in the marine industries has been undertaken along with a review of the important factors that have had a significance in their development, including marine electronic navigation and the use of microprocessors on the bridge, which have had an immense impact on the way one navigates today. The chapter subsequently discusses the integration of navigational data and surveys *state of the art* integrated navigation systems.

- **Chapter 3:** Mathematical Models in Ship Manoeuvring.

  With the introduction of microprocessors on the bridge and advanced ship simulators, there are now many systems that require the use of mathematical models to predict the vessels' manoeuvring characteristics. The definition and general form of the mathematical model are described. The different types and form of model have been investigated and the derivation of their hydrodynamic coefficients is discussed in detail.

- **Chapter 4:** Model Formulation and Simulation.

  The adaptability of the mathematical model is the most important aspect of this research. Manoeuvring simulations have been undertaken using linear holistic, non-linear holistic and non-linear modular models. Simulations of a range of different vessel type and size are shown to verify not only the models accuracy but also its adaptability.

- **Chapter 5:** The Adaptable Modular Model.

  From chapter 4 it is shown that the modular model lends itself to being the most adaptable of the models presented. All the modular components are considered in detail and, where necessary, each component has been altered to improve its adaptability. The propeller thrust has been modelled using the circulation theory and validated against towing tank tests as well as standard propeller series data.

By using the circulation theory it is demonstrated that any propeller of any geometry can accurately be modelled without the use of standard series data that are restricted to a certain blade profile and section. The propeller *paddle wheel effect* has been investigated and a new formula predicting this phenomena is presented. All other model data and additional information required are discussed.

- **Chapter 6:** The PC Based Simulator.

  A PC based simulator has been developed to model vessel manoeuvring. To validate the simulator/model a range of vessels differing in size from 12.5m to 343m have been used. So as to validate the model, *true* data was gathered from actual vessel sea trials that were undertaken on two vessels, the results of which are presented in this chapter, so as total reliance was not placed on published data or simulations of simulations. A comparison between the adaptable modular model and the original non-linear modular model, presented in chapter 4, is shown.

- **Chapter 7:** Automatic Collision Avoidance System (ACAS).

  Previous research, at the University of Plymouth, has resulted in the development of an Intelligent Knowledge-Based System, IKBS, for an ACAS. This system maintains a continuous *watching brief* on ships and other potential hazards in the vicinity and recommends, through a rule structure containing the rules of the road, avoidance action. This system only contained very simplistic ship models where true arcs of circles were used to simulate turns and no speed reduction in the turn was made. This chapter describes the components of the ACAS and shows the inclusion of the adaptable mathematical model into the system. The problem of modelling the *hazard vessel* is addressed and a solution presented.

- **Chapter 8:** Conclusions and Further Work.

  This chapter offers conclusions on the work presented throughout the thesis and then points the way for future developments.

- **Appendix A:** General Vessel Principal Dimensions.

  The principal dimensions of the various vessels that are used in chapter 4 to assess the model's adaptability are presented.

- **Appendix B:** General Vessel Hydrodynamic Coefficients.

  The hydrodynamic coefficients of the various vessels that are used in chapter 4 to assess the models adaptability are presented.

- **Appendix C:** Afterbody Forms.

  Diagrams of the afterbody forms required when calculating the vessels total resistance are shown.

- **Appendix D:** Adaptable Model Vessel Dimensions and Program Input Data.

  All the required information for the adaptable mathematical model programs input are given.

- **Appendix E:** Propeller Geometry.

  The geometric details of the two propellers used to validate the circulation theory, in chapter 5, are shown.

- **Appendix F:** Tank Tests.

  Details of the tank tests carried out at the Royal Naval Engineering College, Manadon, are presented.

- **Appendix G:** Standard Ship Manoeuvres.

  The various standard trials manoeuvres undertaken with Picket Boat 9 and Sand Skua are described.

- **Appendix H:** Trials Data.

  The trials data collected for Picket Boat 9 and Sand Skua are presented in tabulated format for future reference and simulation studies.

- **Appendix I:** List of Publications.

  Papers published by the author are listed chronologically.

CHAPTER 2

AUTOMATIC NAVIGATION

2.1 Introduction

The safe passage of a ship from port to port is the responsibility of the Master, who must use his skills and experience to ensure safe navigation. That none of these skills have been lost is shown in numerous feats of navigation which are frequently reported by the media. So why does the mariner need electronic navigation aids, integrated navigation systems, adaptive autopilots and other systems dependent upon the power of the microprocessor? Is there an argument for increased automation on the bridge? There are several factors which suggest that there is a requirement for moves in this direction, without completely eliminating the mariner from the command loop. This is the case in avionics, where the pilot retains ultimate control of his aircraft, even though automatic navigation and landing systems are installed in the latest generation of airliners. It would be reasonable to suppose that the travelling public would wish this to continue, as the very existence of automatic systems on the flight deck allows the air crew to undertake their tasks more efficiently, and hence, more safely.

Although modern land based marine electronic navigation systems are capable of fixing a vessels position to 50 metres at their best, coverage by many of these systems is restricted to small coastal areas outside of which accuracy is steadily reduced. Modern satellite navigation (Transit) can give a fix anywhere in the world to an accuracy of 100 metres but satellite passes are infrequent, with up to four hours between fixes. The second generation satellite system, Global Positioning System (GPS), is gradually becoming available and will give complete 24 hour coverage at an accuracy to within 100m.

Autopilots are well established navigation aids in modern commercial and military shipping, currently in use on ships simply to maintain a vessel on course in the open sea. Whilst the technology is available to navigate an unmanned ship between ports, avoiding other vessels, with weather routeing and piloting, will the legislation be available to allow such developments, and is this what the operator and the public require?

2.2 Marine Electronic Navigation Systems

There is a Chinese legend that the Emperor Hoang Ti, who reigned about 4300 years ago, succeeded in pursuing his enemy through a thick fog with the aid of a directional device. However, Nedham (1962), suggests the earliest development of a compass in China, or anywhere else in the world, is no earlier than 1088 AD. The sextant and chronometer followed at much later dates, and these three were virtually the only instruments available to the mariner up to the turn of the century. After the development of wireless telegraphy by Marconi and others it was soon realised that the early aerials used had directional properties and that this phenomenon could be used to obtain a bearing. There followed a period of much ingenious work by such pioneers as Marconi, Bellini and Tosi, and Round, to name but a few, Dove and Chudley (1989). The development of flight gave an entirely new emphasis to the importance of navigation, and by 1914 radio direction finding systems and the radio compass, were available, Keen (1938). Air navigation between the two world wars was largely concentrated on developing radio beacons as the counterparts of marine buoys and lighthouses.

The development of modern electronic navigation systems dates from the period 1939-1945. It was to meet the exacting demands of World War 2 that a dramatic phase of development took place, Jones (1975) and Fennessy (1979). This development was to form the basis of many of the systems in use today. The direct measurement of range using electromagnetic waves depends upon accurate measurement of the time taken for the radio signal to travel from transmitter to receiver and back again. Prior to the development of frequency standards and atomic oscillators such measurement for a ship to shore system was impractical and hence the early systems tended to measure the difference in time of arrival of two radio signals, so that position fixes were related to hyperbolic position lines. The Loran system was an early example of such a system. Loran A was developed in the U.S.A. and was in use in World War 2. In the United Kingdom naval scientists developed what was to become known as the Decca Navigator. Both Loran A and the Decca Navigator were in commercial use soon after the end of World War 2. Since 1945 the use of electronic navigation aids has steadily increased; whilst in the period since 1970, with the appearance of minicomputers and microprocessors and the decreasing costs of electronic equipment, the growth has been more spectacular. In particular there has been a vast increase in the use of electronic navigation aids by small craft navigators .

There are two distinctly different satellite navigation systems available to the mariner. The first, known as Transit or NNSS (Navy Navigation Satellite System) was developed to the requirements of the US Navy and has been commercially available since 1967. Each satellite transmits at 150 and 400 MHz and the shipboard receiver measures Doppler shift to determine the relative velocity between satellite and receiver. Use is made of hyperbolic navigation and transferred position line principles to determine the ship's position so that

only a single satellite is required for a fix. A single frequency receiver is adequate for most marine navigational purposes but for highly accurate position fixing a dual frequency receiver is required. Such uses include hydrographic survey, land survey and the accurate positioning of off-shore platforms.

By 1975 a number of individual systems were thus available to the commercial operator. Each had its inherent advantages and disadvantages, so that no single system was completely satisfactory for navigation in all phases of a voyage. The Omega system, for example, provides world wide coverage, but is insufficiently accurate for inshore navigation. The Decca Navigator, or Decca Navigation System (DNS) as it is now being called, will provide accurate position data near the centre of a chain, but its accuracy reduces with increasing range, due mainly to skywave interference. The Transit Satellite System is sufficiently accurate for survey work, provided a two frequency receiver is used, but the time between satellite passes makes it unsuitable for coastal navigation in most cases.

The 1980s have seen the development of the second satellite system, known as Navstar or Global Positioning System (GPS). The original specification was for the needs of the US Airforce because Transit is of little use for aircraft navigation. The advent of GPS may make all other position fixing systems redundant, as it will give continuous 24 hour world wide cover with a high degree of accuracy. The advent of high accuracy crystal oscillators has enabled the system designers to produce a receiver which will give a direct measurement of range. Not all the satellites are yet in orbit and the development of the system was severely retarded by the Challenger shuttle disaster in 1986. It might therefore be the mid 1990s before GPS is fully operational for commercial use. Public access will be provided by the Standard Precision Service (SPS) at a reduced accuracy of 100 metres for 95 per cent of fixes. The exclusively military system and the deliberately introduced degradation of accuracy will thus have some drawbacks. It is worth mentioning at this stage that the Russian Glonass satellite system will have approximately the same level of accuracy as GPS. Despite the global coverage and accuracy of GPS and Glonass, a number of European organisations see the need for alternative civilian satellite based navigation aids, Diederich (1989).

A typical set of equipment fitted in a merchant ship would now comprise a gyro compass with autopilot and repeater compasses, electromagnetic, pressure and/or Doppler log, Decca Navigation System or Loran C, together with Omega and/or Transit Satellite Navigation System. Increasingly there will be a demand for GPS, backed up by a standby system such as Loran C. This would give the navigator reasonable world wide coverage and sufficient accuracy for most of his needs. Radar, automatic radar plotting aid (ARPA) and direction finder would also be fitted. DNS and Loran yield comparable accuracies in the primary coverage areas, however, for coverage of a given area fewer Loran than Decca

stations are required, thus lower operating costs are incurred. Unfortunately the basic accuracies of DNS, Loran and GPS are in many cases inadequate. A further point which needs emphasis, is that high risk transports require a degree of integrity which cannot be provided by any of these systems separately. Thus, even when GPS is fully operational, there will still be a need for alternatives.

The advent of GPS has led to a great deal of debate in Europe, and at least one conference, sponsored by the International Association of Lighthouse Authorities (IALA) in 1987, was held to discuss the need for a European back up system for GPS. One viewpoint being put forward is to extend the Loran coverage to those parts of European and Mediterranean waters not already covered, and to phase out the Decca chains. However there are a large number of small craft Decca users, including increasing numbers in the marine leisure industry. Some 100000 DNS receivers were installed in leisure craft by 1990, with a further 30,000 Transit or Loran receivers, largely in the Mediterranean. It may thus be difficult to phase out any of these systems easily. Political, nationalistic and financial considerations will undoubtedly govern the final choice of an adequate back up system, rather than sound technological judgements.

2.3 Factors in the Development of Automatic Navigation

The period 1945 to 1960 saw little change except that radar, electronic position fixing systems, and autopilots became more widely fitted in merchant vessels. There was also a move away from the towed log to electromagnetic and pressure logs. The 1960s saw the advent of twin radar, twin gyros, and dual channel steering systems, for obvious safety reasons, but there were no new concepts between 1945 and 1970.

By 1970 however it had become apparent that the advent of 'Very Large Crude Carriers', VLCCs, and fast container ships operating in increased traffic density, would require modern navigation systems. These demands, coupled with the dramatic achievements in the world of electronics, paved the way for the systems available today but before dealing with them it is necessary to consider the requirements of the ship owner and the problems associated with the developments.

Ship owners and operators have, by the very nature of their business, been conservative. Tradition dies hard and there were none of the incentives which faced the aircraft industries in 1945. Ship design was stable, diesel engines were being widely fitted, equipment was largely satisfactory and efficient, and there were no spectacular disasters such as those which dogged the development of the world's first commercial jet airliner, the De Haviland Comet. Things remained that way for twenty years or more; perhaps this was a factor in the

decline of European shipbuilding and ship operation, although it was by no means the major or only factor in this decline.

The Torrey Canyon in 1967 was the first disaster to arouse public anger since the Titanic. There was a widely held view that international shipping was not operated as safely as it might be, with the result that more accidents occurred than were acceptable. To the extent that even well found ships were not being equipped with the aids available to them, it could be argued they were being developed in advance of their demand. Furthermore advanced navigation aids were expensive, compared with the more traditional systems available, and there were no definable standards against which to measure improvements in safety. There were a variety of position fixing systems available, but none was completely acceptable, some of the reasons for this have already been mentioned. There were, and still are, difficulties in retaining high calibre trained staff at sea. There was, and still is, a decrease in job satisfaction. Furthermore, the huge oil price increases in the early seventies were a major factor in increased operating costs, leading to a need for optimal operation of ships. Increasing traffic density, particularly in waters such as the Straits of Singapore and the English Channel, increasing ship size and speed, leading to less manoeuvrability, were other contributory factors. Finally environmental factors started to emerge as early the as 1960s. For example the cost of clearing up the environment after the Torrey Canon ran aground was in excess of the value of ship and cargo combined, and this accident saw a huge public outcry at the damage caused to wildlife and the UK coastline, Stratton and Silver (1970).

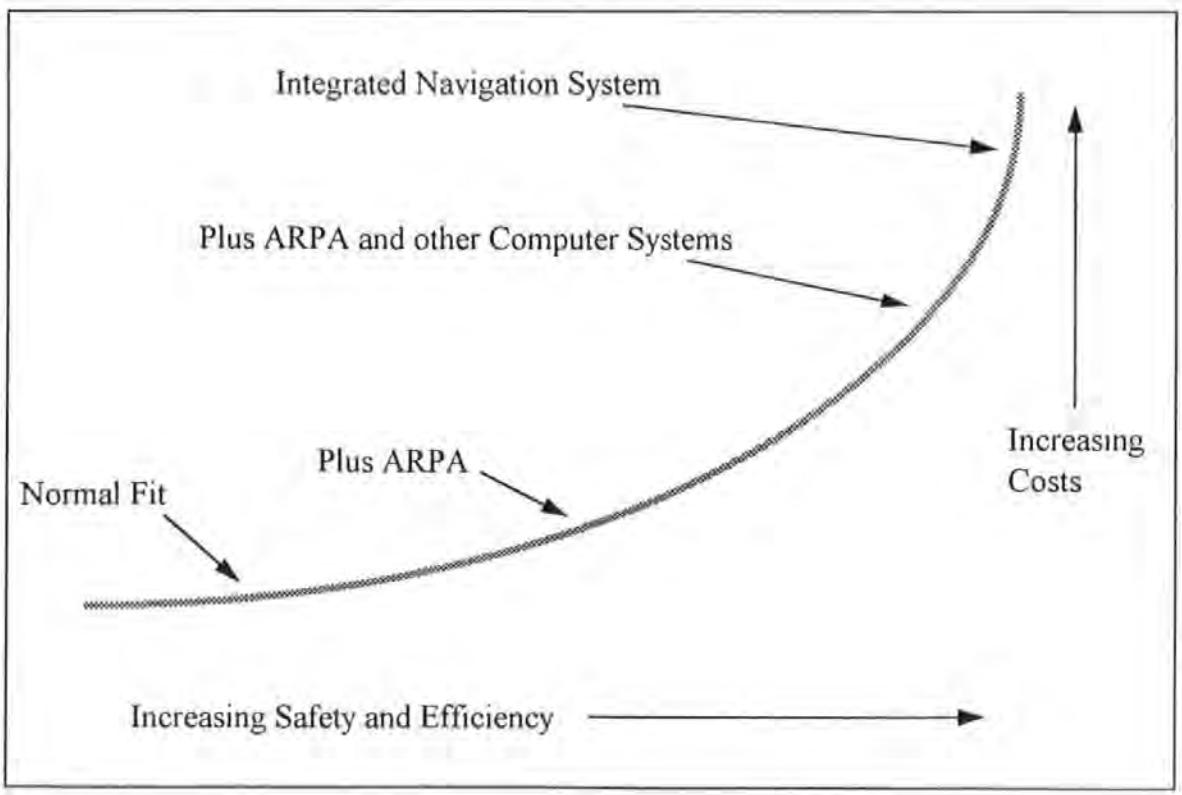


Figure 2.1. Costs of Navaids against benefits.

Among other problems to be considered were the costs of development of a system, which must be set against the fact that the probability of a vessel completing a voyage is almost one, Maybourn and Mateer (1974). Figure 2.1 is an early 1970s attempt to assess the costs of navigation aids against the improving benefits they might bring. Costs have dropped dramatically since then, but, for example, an early Transit satellite system would have cost in the order of 40000 US. dollars for a dual frequency on board receiver. Any equipment developed has to be reliable, particularly in the hostile environmental conditions often encountered at sea, with shore maintenance and back-up facilities maybe over a thousand miles away. If the ARPA is unserviceable at a time when it is most needed, i.e. in the coastal phase of a passage, then there may be insufficient qualified personnel to provide good plotting at a crucial period in the passage, giving rise to the possibility of danger to ship and crew. Finally the automation process itself leads to further decreased job satisfaction for the highly trained personnel who may wish to remain at sea.

Approximately ninety percent of all marine accidents occur in confined waters such as channels, fairways and inshore traffic zones; the vast majority taking the form of collisions or groundings, Cockcroft (1984). Although the implementation of Traffic Separation Zones has significantly reduced the number of such incidents this is far from a complete solution to the problem. Human error, in the form of ignorance or negligence, is estimated to be responsible at least in part, for up to eighty five percent of these accidents, Anon (1976). Figure 2.2 shows this in chart format.

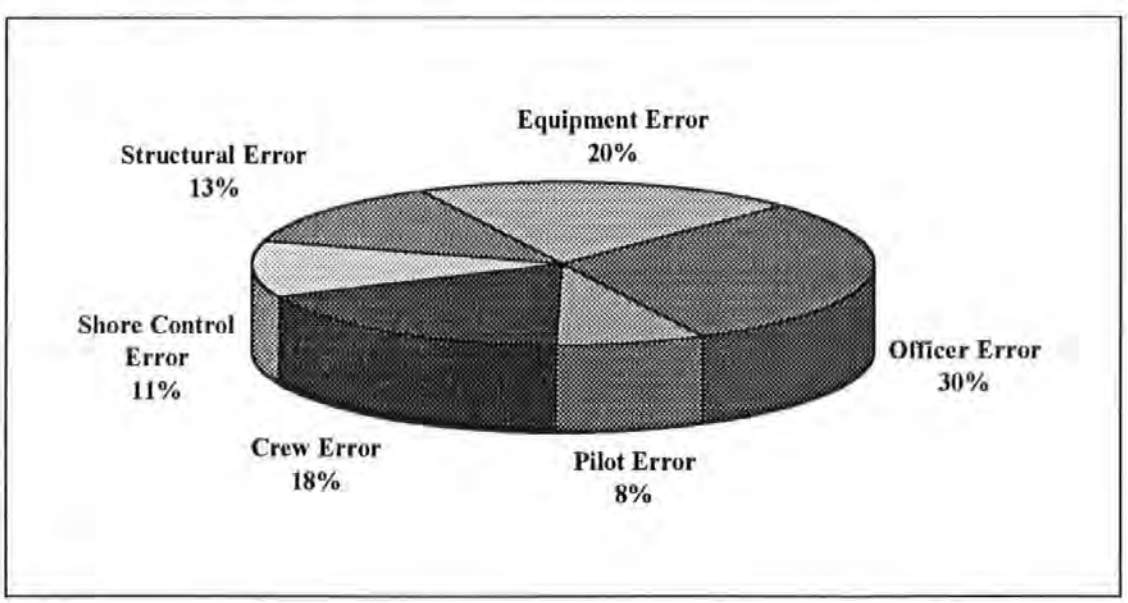


Figure 2.2. Main Causes of Major Shipping Accidents 1987-1991. After Hamer (1993).

The above observations testify to the need for further improvement of marine navigation and guidance. Fundamental to safe navigation and collision avoidance are the provision of an efficient lookout at all times, an awareness of the potential threat posed by static hazards

such as the seabed or navigation marks combined with knowledge of their proximity to the vessel's current position, and an accomplished understanding of the Collision Regulations including where, when and how to take avoiding action for both static and dynamic hazards.

The problems which began to emerge in the 1970s may be divided into two distinct areas, namely the docking and anchoring of large displacement vessels and the handling of large and fast vessels through restricted waters. An additional problem is associated with the emergence of oil and gas platforms and their siting in waters frequently used by trading vessels.

The docking problem was largely one of considering the ship's momentum. Limiting the momentum for a 250,000 tonne ship means the approach speed can only be ten percent of that for a 25,000 tonne ship. Jetty damage was found to be increasing with vessel size, and many port authorities were forced to employ permanent repair gangs for repair of jetties. The demand for decreased approach speed gave extra problems to masters and pilots. For example a normal person cannot sense a yaw rate of less than 0.005 degrees/second (3 degrees/minute). A major factor in solving this problem has been the development of Doppler Sonar and Radar devices, which are normally sited ashore. They measure the vessel's speed as it approaches the berth, after which the information is transmitted to the master and pilot. When the vessel is being manoeuvred into its berth the bow and stern speeds are measured, from which the operator can obtain the overall approach speed and yaw rate of the vessel.

One of the factors associated with the full speed problem was the emergence of too much data on the bridge, so that one man was increasingly unable to handle the increased information flow, whilst undertaking all the other duties required of the Officer of the Watch (OOW). For example he might have several sensors on the bridge, giving him heading (gyro compass), water speed (pressure log), ground speed (Doppler log), collision avoidance information (ARPA), navigational data (X band and S band radar) and positional information (Decca and Loran). The second factor also concerns the vessel's momentum. Large vessels at speed have large momentum and hence require long stopping distances and large diameter turning circles. This all requires more sea room at a time when the vessel's increased draft means the ship may have less space in which to manoeuvre.

2.4 The Use of Microprocessors on the Bridge

Target plotting and tracking was very primitive in the 1950s and 1960s, and consisted mainly of the use of chinagraph pencils to mark a special reflection plotter, which is a detachable optical system, mounted on the front of the radar screen, and on which the

position of other ships is plotted. With larger and faster ships came the demand that the OOW started plotting each target earlier; he was also required to plot more targets, a task which became increasingly difficult. All of this led to the development of Collision Avoidance Systems, (CAS), which were the first navigation aids to use micro computers and which led to the first integrated navigation systems in use at sea. These were later to be called ARPA. Essentially ARPA means interfacing the radar, or radars to a digital computer, which has software programs to solve the collision problem for a number of targets, and to present these solutions to the operator in a form, or forms, which can be easily and quickly interpreted. In order to calculate the true course and speed of each target then "own ship" speed and heading must also be inputs to the computer program. For collision avoidance, speed through the water is required, because the international collision regulations require the give-way vessel to act on the heading of the target and not its track over the ground. This entails the use of a pressure or electromagnetic log. However, if the software is to be used for navigation, then speed over the ground is required; this may be obtained from a 2 axis Doppler log input to the computer.

Once the computer was accepted as part of the bridge equipment, designers wished to use it for other navigational tasks. In the early 1970s the idea of interfacing navigation aids such as Decca and Loran were explored. With the advent of Transit further suggestions were made, and early developers, of whom Sperry and Racal Decca were one of the first, produced a system which not only integrated the navigational aids, but produced an output to control the steering through the autopilot. However, the idea did not fully catch on with ship owners, perhaps due to the conservatism referred to earlier. These concepts are illustrated in figure 2.3.

While the completely integrated bridge system has not found favour in commercial trading vessels, single system deficiencies have led to the development of systems in which the manufacturer has attempted to combine two or more receivers in to one piece of equipment. For example Racal Marine Electronics have produced the MNS2000, which combines the Decca Navigator, Loran-C, Transit and Omega, while Sage and Luce (1983) describe the use of a Kalman filter to combine Omega and Transit, or Omega and Loran. Many of these more sophisticated integrated navigation systems use techniques which have been developed from space navigation.

2.4.1 Integration of Navigational Data.

There are essentially two types of integrated systems, information systems and control systems, Larsen (1989). A typical example of an integrated control system is that of a ship manoeuvring system for docking procedures. The integration of navigational data can be placed under the heading of an information system, the purpose of which is to provide

accurate, current information by combining and processing data from a number of sources. This can be seen in figure 2.4.

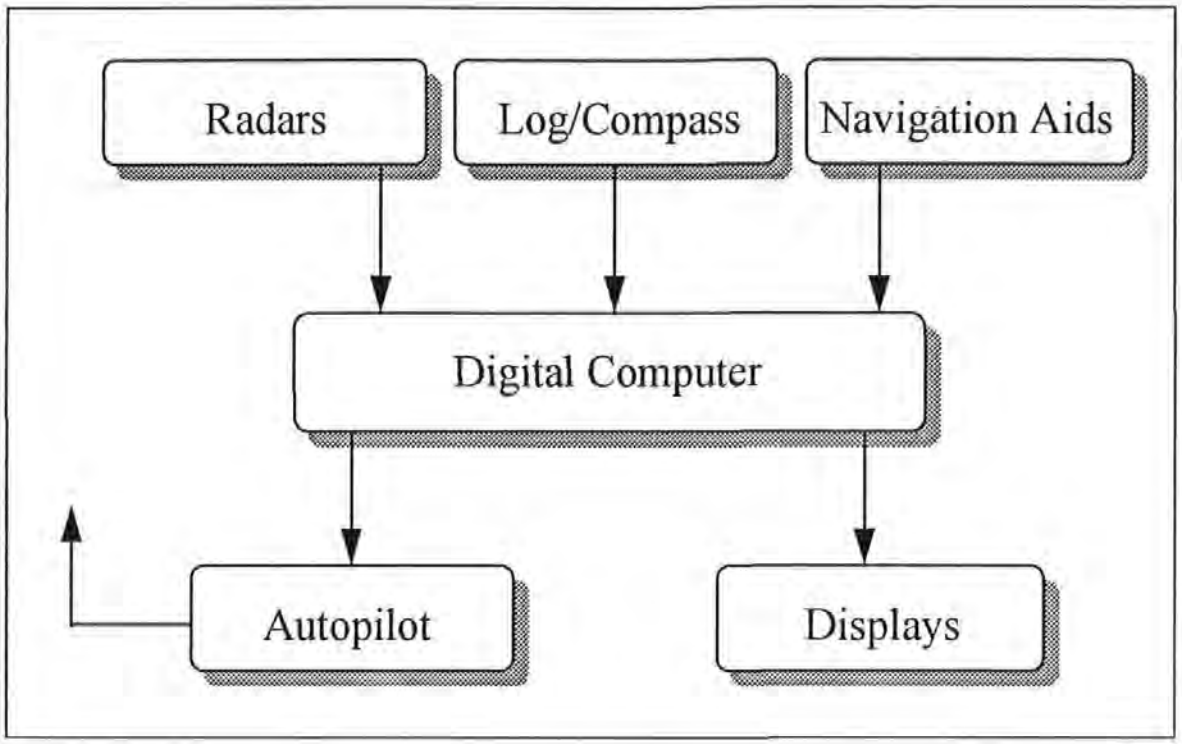


Figure 2.3. Automatic Navigation and Guidance.

To understand this consider the position of the OOW who wishes to fix the position of his vessel. He may plot a number of fixes obtained from different sources. For example, from log and compass, and a knowledge of the set and rate of the current, he can derive an estimated position from a previous fix, from radar information he may obtain a fix, and another fix from an electronic navigation aid such as GPS. Using his knowledge of the likely random errors in all three positions, he may take a weighted mean to establish the most probable position of the vessel. One of the requirements of an integrated navigation system then is to minimise in some way the random errors associated with the position fixing systems. The Decca Navigator Company suggest that the a Gaussian distribution gives the best fit for the spread of random errors in radio navigation aids, so that the problem of minimising those errors can be treated as one of minimising the variances, Decca Navigator Co. Ltd, Anon (1973). This concept has led to the development of Kalman-Bucy filters, which have been used extensively for aerospace, and latterly marine navigation, Miller (1990).

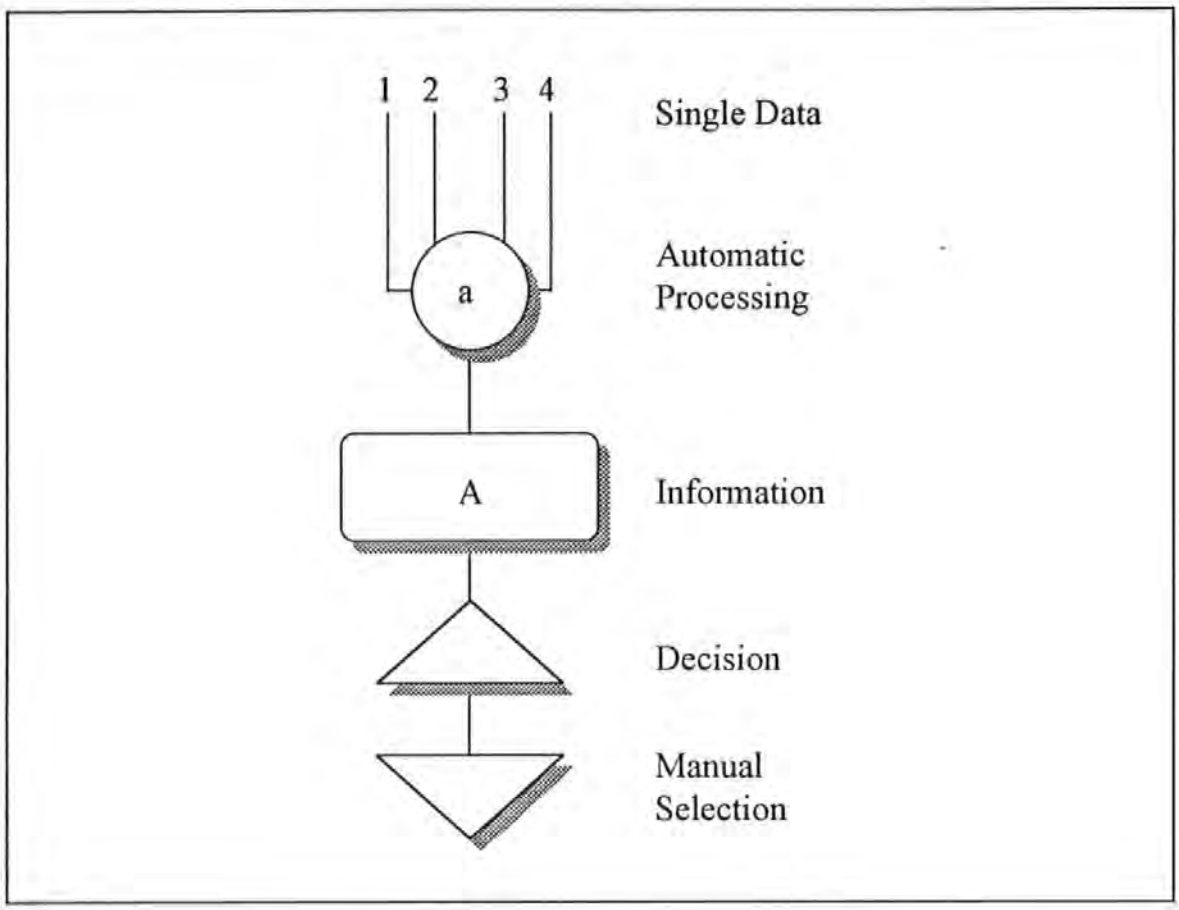


Figure 2.4. Integrated Information System, after Larsen (1989).

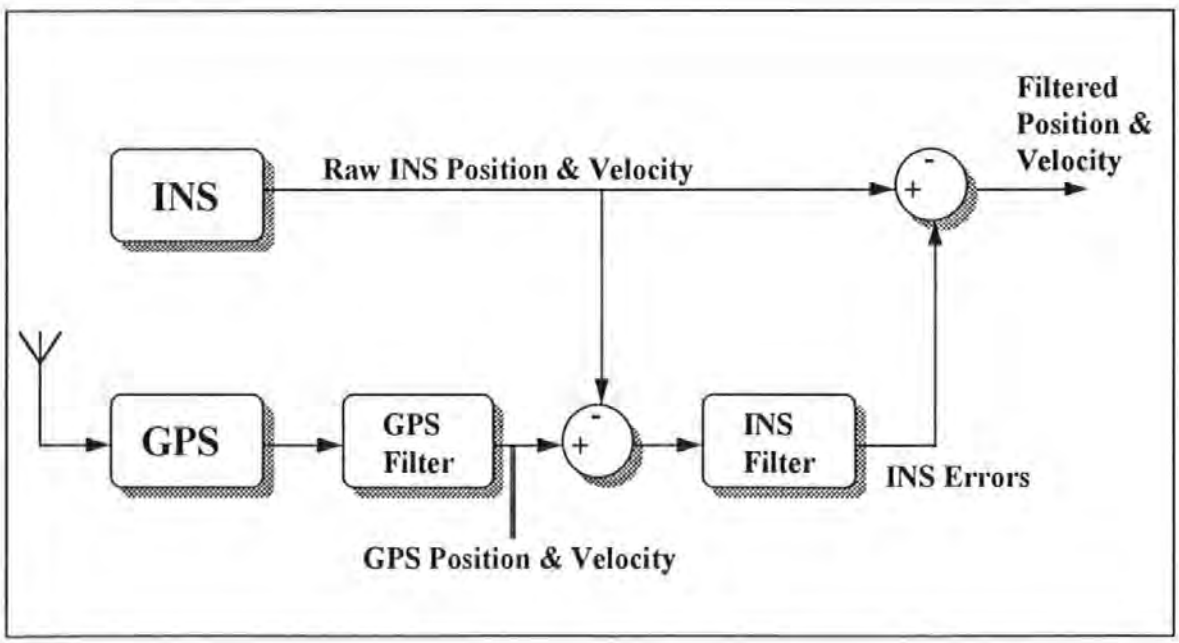


Figure 2.5. Kalman-Bucy Filter for GPS/INS Integration, after Dove and Chudley (1989).

The ship is also acted upon by disturbances such as wind, tide and current. These disturbances may be random, as in a gust of wind for example. As the vessel moves sensors measure the position and velocity, but these measurements may be noisy, that is they contain random errors. The Kalman-Bucy filter is a recursive algorithm which estimates the values of the variables of a stochastic system from measurements which contain randomly fluctuating noise, thus minimising such noise. Figure 2.5 shows how a Kalman-Bucy filter can be used to filter position and velocity values in an integrated GPS/Navigation System; essentially the filter is being used to reduce the random noise to be found in the radio signals from the satellites.

2.5 Integrated Navigation Systems

The operators of today's ocean going and specialist vessels have numerous electronic aids available. The traditional role of each navigation aid has been one of a stand alone unit with the mariner, by his experience and training, co-ordinating the data from all the sources available to him in order to optimise vessel performance. As casualty statistics indicate however, when under stress or at times of peak work load, he may be a poor co-ordinator of information available, particularly when that information is from a number of different sources. The development of automatic navigation will therefore continue with evolution rather than revolution being the key. In West Germany, Japan, the Netherlands, the United Kingdom and France, projects have been undertaken on the "ship of the future". These projects were largely attempts to optimise design, operations, maintenance, investments and energy consumption against the criteria of costs efficiency and safety. Not all of these studies have been successful, and not all of the conclusions have been in favour of increased automation of the navigation process. Automation today is not a question of whether a process can be automated, but whether it should be, taking into consideration various human factors. It is perhaps highly questionable whether total systems safety is always enhanced by allocating functions to automatic devices rather than to human operators, Schuffel et al (1989).

Despite these findings there has been much progress. The Scandinavians require exceptionally high standards for automation in their luxury cruise ferries operating between Stockholm, Turku and Helsinki. These waters consist of a maze of islets which are ice-infested throughout the Baltic winter. During the course of a normal passage, ships may be required to make as many as 120 course alterations without significantly reducing speed, Maconachie (1989). As a direct result of this Krupp Atlas developed the NACOS 25 navigation and command system, one such system is fitted on the bridge of Viking Line's Athena, Anon (1989a). This is a development of the NACOS 20 package developed by Krupp Atlas as part of its involvement in the West German Schiff der Zukunf (ship of the future) project and is a most sophisticated system. There are two radar with slave displays,

a map storage system for the intended routes, an integrated echo sounder, an adaptive track pilot, a nautical information display and Doppler log.

Perhaps one of the most advanced integrated systems offered on the market place at present is from Sperry Marine. Although at present international regulations only permit one man operation of vessels during daylight hours, and then only under certain conditions, the system has been approved by Det Norske Veritas for operation by only one person on the bridge day and night. In 1989 the system was fitted on an 84000 dwt product carrier Petrobulk Mars, since then two sister ships, Petrobulk Jupiter and Petrobulk Zaria, have also been delivered with the system fitted, Anon (1989b). Central to the integrated system is the 'touch screen' controlled Rasterscan Collision Avoidance Radar (RASCAR)/ARPA. This is interconnected to the ADG autopilot, and a Voyage Management Station, all integrated by Sperry Marine's own Seanet Token Ring Data Network, which, in the event of a malfunction of one processor, does not make the whole system inoperative.

The majority of integrated systems are manufactured by a sole company and use all their own equipment; one drawback with this is that an operator might feel that the complete package does not offer all he may require. This is the feeling of the West German firm Anschutz whose philosophy is to integrate equipment from other manufacturers for which the ship owner may have a preference; this is useful for companies who may not offer a complete integrated system. One such company is Kelvin Hughes who do not at present offer an integrated navigation system based on their latest Rasterscan ARPA, the Concept range. They do however realise this potential as the Concept series are equipped with standard interfaces capable of displaying navigation data and machinery data and could be part of a highly advanced bridge. Concept radar/ARPA are of the new generation type capable of carrying on screen map diagrams; once entered maps are maintained correctly in true motion by speed log input and by successive position fixes fed in from Transit, GPS, Decca, Loran-C or Glonass receivers via an RS423 interface to NMEA 0183 standard protocol.

2.6 Conclusion

In conclusion it would seem that the specialist operators such as those engaged in offshore and survey operations are prepared to go for a completely automated navigation and guidance system, whilst the ferry, cruise liner and cargo operators are concentrating on developing ergonomic bridge designs with only a degree of automation in such functions as the autopilot, coupled with integration of two or more navigation aids. However manoeuvring vessels in confined waters is a very feasible application of the use of computers through Dynamic Positioning Systems (DP). For example a vessel fitted with a cheap but reliable DP system would be able to forego the use of tugs. DP has established

itself firmly in the offshore industries and will take an ever increasing role in this sometimes harsh environment. There is then a great deal of room for expansion in dynamically related operations which include enhancement of existing operations, together with applications of DP techniques to vessels in restricted waters and in the deep oceans where the next generation of offshore exploration will take place.

CHAPTER 3

MATHEMATICAL MODELS IN SHIP MANOEUVRING

3.1 Introduction

Researchers at the University of Plymouth have developed and are improving a system for the fully automated, unmanned ship, which, if ever implemented will assist the mariner. Dove (1984), has investigated the use of Kalman filters for improvements to position fixing in the approaches to a port; this work is was studied further by Miller (1990). In joint research with Dove, Burns (1984), has studied the guidance problem; together, the results from these projects form an optimal filter together with an optimal controller, thus breaking the guidance problem down in to two distinct phases. Computer simulations have been carried out, Dove et al (1985), and the system is now installed in the University's Survey Vessel, Burns et al (1988).

Automatic Ship Steering was developed near the beginning of the century, as a direct result of the appearance of the gyrocompass, Sperry (1922). By 1932, four hundred of Sperry's systems had been installed on merchant ships throughout the world. Minorsky (1922) also presented the basic theory for directional stability of automatically steered ships and summarised various control equations that might be applied.

Following this there were a number of studies on steering and turning, the standard work probably being that of Davidson and Schiff (1946), who employed equations of motion with several coefficients. The solution of these equations determined the motion of a ship for a given helm angle. Thus, the dynamic character of a ship in steering is described by the equations and consequently by a set of these coefficients. The majority of modern day research is based upon this work and further work by Abkowitz (1964). Nomoto et al (1957) realised a practical difficulty in the work of Davidson and Schiff (1946), namely determination of the coefficients for a given ship required lengthy experimental procedures. They went on to propose a method of determining the motion of a ship in terms of indices, associated with a transfer function, Nomoto (1966). The use of Nomoto's mathematical model is, however, limited in the manoeuvres it can simulate as it uses a single input/single output approach, Ankudinov et al (1987).

3.2 Definition and General Form of the Mathematical Model

Mathematical models of ship dynamics are required for many different purposes but can generally be considered in one of three categories:

a. ship manoeuvrability analysis;
   i. ship design;
   ii. waterway improvement and port facilities;
   iii. safety regulations and casualty studies;

b. training and research simulators;

c. shipboard manoeuvring predictors.

The research underway at the University of Plymouth is to develop a shipboard manoeuvring predictor, to provide assistance to the navigator in track control and path keeping and otherwise planning the trajectory of the vessel so mishaps are less likely to occur.

The development of the mathematical model starts with a set of generalised equations to express the dynamics of a rigid body in a fluid medium derived from Newton's second law of motion;

$$force = mass \times acceleration \quad \text{.....(3.1)}$$

These equations are then extended to model the complex hydrodynamic forces and moments experienced by a hull manoeuvring in response to the control inputs of rudder and propeller. By numerical integration using small time steps the motions of the vessel can be solved. Further forces and moments are then introduced in response to the disturbance inputs of wind and tide.

A ship at sea can move in all six degrees of freedom of motion, translation along three orthogonal axes and rotation about each of the three axes, Linkens (1980). Employing equations for linear and angular momentum, Abkowitz (1964), demonstrated that the three force equations and the three moment equations may be written as an Eulerian set.

Force Equations

Surge $X = m[\dot{u} + qw - rv - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})]$

Sway $Y = m[\dot{v} + ru - pw - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})]$ .....(3.2)

Heave $Z = m[\dot{w} + pv - qu - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})]$

Moment Equations

$$\begin{aligned}
&\textbf{Roll} && K = I_x\dot{p} + (I_z - I_y)qr + m[y_G(\dot{w} + pv - qu) - z_G(\dot{v} + ru + pw)] \\
&\textbf{Pitch} && M = I_y\dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} + qw - rv) - x_G(\dot{w} + pv - qu)] \\
&\textbf{Yaw} && N = I_z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} + ru - pw) - y_G(\dot{u} + qw - rv)]
\end{aligned} \qquad \text{.....(3.3)}$$

For the majority of ship types a three degree of freedom model is adequate. Although work has been carried out on six degree of freedom models for ships, Matthews (1984), it is not usual for a vessel to be represented by all six equations due to the complexity and cross coupling involved in the equations. Figure 3.1 shows the ship axes co-ordinate system for the manoeuvring equations.

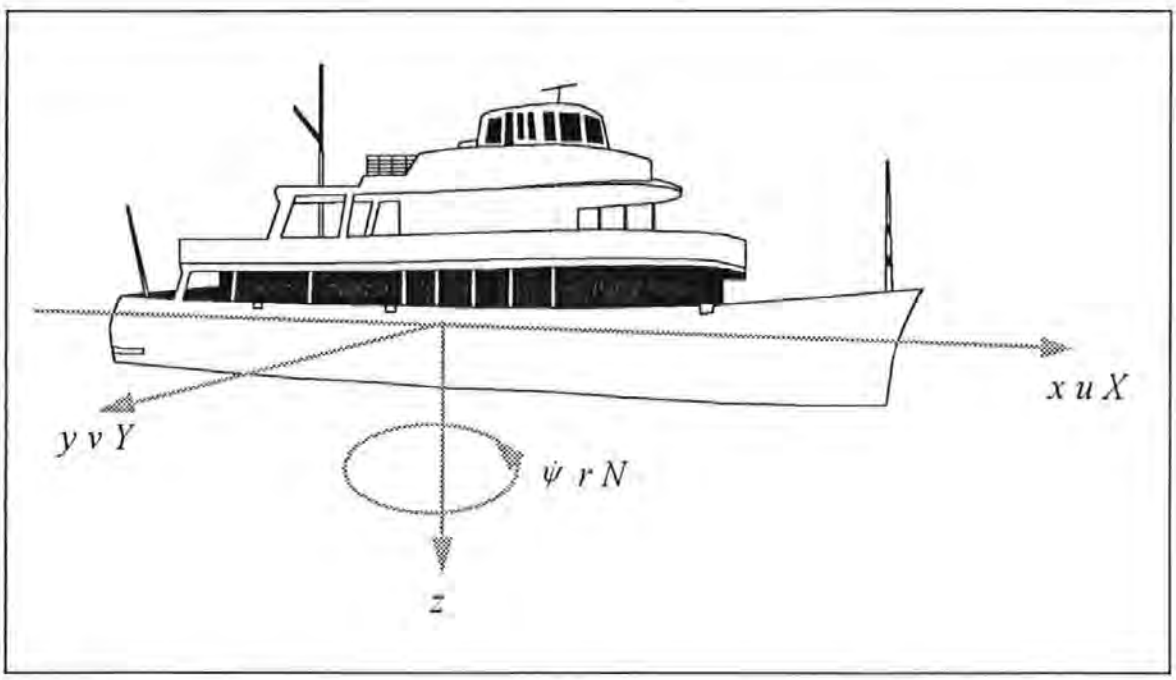


Figure 3.1. Ship axes co-ordinate system.

The equations describing ship motions in the horizontal plane, which typically covers the most practical needs of ship manoeuvring predictors, are a particular case of the general equations of six degrees of freedom, and therefore are reduced to the following three equations by ignoring heave, roll and pitch;

$$\begin{aligned}
X &= m(\dot{u} - vr - r^2 x_G) \\
Y &= m(\dot{v} + ur + \dot{r}x_G) \\
N &= I_z\dot{r} + mx_G(v + ur)
\end{aligned} \qquad \text{.....(3.4)}$$

If the origin of the ship co-ordinate system is selected to coincide with the mass centre of the vessel then the equations reduce still further to;

$$X = m(\dot{u} - vr)$$
$$Y = m(\dot{v} + ur) \quad \text{.....(3.5)}$$
$$N = I_z\dot{r}$$

However, vessels with greater freeboards than ever before are now gracing our seaways and some of these ships, such as container ships and Ro-Ro ferries can generate considerable roll in a manoeuvre. An investigation by Hirano et al (1980), revealed that the manoeuvring motion of ships that can generate large roll angles should be calculated taking the coupling effect due to roll into consideration.

$$K = I_x\dot{p} \quad \text{.....(3.5a)}$$

The forces and moments on the left hand side of the equations represents the complex hydrodynamic and aerodynamic reactions on the hull of the ship in response to the applied control forces, summated with these applied control forces and any other disturbance inputs. Figure 3.2 shows a schematic of a typical ship manoeuvring system, Hagen (1983).

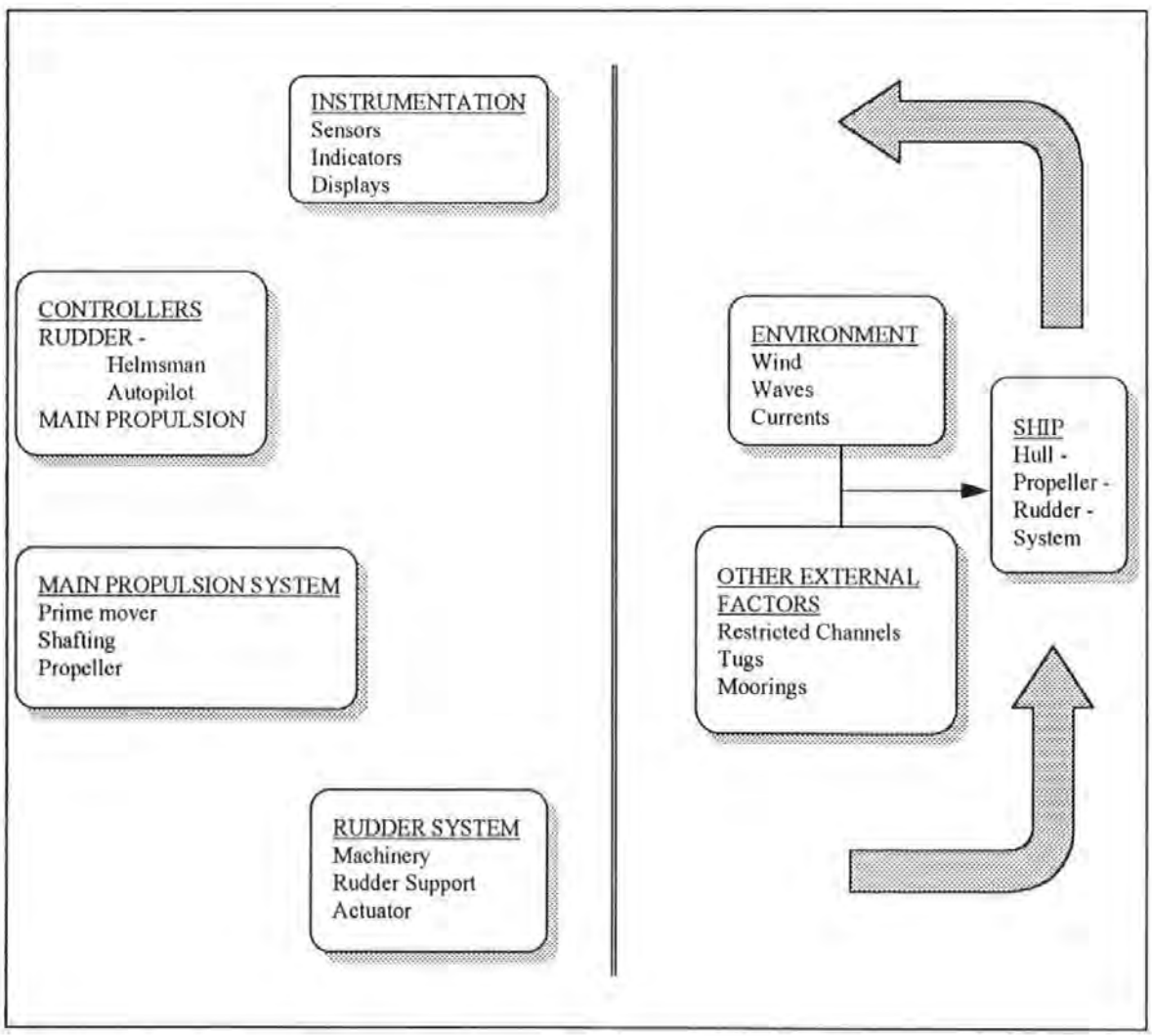


Figure 3.2. Schematic of a typical ship manoeuvring system.

3.3 Types of Mathematical Model

It is well known that the type and complexity of the mathematical model, will depend entirely on the purpose for which the mathematical model is to be used. In the past comparisons of simulator mathematical models have been made by McCallum (1984) and Case et al (1984). Between different research establishments there is little commonality of ship manoeuvring mathematical models and hydrodynamicists have over the years developed models of various forms and fidelity.

The major reason for this is the complexity of the flow phenomena around the hull, propeller, and rudder, particularly due to the generation and losses of vorticity and surface waves, Ankudinov et al (1987). The mathematical model designed for ship manoeuvring must be capable of representing a wide range of ship types and configurations, machinery and propulsion/steering devices. Dependent on the models use the following characteristics of ship dynamics should be inherent in the ship mathematical model:

- realistic turning for all rudder angles including helm delay and loss of speed in the turn; the response to rudder action should also be non-symmetrical for a single screw ship;
- realistic acceleration and deceleration including inertial effects and engine delays;
- ahead and astern motion;
- reduction in ahead motion and effective helm in shallow water;
- drift caused by a variable tidal stream;
- drift and yaw caused by a wind variable in both magnitude and direction acting on the hull and the superstructure of the ship;
- single or twin screw operation, including independent control of each screw in both directions, and turning rate;
- variable pitch operation of the screw;
- squat effect in shallow water;
- ship to ship or ship to shore interaction;
- constraint of ship movement when moored to a buoy or at anchor;
- external forces on the hull caused by tug operation;
- ship motion due to waves;
- the ship model should be amenable to alteration in order to simulate a range of hull forms and vessel sizes ranging from a fishing boat to a super tanker;
- the ship model should ideally be modular in form in order to independently evaluate hull forms, rudder geometry, propeller and engine characteristics, and environmental conditions.

The many differing types of mathematical model, can generally be placed under one of four headings:

i. input-output relationship model;
ii. a holistic model;
iii. a force mathematical model;
iv. a modular manoeuvring model.

Each of these will be briefly described in the following sections.

3.3.1 The Input-Output relationship model

When using this type the researcher starts with the simplest possible model and then tries to fit the model response with the response to the real system. When fitting is not accurate enough, the model can be extended until a fit has been achieved with desired accuracy, Biancardi (1988). If the system requires a non-linear model, the parameters can be derived from full scale trials or from trials with scale models. The simplest model in the input-output approach is known as the first order Nomoto model governing yaw response to rudder motion. This can be expressed as;

$$T\ddot{\psi} + \dot{\psi} = K\delta \qquad \text{.....(3.6a)}$$

By taking Laplace Transforms and assuming the initial conditions are zero, the first order differential equation (3.6a) becomes

$$Ts^2\psi + s\psi = K\delta \qquad \text{.....(3.6b)}$$

giving a transfer function

$$\frac{\psi}{\delta} = \frac{K}{s(sT+1)} \qquad \text{.....(3.6c)}$$

The first order Nomoto model can be expanded to a second order differential equation, Bech (1969):

$$T_1T_2\dddot{\psi} + (T_1+T_2)\ddot{\psi} + \dot{\psi} = K(\delta + T_3\dot{\delta}) \qquad \text{.....(3.7)}$$

where the coefficients T_1, T_2, (T_1+T_2), T_3 and K are functions of the instantaneous values of $\dot{\psi}$ and δ. They are also time constants which are related to the vessel's hydrodynamic coefficients.

Bech (1972), noted that ship manoeuvres could only be accurately described by equation (3.7) in a very small range of ψ and δ. He rewrote the equation to include non-linearities:

$$\dddot{\psi}+\left(\frac{1}{T_1}+\frac{1}{T_2}\right)\ddot{\psi}+\frac{K}{T_1T_2}H(\dot{\psi})=\frac{K}{T_1T_2}(\delta+T_3\dot{\delta}) \quad \text{.....(3.8)}$$

The main non-linearities of this equation have been placed together in the steering characteristic $H(\dot{\psi})$ which describes $\dot{\psi}$ as a function of δ. $H(\dot{\psi})$ can be determined, in general, by the reversed spiral test or in cases of dynamic stability by the Dieudonne spiral test.

The same approach can be followed in order to estimate the sway speed, Biancardi (1988). The simplest linear model is given by:

$$T_1\dot{v}+v=K_1\delta \quad \text{.....(3.9)}$$

This can be expanded to the following:

$$T_1T_2\ddot{v}+(T_1+T_2)\dot{v}+v=K_1\delta+K_1T_3\dot{\delta} \quad \text{.....(3.10)}$$

For use in simplified simulations this type of model for ship manoeuvring will indeed be adequate but for simulating manoeuvres where high order non-linearities occur, its performance is not sufficient. Current practice is that the input-output relationship model should not be used for ship manoeuvring predictors but can be used in applications to ship control, Honderd (1972).

3.3.2 The holistic model

This type of model has proven to be highly successful and is installed in many ship simulators in use today. Racal SMS Systems Ltd, as a marine simulator manufacturer, used this form of ship modelling in early versions of their MRNS9000 navigation simulator. The holistic model has been adopted and refined by many institutions with interests in hydrodynamics.

This type of model is highly formal and systematic. It treats the hull-water interface as a black box and models the system as a complete entity. It is based on the premise that a manoeuvre is a small perturbation from an equilibrium state of steady forward motion at a nominal service speed. It has been used successfully for the simulation of ship manoeuvres by the application of rudder control by Strom-Tejsen (1965), and, in a modified form has been applied to engine manoeuvres by Crane (1973) and Eda (1974), despite the fact that such manoeuvres can hardly be described as small perturbations.

Dand (1987) describes this type of model as

" a model which performs satisfactorily when taken as a whole, but does not allow individual elements to be changed readily as the design is changed"

The former Ship Control Group at the University of Plymouth has used this type of model in past research. The selection of the important non-linear terms were made by reviewing the work of Strom-Tejsen (1965), Lewison (1973), Gill (1976) (1980) and Eda and Crane (1965). The non-linear functions of the control parameters (rudder and propeller) were also required in the final non-linear equations of motion.

The complete set of the holistic model non-linear equations of motion as evaluated by Burns (1984) become:

$$m\dot{u} - mrv = X_{\dot{u}}\dot{u} + X_u(u+u_c) + \overline{X}_{uu}u^2 + \overline{X}_{uuu}u^3 + \overline{X}_{vv}v^2 + \overline{X}_{rr}r^2 + \overline{X}_{\delta\delta}\delta_A{}^2 + \\ \ldots\ldots \overline{X}_{un}un_A + \overline{X}_{nn}n_A{}^2 + x_{u_a}u_a$$

$$m\dot{v} + mur = Y_{\dot{v}}\dot{v} + Y_v(v+v_c) + Y_{\dot{r}}\dot{r} + Y_r r + \overline{Y}_{nn}n_A{}^2 + \overline{Y}_{vvv}v^3 + \overline{Y}_{rvv}rv^2 + \\ \ldots\ldots \overline{Y}_{nn\delta}n_A{}^2\delta_A + \overline{Y}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{Y}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a \qquad \ldots\ldots\ldots(3.11)$$

$$I_z\dot{r} = N_{\dot{v}}\dot{v} + N_v(v+v_c) + N_{\dot{r}}\dot{r} + \overline{Y}_{nn}n_A{}^2 + \overline{N}_{vvv}v^3 + N_r r + \overline{N}_{rvv}rv^2 + \\ \ldots\ldots \overline{N}_{nn\delta}n_A{}^2\delta_A + \overline{N}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{N}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a$$

The above model has been described in various papers, Burns et al (1982) (1985a) and has been shown to give accurate representation of the three degrees of ship motion in all manoeuvring situations. A comparative evaluation of the mathematical model was made with full scale measurements taken for the USS Compass Island by Morse and Price (1981). The USS Compass Island was constructed with a Mariner type hull form and a complete set of hydrodynamic coefficients for this class of vessel have been measured by Chislet and Strom-Tejsen (1965) using the Planar Motion Mechanism Test.

Although this model gives accurate simulations of ship manoeuvring it does not allow rudder, propeller or hull geometry to be changed with ease. Modern day requirements of mathematical models do require the model to be adaptable.

3.3.3 The force mathematical model

This type of model was first proposed by McCallum (1980) and essentially treats the hull as a lifting surface inclined at a drift angle to the water flow, thus generating lift and drag forces, as on an aerofoil section. McCallum postulates that a linear relationship exists between the lift force on the hull to the angle of incidence, up to about one radian, whilst

the drag force increases quadratically from some minimum value at a zero angle of incidence. The rudder, also being a higher aspect ratio aerofoil section, is also modelled in the same manner. It is not to be expected that a simple model of this sort will be able to give accurate manoeuvring predictions over the very wide range of operating conditions experienced.

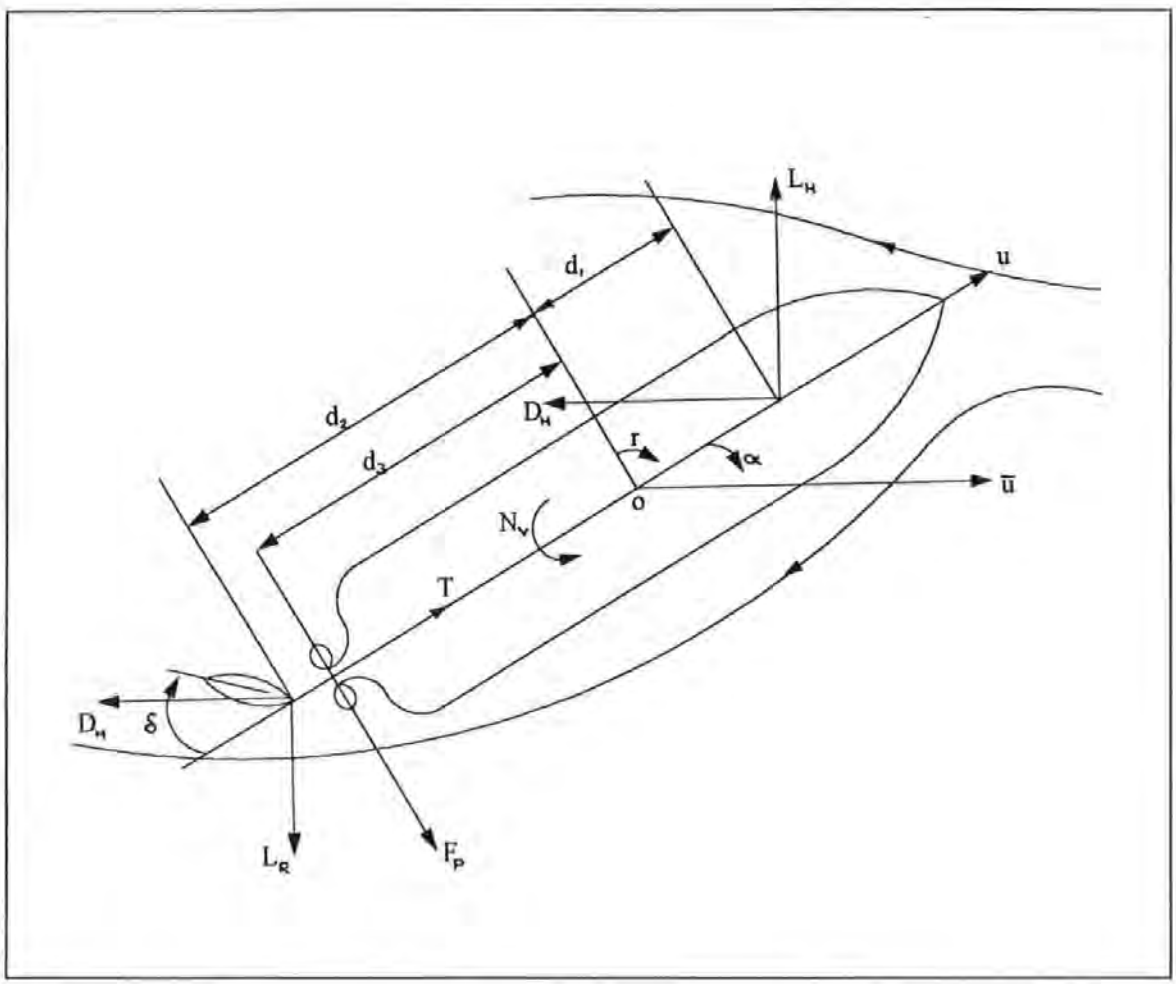


Figure 3.3. Forces and moments acting on a ship.

Figure 3.3 shows the forces and moments acting on the vessel. From these McCallum developed the three equations of motion in the following form.

For the surge equation, the total mass m_1, may be expected to change with the direction of fluid flow.

$$m_1\dot{u} = [T_P + L_H \sin\alpha - D_H \cos\alpha - L_R \sin\alpha_e - D_R \cos\alpha_e + m_2 vr] \quad \text{.....(3.12a)}$$

The sway equation may be similarly written as:

$$m_2\dot{v} = [-L_H \cos\alpha - D_H \sin\alpha + L_R \cos\alpha_e - D_R \sin\alpha_e - m_1 ur + F_p] \quad \text{.....(3.12b)}$$

The yaw equation is obtained by taking moments about the centre of gravity.

$$I_z\dot{r} = [-N_v - L_H d_1 \cos\alpha - D_H d_1 \sin\alpha + L_R d_2 \cos\alpha_e - D_R d_2 \sin\alpha_e + d_3 F_P] \quad \text{.....(3.12c)}$$

Research work is still continuing to refine this type of model and to investigate different methods of calculating the hydrodynamically generated forces by both slender-body theory and wind tunnel experiments, Pourzanjani et al (1987). The later versions of the Racal Marine Systems Ltd MRNS9000 navigation simulator employ models based on this approach and incorporates a basic ship's editor to enable other ship types to be modelled.

3.3.4 The modular manoeuvring model

Current research on ship manoeuvring modelling tends to favour this type of model as shown by the Mathematical Model Group (MMG) of the Society of Naval Architects of Japan, Ogawa (1978). This was subsequently followed by various papers on the subject, Inoue et al (1981), Kose (1982), and a further refined model in 1984 to simulate various ship manoeuvring motions in harbour, Kose (1984). Research in Germany, by Oltmann and Sharma (1984), is based on the modular concept, as is the modular manoeuvring model developed at British Marine Technology Ltd (BMT) between 1983 and 1984.

A modular manoeuvring model is one in which the individual elements, such as the hull, propeller, rudder, engines, and external influences, of a manoeuvring ship are each represented as separate interactive modules. Each module, whether it relates to hydrodynamic or control forces or external effects is self-contained. The modules are constructed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and expressing their interaction by other physical expressions.

The equations of motion for a modular manoeuvring model are generally expressed by:

$$\begin{aligned} m\dot{u} - mrv &= X_H + X_P + X_R + X_E \\ m\dot{v} - mru &= Y_H + Y_P + Y_R + Y_E \\ I_Z\dot{r} &= N_H + N_P + N_R + N_E \end{aligned} \quad \text{.....(3.13)}$$

where the suffixes H, P, R and E denote components of hull, propeller, rudder and external forces.

The model arranged in this way lends itself to a number of applications. For example it allows research on one particular module and the effect that module has on the system

model as a whole. This is invaluable when trying to determine the effect of various rudder areas on the manoeuvring performance of a vessel. Previously a series of captive model tests had to be undertaken to select optimal rudder area. Advances in any particular field of related research can be incorporated into a module and into the system as a whole without having to alter other system modules.

Other advantages of this approach are the expansion facilities it allows. In addition to the modules shown in equation set (3.13), extra modules can be employed to simulate bow thrusters and stern thrusters for example. The surge equation would then look like:

$$m\dot{u} - mrv = X_H + X_P + X_R + X_E + X_B + X_S \quad \text{.....(3.14)}$$

where the suffixes B and S denote the components of bow and stern thrusters. Hence the model can be tailored to suit a number of applications and such effects as ship to shore and ship to ship interaction can be investigated. Gradually a very sophisticated model incorporating all of the more specialised attributes was developed by Tapp (1989), which will be shown in detail in a later section along with simulated results.

3.4 Hydrodynamic Coefficients

It has already been seen that the equations of motion to represent a ship contain the hydrodynamic coefficients. The hydrodynamic forces of a rigid body, travelling with forward speed in free surface waves, is a complicated problem, Abkowitz (1969), Baar (1984). Hence, the accuracy of the motion predicted not only depends on the type of mathematical model, but significantly on the ability to determine these hydrodynamic forces, Abkowitz (1980).

The hydrodynamic coefficients required in the equations of motion of a body moving through a fluid are usually classified into three general categories, Barr (1987):

i. static - coefficients due to the components of linear velocities of the body relative to the fluid;

ii. rotary - coefficients due to components of angular velocity;

iii. acceleration - coefficients due to either linear or angular acceleration components, also termed 'added mass' coefficients.

The number and types of hydrodynamic coefficients required will vary depending upon on the complexity of the problem being investigated, the type of mathematical model, and the

extent to which various hydrodynamics effects are included in the representation. There is little point increasing the number of coefficients in the mathematical model if their effect is a marginal contribution to the main forces and moments acting on the ships hull.

3.4.1 Derivation of Hydrodynamic Coefficients

Various methods for deriving the hydrodynamic coefficients may be summarised as follows.

- Estimation and extrapolation from already available models may be held in some form of data base, Oltmann and Sharma (1984). Ship manoeuvring performance data bases, containing data from ships trials and model tests can provide hydrodynamic coefficients from a number of vessels. One such data base is that established by the US. Coast Guard, Barr and Miller (1983).

- Captive model tests made in a towing tank, Gill and Price (1977). This method is expensive and only available to large research establishments specialising in hydrodynamic investigations. It includes such tests as the Planar Motion Mechanism and the Rotating Arm.

- Free running model experiments, De Vries (1984). This method entails access to an open stretch of sheltered water and involves considerable instrumentation implementation to obtain worthwhile data. One methodology by which this is accomplished is termed 'parameter identification'.

- Calculation of the constants from hydrodynamic theory, Mikelis (1982). Such methods are particularly useful for the estimation of the 'acceleration derivatives'.

- Empirical calculation methods related to the basic geometry of the ship, Clarke (1983).

- Wind tunnel tests. Pourzanjani et al (1987).

- Full scale ship trials, Norrbin (1971) and Burns et al (1985b). By suitable instrumentation all the necessary coefficients may be derived by this method without the necessity of scaling, as required by model experiments. The basic trial needed to derive the equations of motion is a spiral manoeuvre, such as the Bech reverse-spiral technique, Bech (1966).

- System identification methods, Abkowitz (1980). If all of the inputs and the associated outputs of a system are known, then the system can be 'identified'. In the case of a manoeuvring ship if the inputs (control actions) are known and the ensuing outputs

(the ship's motion responses) are known, the equations of motion and the numerical values of the coefficients can be determined.

CHAPTER 4

MODEL FORMULATION AND SIMULATION

4.1 Introduction

The four general mathematical types outlined in chapter 3 can, and do, produce accurate simulations. However, the ACAS requires the model to be both accurate and adaptable. This chapter will undertake simulations using various model types with the aim of concluding which model lends itself to the requirements of the ACAS.

The single input-output and force mathematical model have been discarded at this stage, the reason being that both of these model types require vessel trials or tank tests to obtain the required model components. The holistic and modular model hydrodynamic coefficients can either be calculated, estimated or obtained from published data.

The models used in the simulation exercise include:

1. Three degree of freedom linear holistic;
2. Four degree of freedom linear holistic;
3. Three degree of freedom non-linear holistic;
4. Four degree of freedom non-linear holistic;
5. Three degree of freedom non-linear modular.

For ease of comparison it was assumed that there was no current or wind and that all simulations were taking part in a flat calm seaway with no external influences.

A number of different vessel types were used throughout this study to assess the developed models adaptability. The vessels used include:

1. 25m training vessel - ITV Somerset;
2. 63m converted dredger - Sand Skua;
3. 11m catamaran - Catfish;
4. 325m tanker - Esso Osaka;
5. 161m Mariner hull;

6. 13m training vessel - Picket Boat 9;
7. 150m ro/ro ferry - MS Zenobia;
8. 152m container ship;
9. 150m car ferry.

The full details of these vessels are shown in appendix A and a full listing of coefficients derived/used are given in appendix B.

4.2 Manoeuvring Simulations

The model equations used in the simulation exercise are shown in sections 4.2.1-2.

4.2.1 The Holistic Model

Section 3.3.2 described the holistic model as

" a model which performs satisfactorily when taken as a whole, but does not allow individual elements to be changed readily as the design is changed "

This statement is due to the black box approach used by the holistic type model; the equation represents the whole vessel.

Roll has been included into some of the holistic models to see if accuracy can be improved. There is a natural roll caused by rudder movement and the turning of the vessel. Due to rudder motion the vessel will initially roll into the turn before sway forces make the vessel roll in the opposite direction and sustain this angle throughout the turning manoeuvre.

4.2.1.1 Three Degree of Freedom Linear Model

Surge is assumed constant in the linear model

$$m\dot{v} + mur = Y_v v + Y_{\dot{v}}\dot{v} + Y_r r + Y_{\dot{r}}\dot{r} + Y_\delta \delta$$

$$I_z\dot{r} = N_v v + N_{\dot{v}}\dot{v} + N_r r + N_{\dot{r}}\dot{r} + N_\delta \delta \qquad \text{.....(4.1)}$$

4.2.1.2 Four Degree of Freedom Linear Model

Surge is assumed constant in the linear model

$$m\dot{v} + mur = Y_v v + Y_{\dot{v}}\dot{v} + Y_r r + Y_{\dot{r}}\dot{r} + Y_\delta \delta + Y_p p + Y_{\dot{p}}\dot{p} + Y_\Phi \Phi$$

$$I_z \dot{r} = N_v v + N_{\dot{v}}\dot{v} + N_r r + N_{\dot{r}}\dot{r} + N_\delta \delta + N_p p + N_{\dot{p}}\dot{p} + N_\Phi \Phi \qquad \text{.....(4.2)}$$

$$I_x \dot{p} = K_v v + K_{\dot{v}}\dot{v} + K_r r + K_{\dot{r}}\dot{r} + K_\delta \delta + K_p p + K_{\dot{p}}\dot{p} + K_\Phi \Phi - mgGM\Phi$$

As calm water is only being considered here, the term $mgGM\Phi$ represents the vessels righting moment considered within the limits of its initial stability, i.e. the roll equation can be considered as;

$$\textit{Resultant moment} = \textit{Rolling moment} - \textit{Righting moment} \qquad \text{.....(4.2a)}$$

where the rolling moment is represented by the various hydrodynamic coefficients.

4.2.1.3 Three Degree of Freedom Non-linear Model

$$m\dot{u} - mrv = X_{\dot{u}}\dot{u} + X_u(u + u_c) + \overline{X}_{uu}u^2 + \overline{X}_{uuu}u^3 + \overline{X}_{vv}v^2 + \overline{X}_{rr}r^2 + \overline{X}_{\delta\delta}\delta_A{}^2 +$$
$$\ldots\ldots \overline{X}_{un}un_A + \overline{X}_{nn}n_A{}^2 + x_{u_a}u_a$$

$$m\dot{v} + mur = Y_{\dot{v}}\dot{v} + Y_v(v + v_c) + Y_{\dot{r}}\dot{r} + Y_r r + \overline{Y}_{nn}n_A{}^2 + \overline{Y}_{vvv}v^3 + \overline{Y}_{rvv}rv^2 +$$
$$\ldots\ldots \overline{Y}_{nn\delta}n_A{}^2\delta_A + \overline{Y}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{Y}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a \qquad \text{.....(4.3)}$$

$$I_z\dot{r} = N_{\dot{v}}\dot{v} + N_v(v + v_c) + N_{\dot{r}}\dot{r} + \overline{Y}_{nn}n_A{}^2 + \overline{N}_{vvv}v^3 + N_r r + \overline{N}_{rvv}rv^2 +$$
$$\ldots\ldots \overline{N}_{nn\delta}n_A{}^2\delta_A + \overline{N}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{N}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a$$

4.2.1.4 Four Degree of Freedom Non-linear Model

$$m\dot{u} - mrv = X_{\dot{u}}\dot{u} + X_u(u + u_c) + \overline{X}_{uu}u^2 + \overline{X}_{uuu}u^3 + \overline{X}_{vv}v^2 + \overline{X}_{rr}r^2 + \overline{X}_{\delta\delta}\delta_A{}^2 +$$
$$\ldots\ldots \overline{X}_{un}un_A + \overline{X}_{nn}n_A{}^2 + x_{u_a}u_a$$

$$m\dot{v} + mur = Y_{\dot{v}}\dot{v} + Y_v(v + v_c) + Y_{\dot{r}}\dot{r} + Y_r r + \overline{Y}_{nn}n_A{}^2 + \overline{Y}_{vvv}v^3 + \overline{Y}_{rvv}rv^2 +$$
$$\ldots\ldots \overline{Y}_{nn\delta}n_A{}^2\delta_A + \overline{Y}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{Y}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a + Y_\Phi\Phi +$$
$$\ldots\ldots Y_p p + Y_{\dot{p}}\dot{p} + \overline{Y}_{up}up + \overline{Y}_{ur\Phi}ur\Phi + \overline{Y}_{uu\Phi}uu\Phi + \overline{Y}_{uv\Phi}uv\Phi$$

.....(4.4)

$$I_z\dot{r} = N_{\dot{v}}\dot{v} + N_v(v+v_c) + N_{\dot{r}}\dot{r} + \overline{Y}_{nn}n_A{}^2 + \overline{N}_{vvv}v^3 + N_r r + \overline{N}_{rvv}rv^2 +$$
$$\ldots\ldots\overline{N}_{nn\delta}n_A{}^2\delta_A + \overline{N}_{nn\delta\delta\delta}n_A{}^2\delta_A{}^3 + \overline{N}_{\delta vv}\delta_A v^2 + Y_{v_a}v_a + N_\Phi\Phi +$$
$$\ldots\ldots N_p p + N_{\dot{p}}\dot{p} + \overline{N}_{up}up + \overline{N}_{uv\Phi}uv\Phi$$

$$I_x\dot{p} = K_v v + K_{\dot{v}}\dot{v} + K_r r + K_{\dot{r}}\dot{r} + K_\delta\delta + K_p p + K_{\dot{p}}\dot{p} + K_\Phi\Phi +$$
$$\ldots\ldots\overline{K}_{up}up + \overline{K}_{uv}uv + \overline{K}_{vv}vv + \overline{K}_{pp}pp - mgGM\Phi$$

4.2.2 Three Degree of Freedom Non-linear Modular Model

This model has the general form of equation set 4.5.

$$\begin{aligned} m\dot{u} - mrv &= X_H + X_P + X_R + X_E \\ m\dot{v} - mru &= Y_H + Y_P + Y_R + Y_E \\ I_Z\dot{r} &= N_H + N_P + N_R + N_E \end{aligned} \qquad \ldots\ldots\ldots(4.5)$$

Taking this equation set each of the modules can be looked at in turn.

4.2.2.1 Hull Forces and Moments

The hull forces and moments module contains all the hydrodynamic data which is specific to the hull alone. They can be expressed by equation set 4.6.

$$X_H = X_{\dot{u}}\dot{u} + X_{vr}vr + X_{vv}v^2 + \frac{u}{|u|}X_{rr}r^2 + X_u u + \frac{u}{|u|}X_{uu}u^2 + X_{uuu}u^3$$

$$Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{uv}uv + \frac{u}{|u|}Y_{ur}r + Y_{vvv}v^3 + Y_{rvv}rv^2$$

$$N_H = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{ur}r + \frac{u}{|u|}N_{uv}v + N_{vvv}v^3 + N_{rvv}rv^2 \qquad \ldots\ldots\ldots(4.6)$$

The equations are a further development of previous research work, Burns (1984), on the holistic type model with the important non-linear terms being similar to enable comparisons of the models to be made. The multiplier $u/|u|$ included in some of the terms is to correct the sign of the derivative during astern motion of the ship.

4.2.2.2 Propeller Forces and Moments

In order to model the motion of a ship for both ahead and astern motion it is important to determine correctly the propeller forces and moments. Tapp (1989), to cover all manoeuvring regimes, adopted the method of modelling the propeller forces and moments published by Oltmann and Sharma (1984) and Mikelis (1985). This method is based upon knowledge of the thrust coefficient:

$$C_T^* = \frac{2T_P}{\rho A_o (up^2 + cp^2)} \qquad \text{.....(4.7)}$$

for the whole range of the hydrodynamic advance angles, ε, for the propeller.

$$\tan\varepsilon = \frac{up}{cp} = \frac{up}{0.7\pi nD} \qquad \text{.....(4.8)}$$

The hydrodynamic advance angle can be defined in any of four quadrants to cover the entire range of propeller operating conditions as can be seen in figure 4.1.

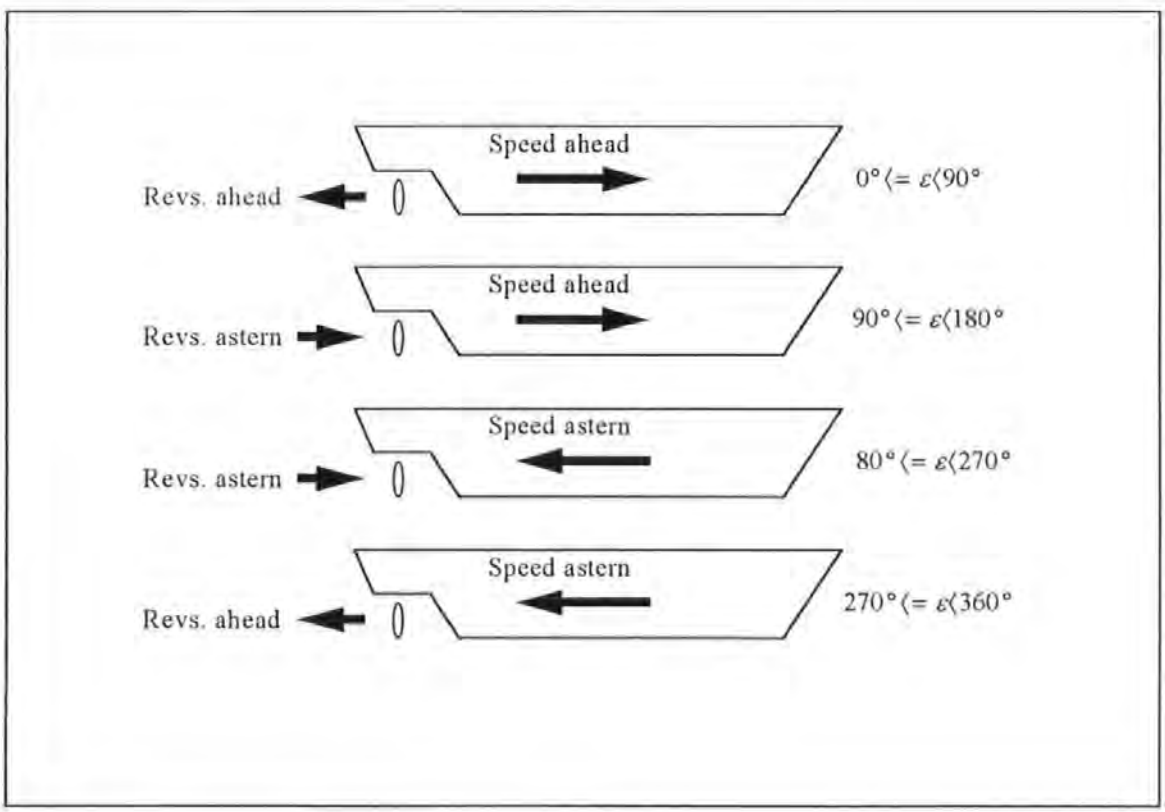


Figure 4.1. Four quadrant propeller operation.

Van Lammeren et al (1969) published data on the Wageningen B-series propellers operating in four quadrants. Figure 4.2 shows the open water test results for the B4.70 series, 4 bladed with a 0.70 disc area ratio, for various pitch/diameter ratios.

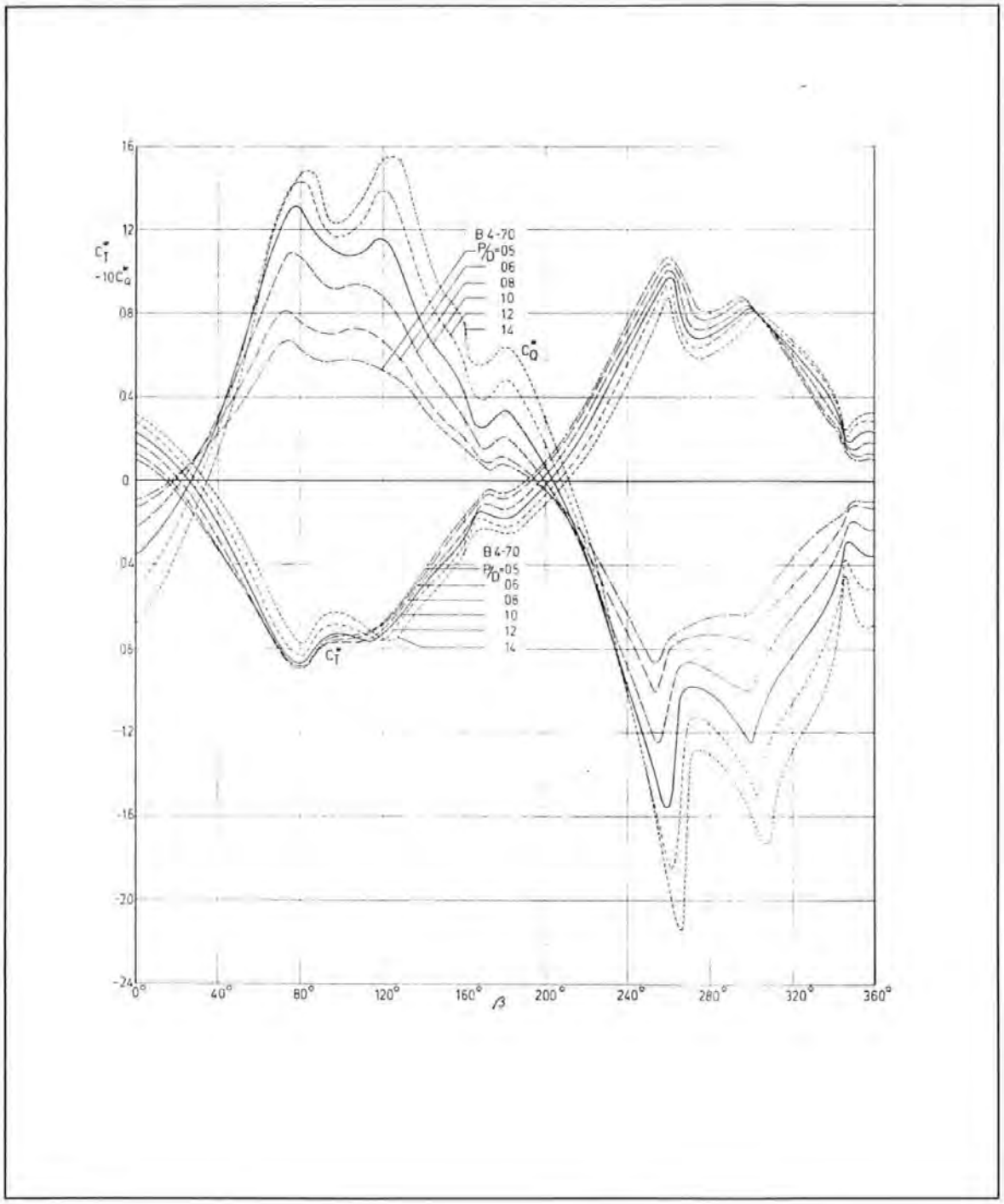


Figure 4.2. Open water test results for the B4.70 propeller operating in four quadrants, after Van Lammeren et al (1969).

For the given advance angle the thrust coefficient for that operating condition can be obtained. For use in a simulation program the thrust coefficient, and hence the propeller thrust, can be modelled by fitting a Fourier series or least squares polynomial fit to the required *P/D* curve.

Once the thrust has been obtained the surge, sway and yaw terms can be determined:

$$X_P = (1-t)T$$

$$Y_P = Y_{nn} n^2$$

$$N_P = N_{nn} n^2 \qquad \text{.....(4.9)}$$

4.2.2.3 Rudder Forces and Moments

From Hirano et al (1987), and using the sign convention adopted by Tapp (1989), the forces and moments induced on the ship due to rudder action are given by:

$$X_R = (1-t_R)F_N \sin(\delta)$$

$$Y_R = -(1+a_H)F_N \cos(\delta)$$

$$N_R = (1+a_H)F_N X_R \cos(\delta) \qquad \text{.....(4.10)}$$

F_N is the normal force produced by the rudder, and may be defined by:

$$F_N = \frac{\rho}{2}\frac{6.13\lambda}{\lambda+2.25} A_R \overline{ur}^2 \sin(\alpha_R) \qquad \text{.....(4.11)}$$

where λ is the rudder aspect ratio. $\overline{ur}^2$, the mean squared slipstream velocity, and α_R, the rudder angle of attack, can be calculated as shown by Tapp (1989).

a_H and t_R are correction factors to adapt the open-water characteristics of the rudder to behind-hull conditions. From figure 4.3, a_H can be determined from knowledge of the form factor of the hull, C_B. The value of t_R can be estimated from the reduction in forward speed of the ship when turning.

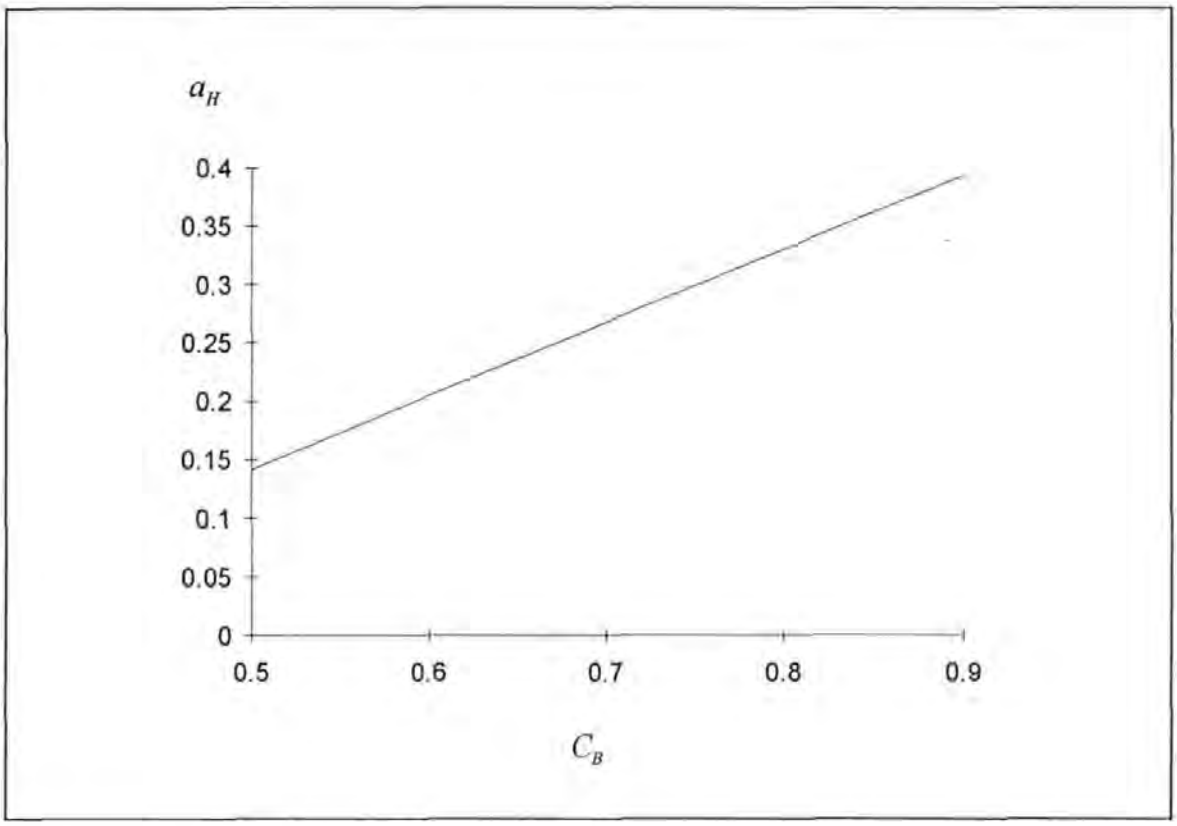


Figure 4.3. Ratio of induced force ship on hull by rudder action to the normal rudder force against hull form factor.

4.2.3 Simulations

Computer programs were developed using FORTRAN 77 on a Prime main-frame computer for the holistic models and Microsoft 'C' on a PC based 486 machine for the modular model. The reason for using the Prime main-frame computer was to use and edit a simple linear model that already existed, Dove (1984). Simulations were run of the following.

1. Turning circles. The simulations were performed with rudder angles +/- 5, 10, 20, and 30 degrees.
2. Kempf Zig-Zag manoeuvres. These give an indication of the effectiveness of the rudder to initiate and check changes in heading and will also show if there is any build up of roll caused by sudden changes in rudder. Deviations about headings of 5, 10 and 20 degrees were simulated.
3. A simple alteration in heading by a change of course is simulated to show the roll angle that is most likely to be experienced in normal practice.

Figures 4.4-4.10 show a range of plots for the various models.

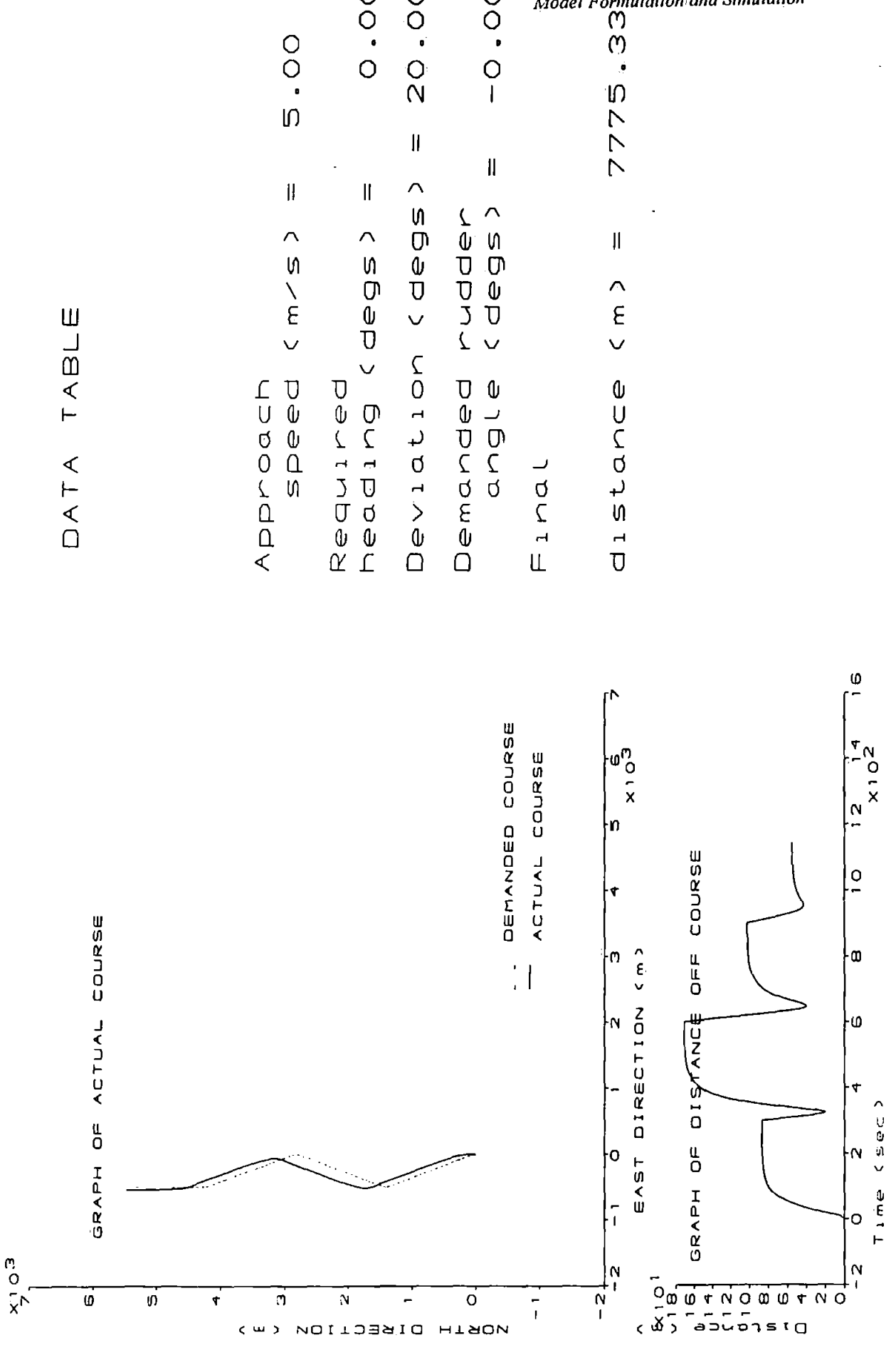


Figure 4.4a. Linear 3 degree holistic model (container vessel).

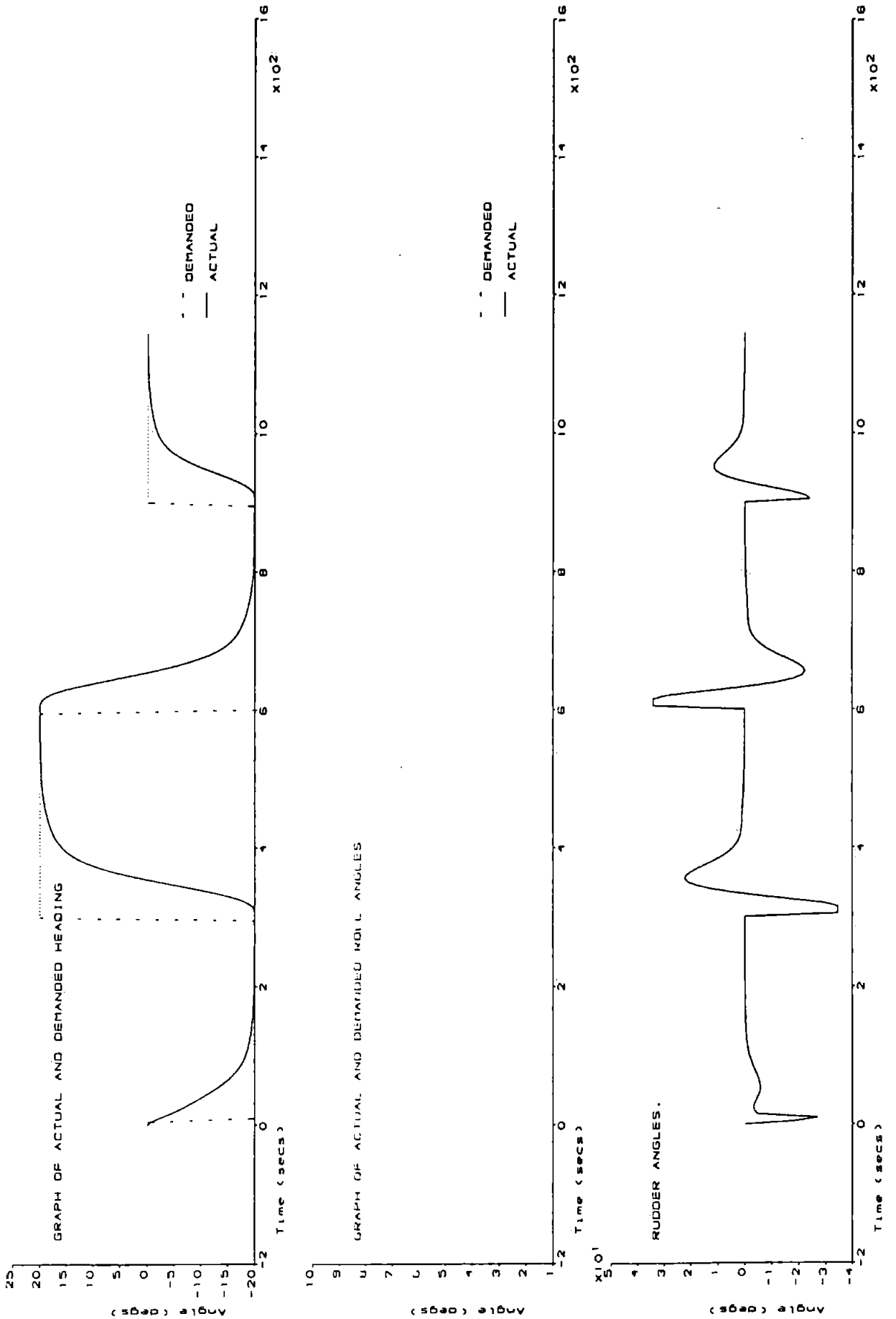

GRAPH OF ACTUAL AND DEMANDED HEADING
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
GRAPH OF ACTUAL AND DEMANDED ROLL ANGLES
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
RUDDER ANGLES.
x10¹
Angle (degs)
Time (secs)
x10²

Figure 4.4b.

DATA TABLE

Approach speed (m/s) =	5.00
Required heading (degs) =	45.00
Deviation (degs) =	-0.00
Demanded rudder angle (degs) =	-0.00
Final distance (m) =	5955.40

Figure 4.5a. Linear 3 degree holistic model (container vessel).

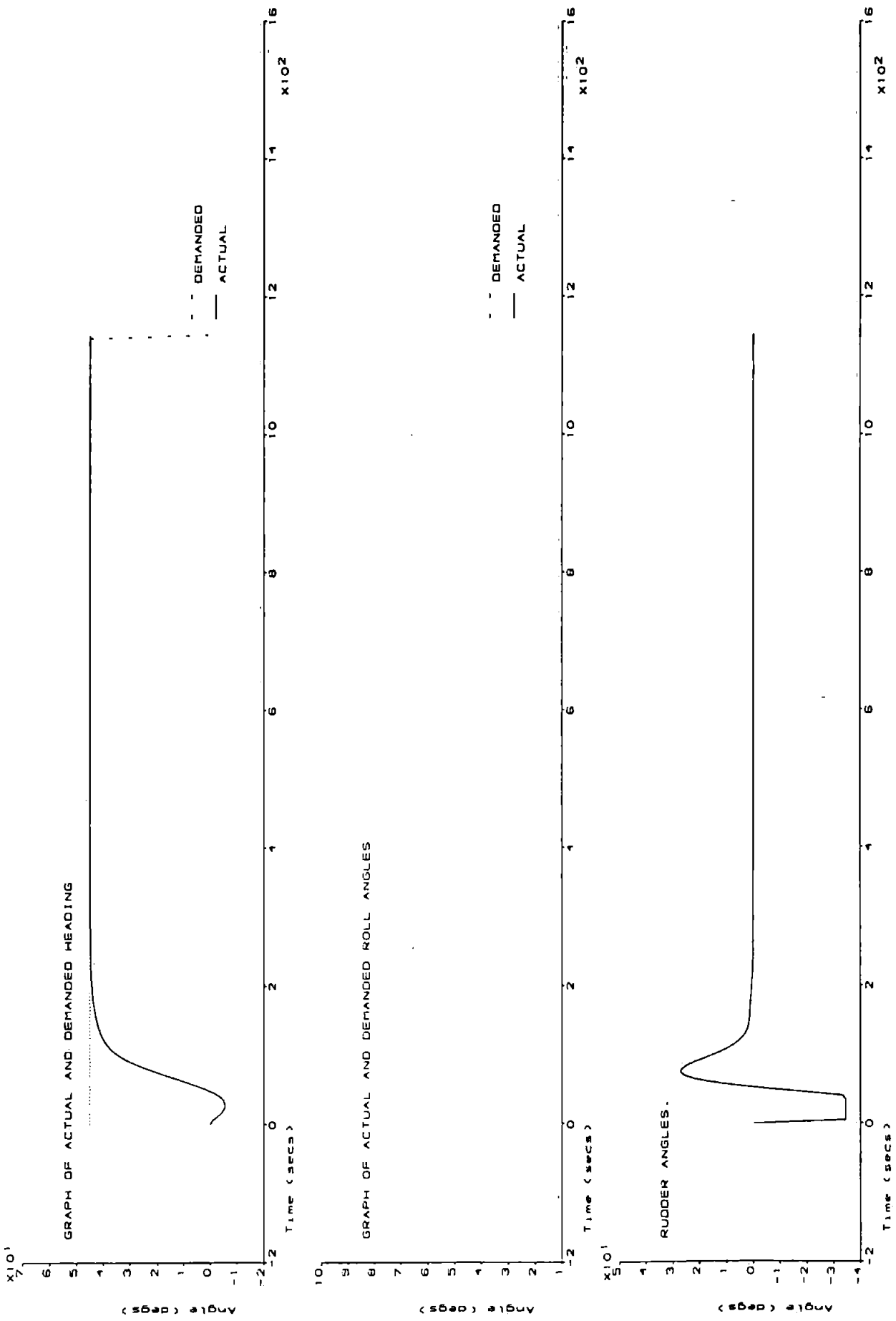

GRAPH OF ACTUAL AND DEMANDED HEADING
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
GRAPH OF ACTUAL AND DEMANDED ROLL ANGLES
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
RUDDER ANGLES.
Angle (degs)
Time (secs)
x10²

Figure 4.5b.

DATA TABLE

Approach speed (m/s) =	5.00
Required heading (degs) =	0.00
Deviation (degs) =	20.00
Demanded rudder angle (degs) =	-0.00
Max roll (degs) =	7.23
Final distance (m) =	7816.92

Figure 4.6a. Linear 4 degree holistic model (container vessel).

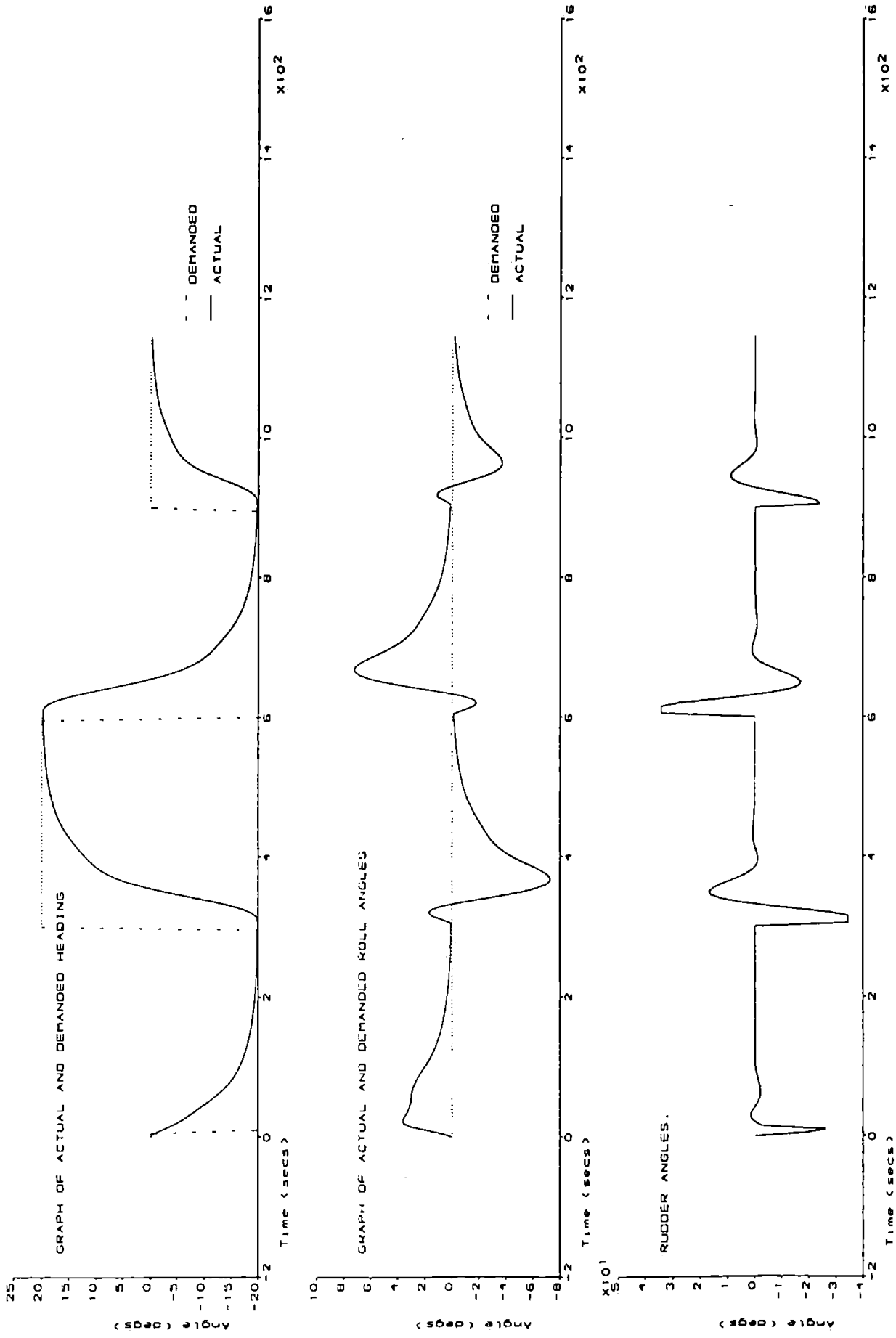

GRAPH OF ACTUAL AND DEMANDED HEADING
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
GRAPH OF ACTUAL AND DEMANDED ROLL ANGLES
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
RUDDER ANGLES.
x10¹
Angle (degs)
Time (secs)
x10²

Figure 4.6b.

DATA TABLE

Approach speed (m/s) =	5.00
Required heading (degs) =	45.00
Deviation (degs) =	-0.00
Demanded rudder angle (degs) =	-0.00
Max roll (degs) =	8.62
Final distance (m) =	5993.05

Figure 4.7a. Linear 4 degree holistic model (container vessel).

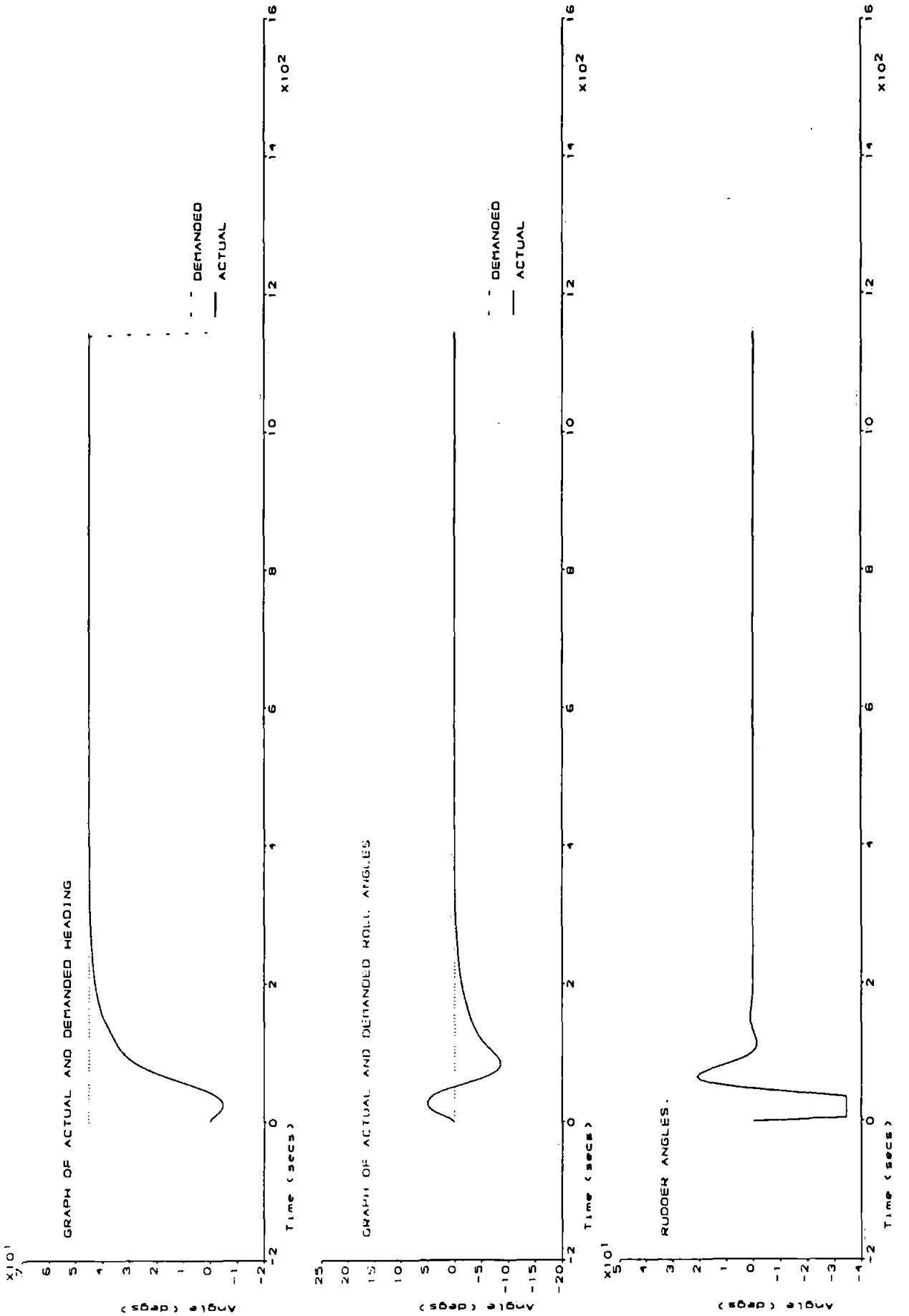

GRAPH OF ACTUAL AND DEMANDED HEADING
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
GRAPH OF ACTUAL AND DEMANDED ROLL ANGLES
DEMANDED
ACTUAL
Angle (degs)
Time (secs)
x10²
RUDDER ANGLES.
Angle (degs)
Time (secs)
x10²

Figure 4.7b.

DATA TABLE

Approach speed (m/s) = -0.00

Required heading (degs) = 0.00

Deviation (degs) = 20.00

Demanded rudder angle (degs) = -0.0(

Max roll (degs) =-0.00

Final distance (m) = 4259.44

Figure 4.8a. Non-linear 3 degree holistic model (150m Ro/Ro ferry).

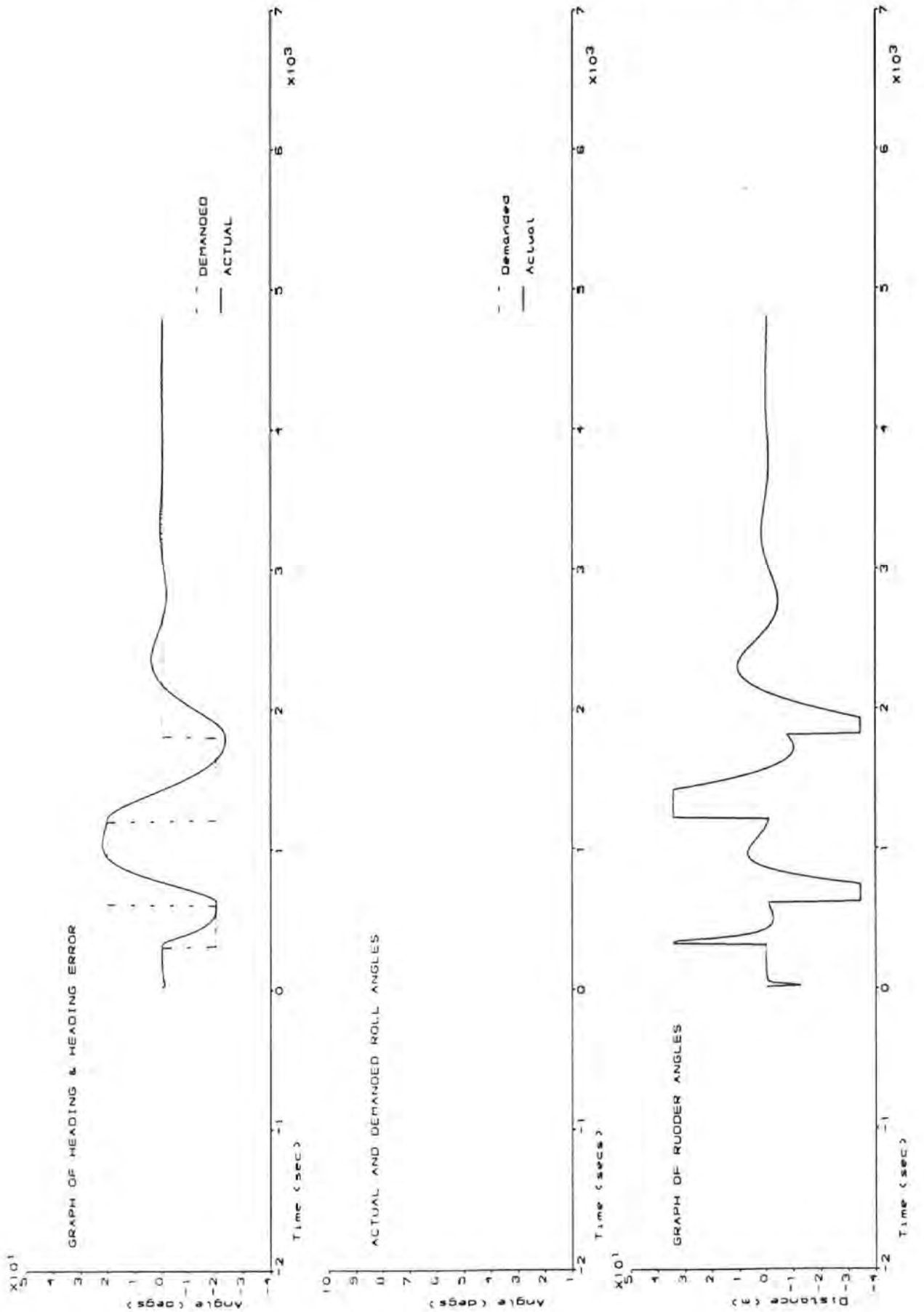

GRAPH OF HEADING & HEADING ERROR
DEMANDED
ACTUAL
Angle (degs)
Time (sec)
x10³
ACTUAL AND DEMANDED ROLL ANGLES
Demanded
Actual
Angle (degs)
Time (secs)
x10³
GRAPH OF RUDDER ANGLES
Distance (m)
Time (sec)
x10³

Figure 4.8b.

DATA TABLE

Approach speed (m/s) = -0.00

Required heading (degs) = 45.00

Deviation (degs) = -0.00

Demanded rudder angle (degs) = -0.0(

Max roll (degs) =-0.00

Final distance (m) = 2656.23

Figure 4.9a. Non-linear 3 degree holistic model (150m Ro/Ro ferry).

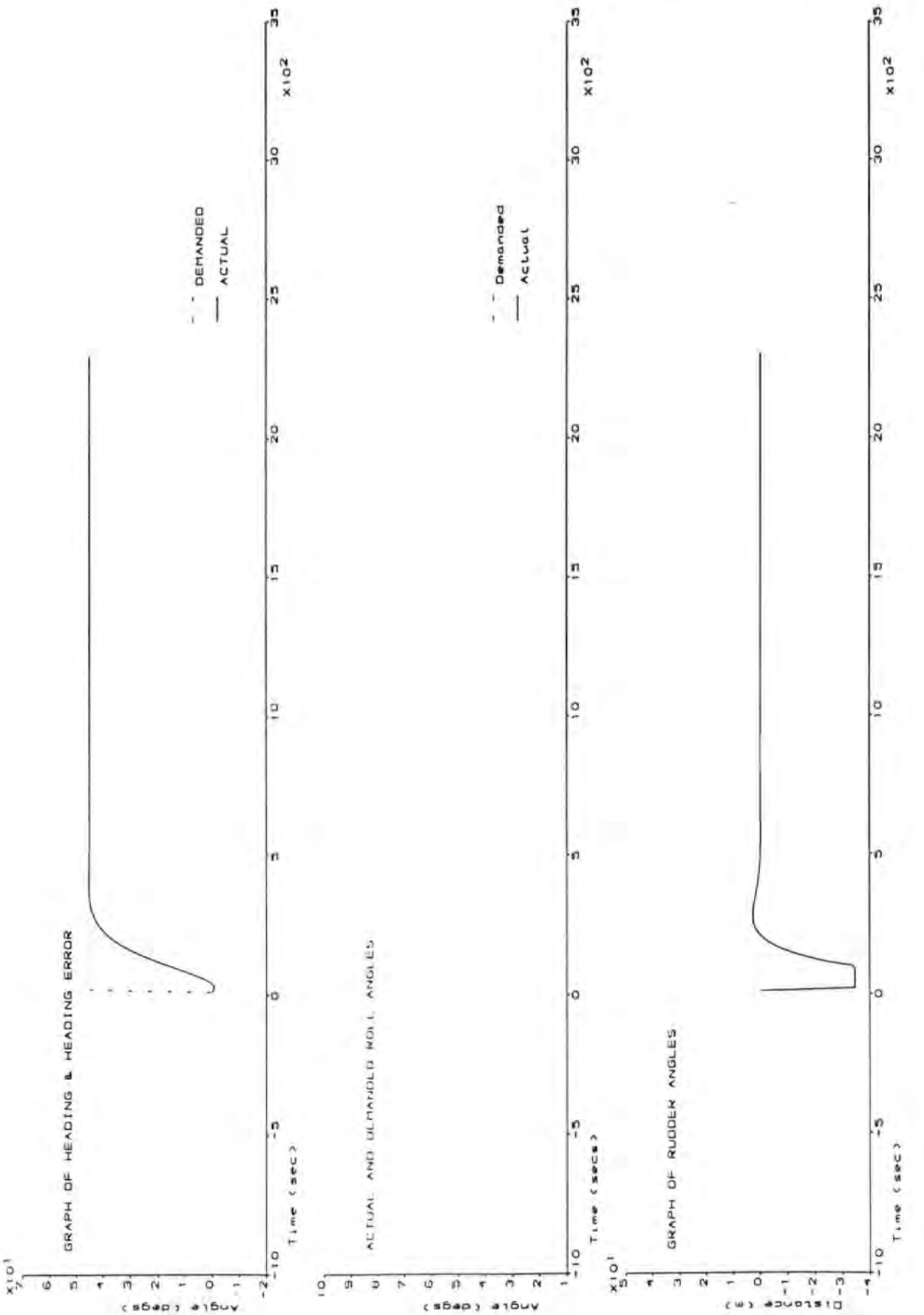

GRAPH OF HEADING & HEADING ERROR
DEMANDED
ACTUAL
Angle (degs)
Time (sec)
x10²
ACTUAL AND DEMANDED ROLL ANGLES
Demanded
Actual
Angle (degs)
Time (secs)
x10²
GRAPH OF RUDDER ANGLES
Distance (m)
Time (sec)
x10²

Figure 4.9b.

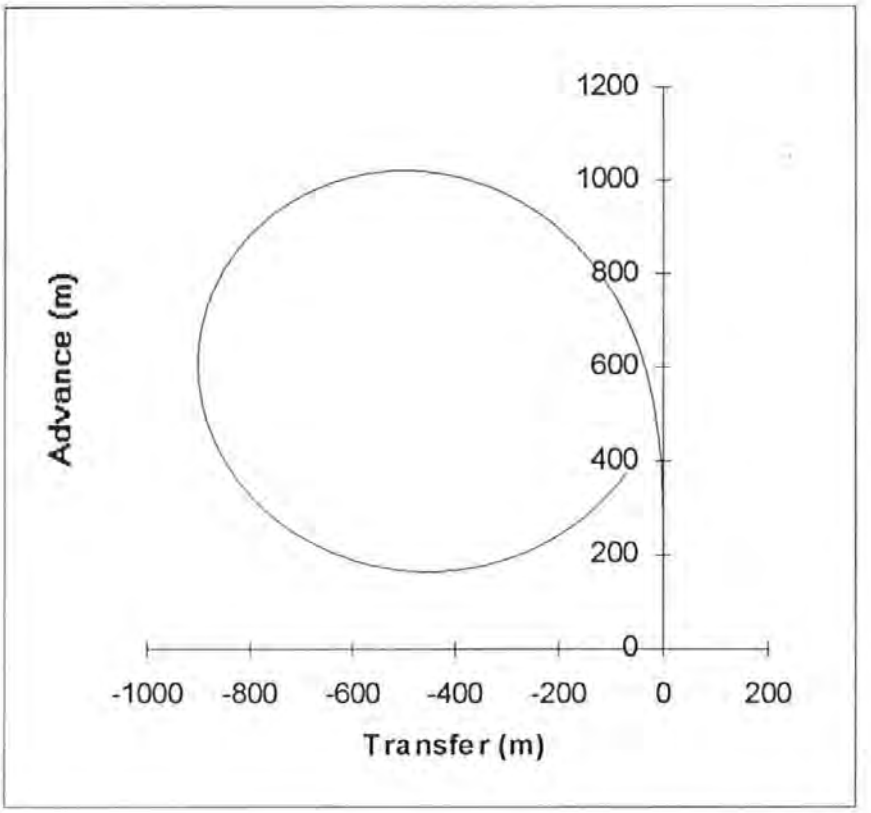


Figure 4.10a. Non-linear 3 degree modular model (Esso Osaka). 35° Port turning circle.

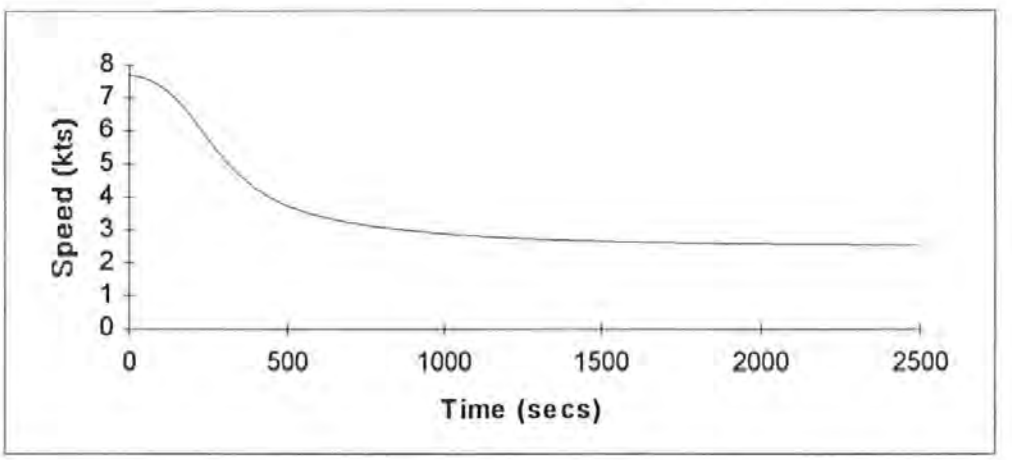


Figure 4.10b. Speed reduction

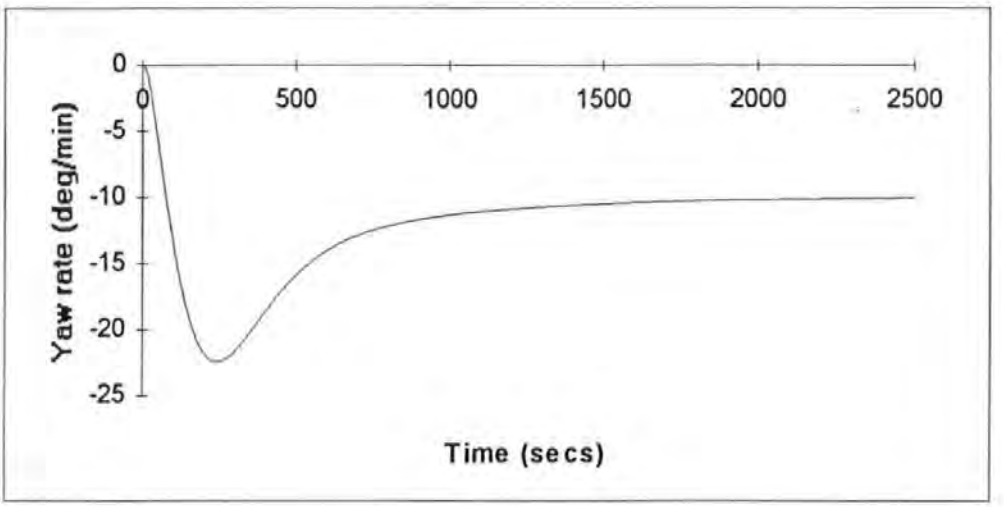


Figure 4.10c. Yaw rate.

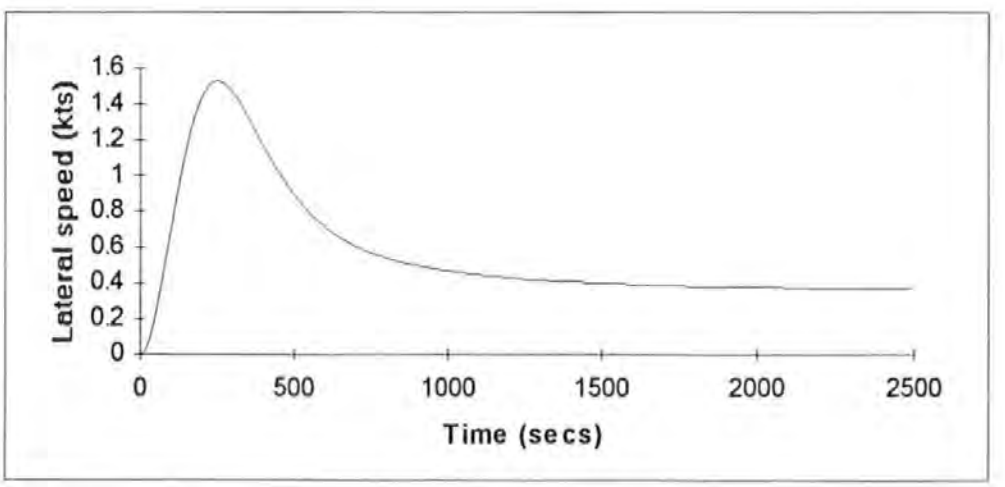


Figure 4.10b. Lateral speed.

4.3 Discussion

The difficulty when undertaking a comparison of various models and vessels is to obtain all the required hydrodynamic coefficients and model components. The coefficients for the simulated vessels were obtained from various references, as shown in appendix B, and where they could not were calculated or estimated.

A direct comparison between different model types was not the ultimate aim of this exercise. All models, for a particular vessel, can be made to work and produce accurate results. This may seem a very bold statement but with the correct model input data holds true. The requirement of this exercise, in the model formulation and simulation, is to find the most adaptable model with an acceptable accuracy. Each model will now be discussed in turn.

4.3.1 Three Degree of Freedom Linear Holistic

This model lends itself to being adaptable as all of the required hydrodynamic coefficients can easily be obtained due to them being linear. However, this model cannot be considered accurate as the forward velocity of the vessel is assumed to remain constant during a turning manoeuvre. Reduction in speed during a turn could be an important aspect for the ACAS and therefore this model is not suitable.

4.3.2 Four Degree of Freedom Linear Holistic

Accuracy over the three degree of freedom linear holistic model could be improved slightly if a vessel with a high freeboard or superstructure were to be modelled. This model will be unsuitable for the ACAS for the same reasons given in section 4.3.1.

4.3.3 Three Degree of Freedom Non-Linear Holistic

This model proved to be accurate when modelling a number of vessels. The majority of hydrodynamic coefficients could be obtained reasonably well, however, some of the higher order non-linear terms could only be obtained from publications containing full scale or tank test results. A model that works well with questionable adaptability.

4.3.4 Four Degree of Freedom Non-Linear Holistic

As with the three degree of freedom non-linear model this model can produce accurate simulations. However, due to the extra degree of freedom and hence, the extra hydrodynamic coefficients, it does not lend itself to be adaptable.

4.3.5 Three Degree of Freedom Non-Linear Modular

This model proved accurate and showed the most promise in terms of its adaptability. The formulation of the model being separated into modules allows for propeller, rudder data or external influences to be altered without resulting in the whole model being recalculated. Some of the higher order non-linear hull terms were difficult to obtain, however, this problem will be addressed in chapter 5 now that this model has shown itself to be the most suitable.

CHAPTER 5

THE ADAPTABLE MODULAR MODEL

5.1 Introduction

During the past ten years fellow researchers at the University of Plymouth have developed a comprehensive range of mathematical models, of various forms and fidelity, for many different ship types, Burns (1984), Tapp (1989) and Miller (1990). The main drawback with these models is that they are time consuming to formulate and expensive to produce, requiring tank tests or full scale trials to obtain the necessary hydrodynamic coefficients. An adaptable mathematical model, when fitted into the ACAS, should allow the system to be 'portable' between vessels without requiring expensive trials.

In chapter 4 it was concluded that the modular model had the greatest potential to be 'adaptable'. The model presented in section 4.4 will be investigated in greater detail and modified to create an adaptable mathematical model. Methods to calculate all necessary hydrodynamic coefficients, forces and moments will be developed.

5.1.1 Derivation of Modules and their Coefficients

It has already been seen that the modular manoeuvring model is one in which the individual elements, such as the hull, propeller, rudder, engines and external influences of a manoeuvring ship are each represented as separate interactive modules. This philosophy is demonstrated in figure 5.1, where it can also be seen that additional modules can be continuously added. Each module, whether it relates to hydrodynamic or control forces or external effects, is self contained. The modules are constructed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and describing their interaction by other physical expressions.

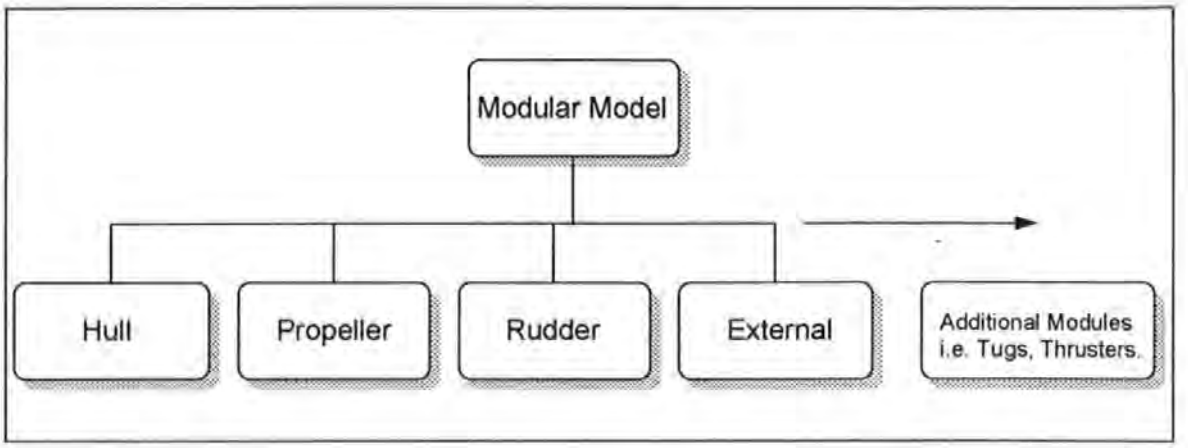


Figure 5.1. Structure of the modular model.

5.2 Hull Forces and Moments

The equations for the hull forces and moments have already been shown in equation set 4.6. The modified set for the adaptable model are shown below.

$$X_H = X_{\dot{u}}\dot{u} + R_H$$
$$Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{uv}v + \frac{u}{|u|}Y_{ur}r \qquad \text{.....(5.1)}$$
$$N_H = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{ur}r + \frac{u}{|u|}N_{uv}v$$

It will be seen that this is a reduced equation set with the following terms deleted:

$$X_{vr}vr,\ X_{vv}v^2,\ X_{vr}vr,\ X_{rr}r^2,\ Y_{vvv}v^3,\ Y_{rvv}rv^2,\ N_{vvv}v^3 \text{ and } N_{rvv}rv^2.$$

These coefficients are difficult to obtain without full scale trials or tank tests and were found not to affect the models performance to any great extent. This will be demonstrated in section 6.4.4 where it can be seen that only the vessels initial turning characteristics are affected, resulting in a slightly tighter turning circle.

5.2.1 Sway and Yaw Terms

Clarke (1982) published work allowing empirical methods to be used for deducing linear acceleration and velocity derivatives from a basis of hull geometry. Clarke analysed sets of data from captive model experiments by multiple regression analysis and developed a set of

parametric equations to calculate the hydrodynamic derivatives of the hull form. These can be seen in equation set (5.2).

$$Y_{\dot{v}}' = -\pi\left(\frac{T}{L}\right)^2\left(1+0.16C_B\frac{B}{T}-5.1\left(\frac{B}{L}\right)^2\right)$$

$$Y_{\dot{r}}' = -\pi\left(\frac{T}{L}\right)^2\left(0.67\frac{B}{L}-0.0033\left(\frac{B}{L}\right)^2\right)$$

$$N_{\dot{v}}' = -\pi\left(\frac{T}{L}\right)^2\left(1.1\frac{B}{L}-0.041\frac{B}{T}\right)$$

$$N_{\dot{r}}' = -\pi\left(\frac{T}{L}\right)^2\left(\frac{1}{12}+0.017C_B\frac{B}{T}-0.33\frac{B}{L}\right)$$

$$Y_v' = -\pi\left(\frac{T}{L}\right)^2\left(1+0.4C_B\frac{B}{T}\right)$$

$$Y_r' = -\pi\left(\frac{T}{L}\right)^2\left(-0.5+2.2\frac{B}{L}-0.08\frac{B}{T}\right)$$

$$N_v' = -\pi\left(\frac{T}{L}\right)^2\left(0.5+2.4\frac{T}{L}\right)$$

$$N_r' = -\pi\left(\frac{T}{L}\right)^2\left(0.25+0.039\frac{B}{T}-0.56\frac{B}{L}\right)$$

.....(5.2)

Two systems exist for the non-dimensional analysis of parameters used in ship mathematical modelling.

i. The SNAME *prime* system, Lewis (1988); the units of mass, length and time are given by the mass of the ship, m, its length, L, and the time taken by the ship to cover the distance of its own length at its instantaneous speed, U.

ii. The *Bis* system, Norrbin (1971); the unit of mass becomes the mass of the water displaced by the ship, $\rho\nabla$; the unit of length is the length of the ship, L; and the unit of time becomes the time required for travelling one ship length at a speed corresponding to $F_n = 1$, i.e. $\sqrt{L/g}$.

The equations developed by Clarke (1982) give the non-dimensional hydrodynamic derivatives in terms of the *prime* system, this system was used in the holistic model calculations. When the original modular model was developed by Tapp (1989), he decided to adopt the *bis* system and this system was carried forward into the present research. Tapp used the *bis* system as it is applicable to ship manoeuvring in all regimes; the *prime* system uses instantaneous speed as one of its dimensionalising quantities, problems therefore occur when the instantaneous speed is zero, i.e. when reversing from ahead to astern. To convert the acceleration derivatives to the *bis* system of non-dimensionalisation it is necessary to multiply by a factor of $L^3/2\nabla$; to convert the velocity derivatives the correction factor is $L^3\,U/2\nabla\sqrt{gL}$. As an alternative to converting the velocity derivatives Norrbin (1971) derived the following formulae:

$$Y_{uv}'' = -\frac{\pi}{2} \times \frac{LT^2}{\nabla} \times 1.69 - 0.04$$

$$N_{uv}'' = -\frac{\pi}{4} \times \frac{LT^2}{\nabla} \times 1.28 + 0.02$$

$$Y_{ur}'' = \frac{\pi}{4} \times \frac{LT^2}{\nabla} \times 1.29 - 0.18 \qquad \text{.....(5.3)}$$

$$N_{ur}'' = -\frac{\pi}{8} \times \frac{LT^2}{\nabla} \times 1.88 + 0.09$$

To aid in the computation of the coefficients table 5.1 can be used to check the sign of the derivative.

Derivative	Sign of the derivatives
Y_v'	always negative
N_r'	always negative
N_δ'	always negative
N_v'	either positive or *negative*
Y_r'	either positive or *negative*
Y_δ'	always positive

N.B. Signs in italics refer to the signs of derivatives for usual ship forms.

Table 5.1. Signs of the Hydrodynamic Derivatives.

5.2.2 Surge Terms

The term R_H, in the surge equation of the modular model, represents the ship's total resistance on a straight course and is modelled by the following expression:

$$R_H = X_u u + \frac{u}{|u|} X_{uu} u^2 + X_{uuu} u^3 \quad \text{.....(5.4)}$$

A third order polynomial fit of the plot of the total resistance for a particular vessel against the associated longitudinal velocity, results in a cubic function of the form:

$$X = au + bu^2 + cu^3 \quad \text{.....(5.5)}$$

where; u = longitudinal velocity

X = total resistance

a = normal multiplier = X_u

b = square multiplier = $\overline{X}_{uu} = \frac{X_{uu}}{2}$

c = cubic multiplier = $\overline{X}_{uuu} = \frac{X_{uuu}}{6}$

The multipliers a, b, and c, and hence X_u, X_{uu} and X_{uuu}, can be determined by fitting a Lagrange polynomial to the total resistance curve, a routine is included in the model programme to undertake this. It is therefore necessary to obtain the total resistance of the vessel over the operating speed range by numerical means. The method adopted is detailed in section 5.3.

The final surge term, $X_{\dot{u}}$, has a constant value of -0.05. It was found to have this value after numerous simulation runs with varying vessel types.

5.3 Total Resistance

The total resistance to motion of a vessel in a calm seaway can be considered as summation of the individual components, Holtrop and Mennen (1982) and Holtrop (1984):

$$R_{Total} = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad \text{.....(5.6)}$$

where:

R_F = frictional resistance according to the ITTC[1]-1957 formula;

$1+k_1$ = form factor of the hull;

[1]ITTC is the International Towing Tank Conference.

R_{APP} = appendage resistance;
R_W = wave resistance;
R_B = additional pressure resistance of bulbous bow near the water surface;
R_{TR} = additional pressure resistance due to transom immersion;
R_A = model-ship correlation resistance.

5.3.1 Frictional Resistance ($R_F(1+k_1)$)

Water flowing past the wetted hull of a ship, by means of the boundary layer, exerts a shear force on the solid boundary in the direction of motion of the stream. This shear force is known as surface friction resistance. Due to the very large wetted surface area of the ship's hull, surface friction resistance is normally the largest component of the total resistance to motion of a vessel.

$$R_F = 0.5\rho S V_s^2 C_F \quad \text{.....(5.7)}$$

C_F is the coefficient of frictional resistance and, according to the 1957 ITTC, can be given by:

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \quad \text{.....(5.8)}$$

where S is the wetted surface area of the ship's hull. If unknown, S can be estimated from the following, statistically derived formula, Lewis (1988);

$$S = L(2T + B)C_M^{0.5}(0.4530 + 0.4425C_B - 0.2862C_M - 0.003467B/T + 0.3696C_{WP}) + 2.38A_{BT}/C_B \quad \text{.....(5.9)}$$

5.3.1.1 Form Factor of the Hull ($1+k_1$)

The form factor is assumed to be invariant with R_n, Lewis (1988), and relates the two-dimensional frictional resistance to the three-dimensional ship's hull. Holtrop (1984) gives the following formula for the form factor:

$$1 + k_1 = 0.93 + 0.487118c_{14}(B/L)^{1.06806}(T/L)^{0.46106}(L/L_R)^{0.121563}(L^3/\nabla)^{0.36486}(1 - C_P)^{-0.604247} \quad \text{.....(5.10)}$$

L_R is defined by;

$$L_R = L(1 - C_P + 0.06C_P\, lcb/(4C_P - 1)) \quad \text{.....(5.11)}$$

where *lcb* is the longitudinal position of the centre of buoyancy forward of 0.5 L as a percentage of L.

The coefficient c_{14} accounts for the stern shape. It depends on the stern shape coefficient C_{stern} for which figures are given in table 5.2.

Afterbody form	C_{stern}
Pram with gondola	-25
V-shaped sections	-10
Normal section shape	0
U-shaped sections with Hogner stern	10

$$c_{14} = 1 + 0.011C_{stern}$$

Table 5.2. Stern shape coefficient. After Holtrop (1984)

Figures showing the afterbody form are given in appendix C.

5.3.2 Appendage Resistance (R_{APP})

Rudders, shaft brackets, stabiliser fins, bilge keels, wake fins and sonar domes are some of the principal appendages that can add as much as 10% to the resistance to forward motion of a ship. The appendage resistance can be determined from:

$$R_{APP} = 0.5\rho V^2 S_{APP}(1 + k_2)_{eq} C_F \quad \text{.....(5.12)}$$

where S_{APP} is the wetted surface area of the appendages and $1 + k_2$ is the appendage resistance factor, tentative values of which are given in table 5.3.

The $1 + k_2$ value for a summation of appendages is given by:

$$(1 + k_2)_{eq} = \frac{\sum (1 + k_2) S_{APP}}{\sum S_{APP}} \quad \text{.....(5.13)}$$

rudder behind skeg	1.5-2.0
rudder behind stern	1.3-1.5
twin screw balanced rudders	2.8
shaft brackets	3.0
skeg	1.5-2.0
strut bossings	3.0
hull bossings	2.0
shafts	2.0-4.0
stabiliser fins	2.8
dome	2.7
bilge keels	1.4

Table 5.3. Approximate $1+k_2$ values. After Holtrop and Mennen (1982).

5.3.3 Wavemaking Resistance (R_W)

Pressure variations around a ship's hull when it is in a forward motion generate waves on the surface of the sea, the energy in the wave systems being derived from the ship's propulsion system.

Holtrop and Mennen (1982) undertook a statistical analysis to determine the wave resistance. This was re-analysed with a greater sample, Holtrop (1984), and two formulae were derived dependant on the vessels speed range in terms of the F_n:

for the speed range $F_n \rangle 0.55$;

$$R_{W-B} = c_{17} c_2 c_5 \nabla \rho g \exp\left\{m_3 F_n^d + m_4 \cos(\lambda F_n^{-2})\right\} \quad \text{.....(5.14)}$$

for the speed range $F_n \langle 0.40$;

$$R_{W-A} = c_1 c_2 c_5 \nabla \rho g \exp\left\{m_1 F_n^d + m_4 \cos(\lambda F_n^{2})\right\} \quad \text{.....(5.15)}$$

For the speed range $0.40 \langle F_n \langle 0.55$ a simple interpolation formula can be determined:

$$R_W = R_{W-A_{0.4}} + \frac{(10F_n - 4)(R_{W-B_{0.55}} - R_{W-A_{0.4}})}{1.5} \quad \text{.....(5.16)}$$

where;

$R_{W-A_{0.4}}$ is the wave resistance prediction for $F_n = 0.40$
$R_{W-B_{0.55}}$ is the wave resistance prediction for $F_n = 0.55$

The various coefficients and variables in equations (5.12)-(5.16) can be calculated using the following formulae, Holtrop (1984):

$$m_1 = 0.0140407\,L/T - 1.75254\,\nabla^{1/3}/L - 4.79323\,B/L - c_{16}$$

$$m_3 = -7.2035(B/L)^{0.326869}\,(T/B)^{0.605375}$$

$$m_4 = c_{15}\,0.4\exp\{-0.034F_n^{-3.29}\}$$

$$\lambda = 1.446C_P - 0.03\,L/B \quad \text{when } L/B\langle 12$$

$$\lambda = 1.446C_P - 0.36 \quad \text{when } L/B\rangle 12$$

$$d = -0.9$$

$$c_1 = 2223105c_7^{3.78613}\,(T/B)^{1.07961}\,(90 - i_E)^{-1.37565}$$

$$c_2 = \exp\{-1.89\sqrt{c_3}\}$$

$$c_3 = (0.56\,A_{BT}^{1.5})/(BT(0.31\sqrt{A_{BT}} + T_F - h_B))$$

The coefficient c_3 determines the influence of the bulbous bow on the wave resistance.

$$c_5 = (1 - 0.8\,A_T)/(BTC_M)$$

$$c_7 = 0.229577(B/L)^{0.33333} \quad \text{when } B/L\langle 0.11$$

$$c_7 = B/L \quad \text{when } 0.11\langle B/L\langle 0.25$$

$$c_7 = 0.5 - 0.0625\,L/B \quad \text{when } B/L\rangle 0.25$$

$$c_{15} = -1.69385 \quad \text{when } L^3/\nabla\langle 512$$

$$c_{15} = -1.69385 + (L/\nabla^{1/3} - 8)/2.36 \quad \text{when } 512\langle L^3/\nabla\langle 1726.91$$

$$c_{15} = 0 \quad \text{when } L^3/\nabla\rangle 1726.91$$

$$c_{16} = 8.07981C_P - 13.8673C_P^2 + 6.984388C_P^3 \quad \text{when } C_P < 0.8$$

$$c_{16} = 1.73014 - 0.7067C_P \quad \text{when } C_P > 0.8$$

$$c_{17} = 6919.3C_M^{-1.3346}(\nabla/L^3)^{2.00977}(L/B-2)^{1.40692}$$

The half angle of entrance, i_e, is that made at the waterline, by the bow, by neglecting the stem, and unless known can be approximated by:

$$i_e = 1 + 89\exp\left\{(L/B)^{0.80856}(1-C_{WP})^{0.30484}(1-C_P-0.0225lcb)^{0.63767}(L_R/B)^{0.34574}(100\nabla/L^3)^{0.16302}\right\}$$

5.3.4 Additional Resistance due to Bulbous Bow (R_B)

If a bulb is fitted to the bow of a ship below the waterline, the waves it generates will interfere with those generated by the bow. With careful design and positioning of the bulb it is possible for the two wave systems to be in antiphase at the ship's cruising speed with consequent destructive interference and reduction of wavemaking resistance. However, a contribution of additional resistance has to be taken into account due to the bulbs wetted surface area and its presence near the surface. This can be given by Holtrop (1984):

$$R_B = 0.11\exp\left\{-3P_B^{-2}\right\}F_{ni}^3 A_{BT}^{1.5}\frac{\rho g}{(1+F_{ni}^2)} \quad \text{.....(5.17)}$$

where F_{ni} is the Froude number based on the immersion of the bulb and P_B is a measure of the emergence of the bow.

$$F_{ni} = \frac{V}{\sqrt{g(T_F - h_B - 0.25\sqrt{A_{BT}}) + 0.15V^2}}$$

$$P_B = \frac{0.56\sqrt{A_{BT}}}{(T_F - 1.5h_B)}$$

5.3.5 Additional Resistance due to Immersed Transom (R_{TR})

The immersion of the transom causes an added resistance and is a function of the immersed transom transverse area and the vessel speed:

$$R_{TR} = 0.5\rho V^2 A_T c_6 \quad \text{.....(5.18)}$$

$$c_6 = 0.2(1-0.2F_{nT}) \qquad \text{when } F_{nT} \langle 5$$

$$c_6 = 0 \qquad \text{when } F_{nT} \geq 5$$

$$F_{nT} = \frac{V}{\sqrt{2g\,A_T/(B+BC_{WP})}}$$

5.3.6 Model-ship Correlation Resistance (R_A)

The model-ship correlation allowance is necessary to add an additional resistance to the smooth-ship resistance to obtain the actual value for the 'real' ship, Harvald (1978).

$$R_A = 0.5\rho S V^2 C_A \qquad \text{.....(5.19)}$$

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}C_B^4 c_2 (0.04 - c_4)$$

$$c_4 = T_F/L \qquad \text{when } T_F/L \leq 0.04$$

$$c_4 = 0.04 \qquad \text{when } T_F/L \rangle 0.04$$

5.3.7 Resistance Calculations

The Holtrop and Mennen (1982) and Holtrop (1984) algorithms, outlined in sections 5.3.1-5.3.6, have been utilised to find the model vessels total resistance curve. Figures 5.2-5.4 show the total resistance curves and their individual components for a range vessels, details of which can be found in appendix D.

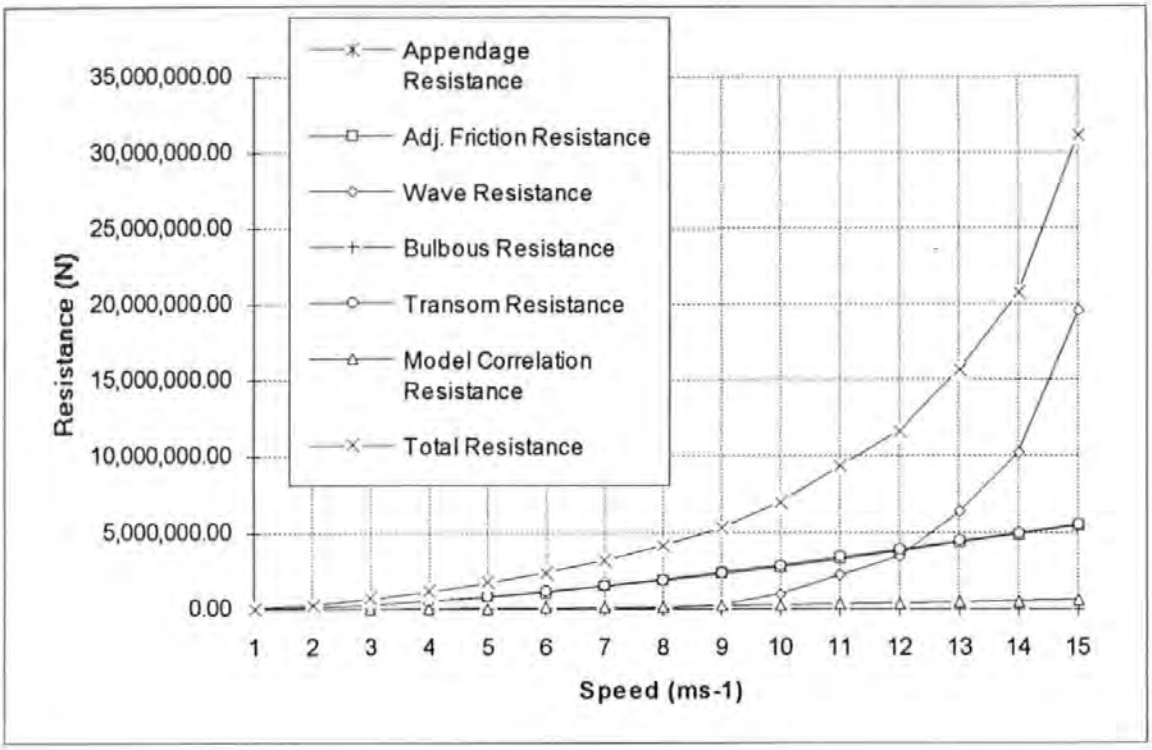


Figure 5.2. Total Resistance Curve for the "Esso Osaka", a 278000 dwt Oil Tanker.

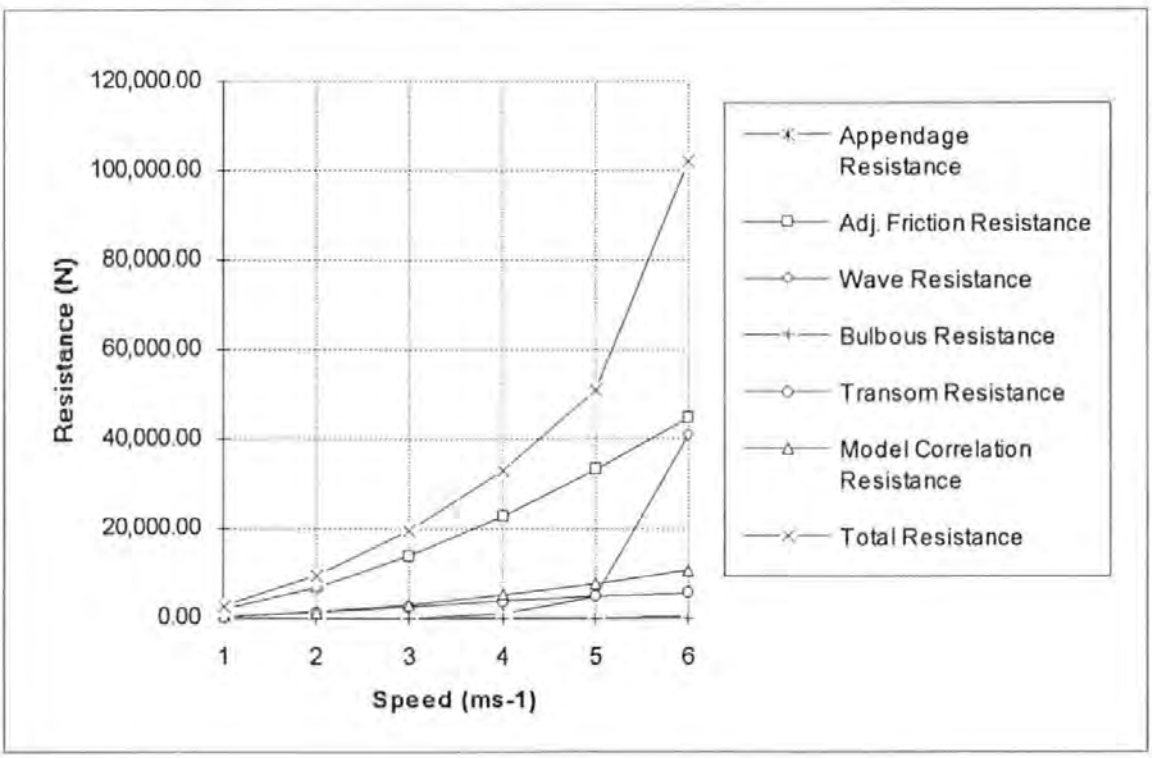


Figure 5.3. Total Resistance Curve for the "Sand Skua", a 63m Converted Sand Dredger.

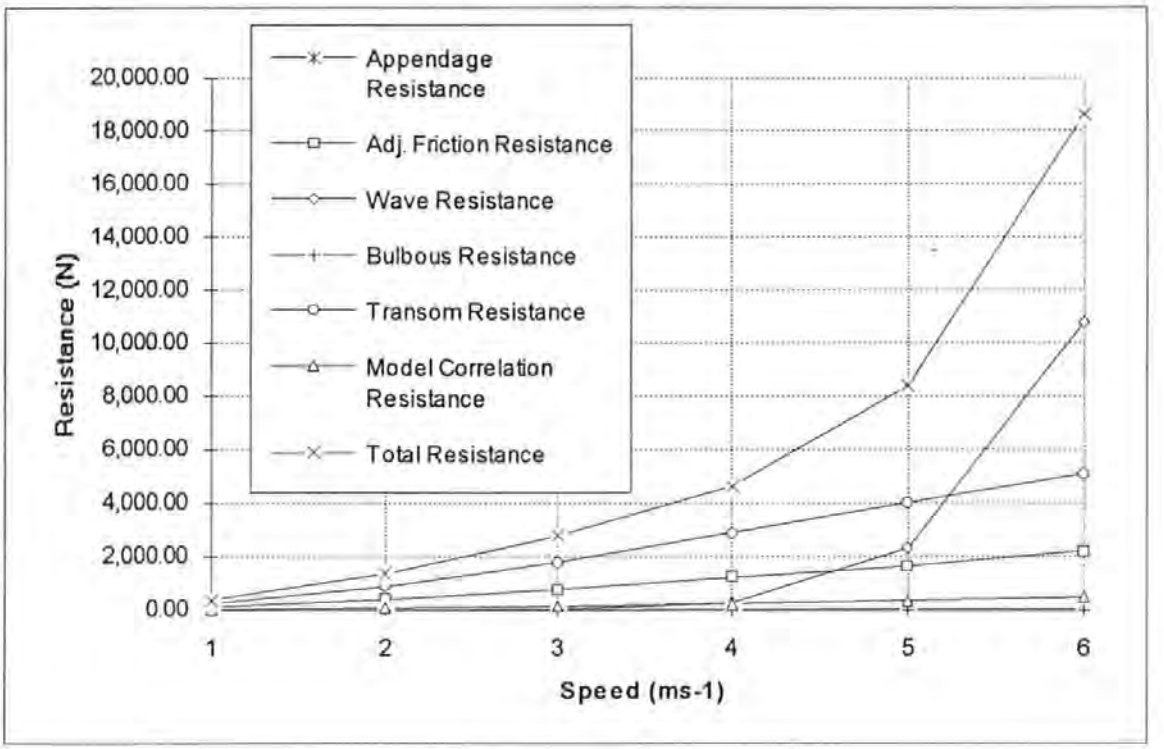


Figure 5.4. Total Resistance Curve for "Picket Boat 9", a 13m Navy Training Vessel.

5.4 Circulation Theory Applied to Propeller Modelling

In order to model the vessel, for both forward and astern motion, it is important to determine the propeller forces and moments correctly. However, for the model to be adaptable, these should be obtained by theoretical methods. The traditional technique for modelling the propeller has been explained in chapter 4.2.2.2 and from this it can be seen that the forces and moments are dependant on data obtained from open water tank tests that are presented in four quadrant propeller design charts. The types of propeller that can be modelled by using these design charts are restricted as published data on the complete B-series range is limited.

A novel approach, in terms of manoeuvring mathematical models, is to adopt the use of circulation theory techniques to predict the propeller thrust. By adopting this method the use of propeller design charts, or data based on open water model tests, is not required. Hence, propeller modelling is not limited only to propellers of the B-series form.

5.4.1 Basic Circulation Theory

The modern theoretical methods of circulation theory used to design propellers are based upon the concept, due to Lanchester (1907), that the lift developed by the propeller blade is caused by a circulation flow that takes place around the blade. The theory is based upon the lifting force experienced on a rotating cylinder in a stream called the *Magnus effect*, Magnus (1853).

If a cylinder is placed in a uniform stream in a non-viscous fluid, without any circulation flow, the streamlines will be symmetrical about the flow axis, and no force will be exerted upon the cylinder, Figure 5.5(a). The stagnation points upon the cylinder occur at 0° and 180°, i.e. 0° is the incident flow axis.

If now a circulation flow is developed around the cylinder, the flow pattern becomes asymmetrical and the stagnation points move towards each other, Figure 5.5(b). The velocities due to the circulation and to the free stream are added vectorially at every point around the cylinder. At the point E the velocity parallel to the flow axis is increased $(V_o + v)$, while at F the velocity is decreased $(V_o - v)$. This asymmetry of velocity distribution gives rise to an asymmetry in the pressure distribution. A lifting force is then produced across the pressure gradient , perpendicular to the uniform stream flow.

The circulation around a foil can be considered in a similar manner, mapped to a cylinder by the *Joukowski Transformation*, O'Brien (1969). The position of the stagnation points is determined from the physical requirements of flow about a foil and these points mapped back to a cylinder, calculating the circulation from simpler mathematical analysis.

As fluid starts to flow past the foil, the stagnation points tend to form at the ends of the foil (at 0° and 180° on the corresponding cylinder), Figure 5.6(a). The angle of attack, α, governs the position of these points. In real fluid flow, at the trailing edge where the underside fluid tries to flow around the sharp edge, violent separation occurs. This only occurs for an instant, as point (b) is then swept back to the trailing edge , Figure 5.6(b). According to the *stagnation hypothesis* of Joukowski, O'Brien (1969), this is necessary to avoid an infinite velocity around the cusp of the foil. This shift in the rear stagnation point corresponds to a shift in the rear stagnation point on the cylinder, and to provide vertical symmetry, a downward shift in the forward stagnation point. A theoretical circulation has now been established around the foil. The magnitude of this circulation is determined by the movement of the stagnation points.

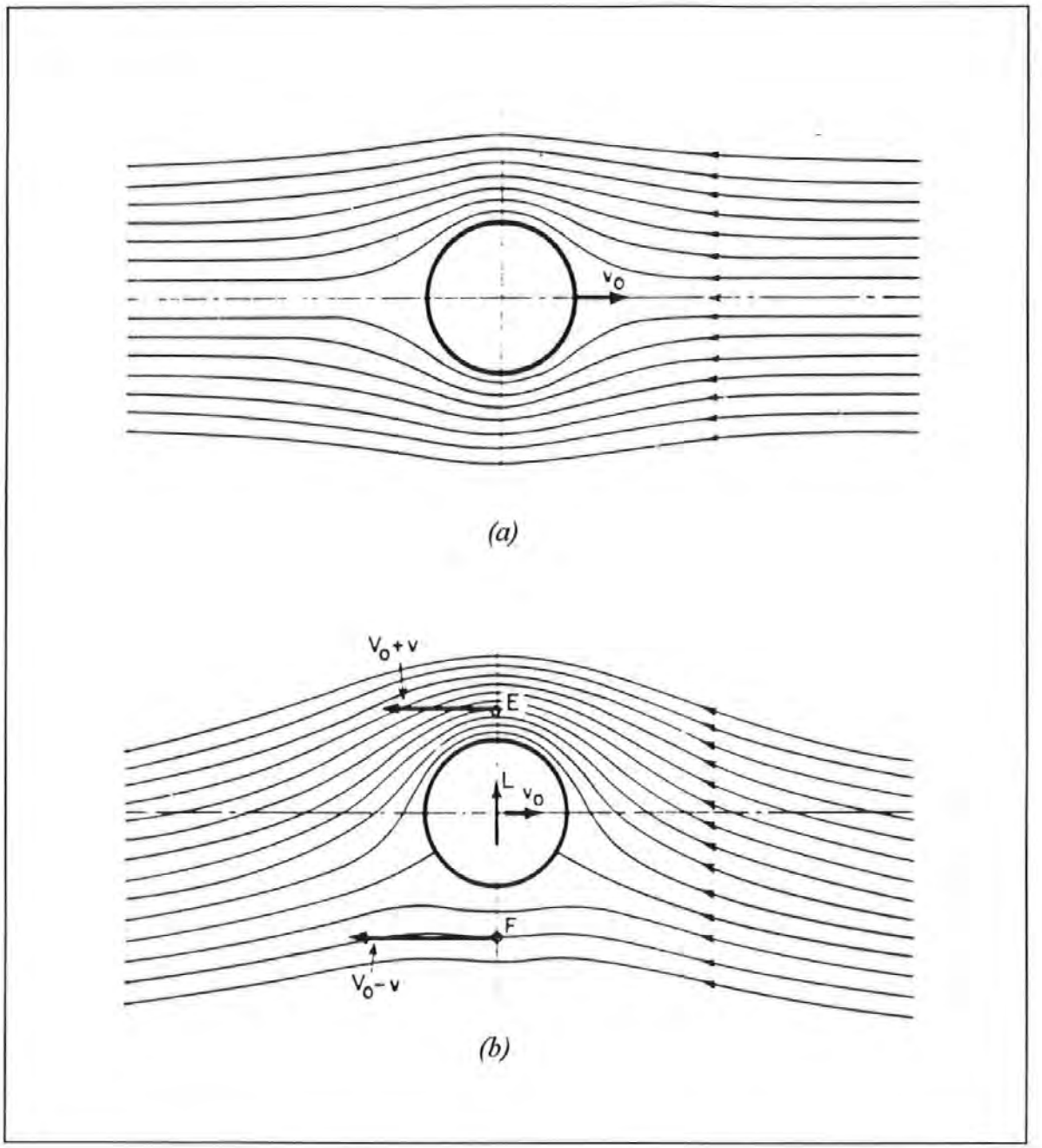


Figure 5.5. Streamline flow around a cylinder (a) without circulation (b) with circulation, after Lewis (1988).

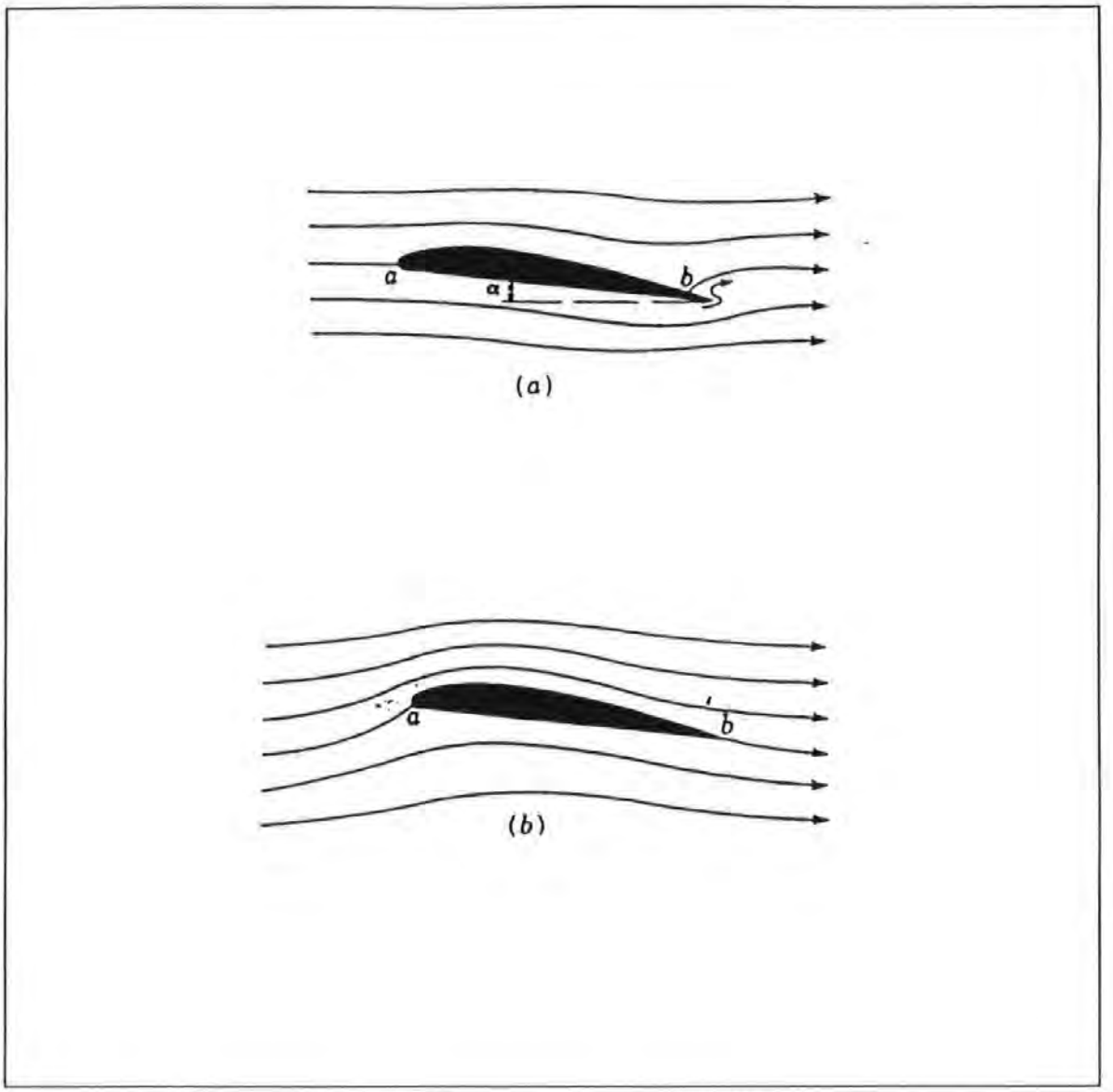


Figure 5.6. Adjustment of stagnation points to avoid infinite velocity at trailing edge, after Daugherty (1989).

5.4.2 A Mathematical Approach to Circulation

Consider the type of streamline flow shown in figure 5.7, which is defined by the equation:

$$rv = \text{constant} = c \qquad \text{.....(5.20)}$$

where: r = radius vector drawn from the origin, O;
v = velocity at any point, which is always normal to the radius vector.

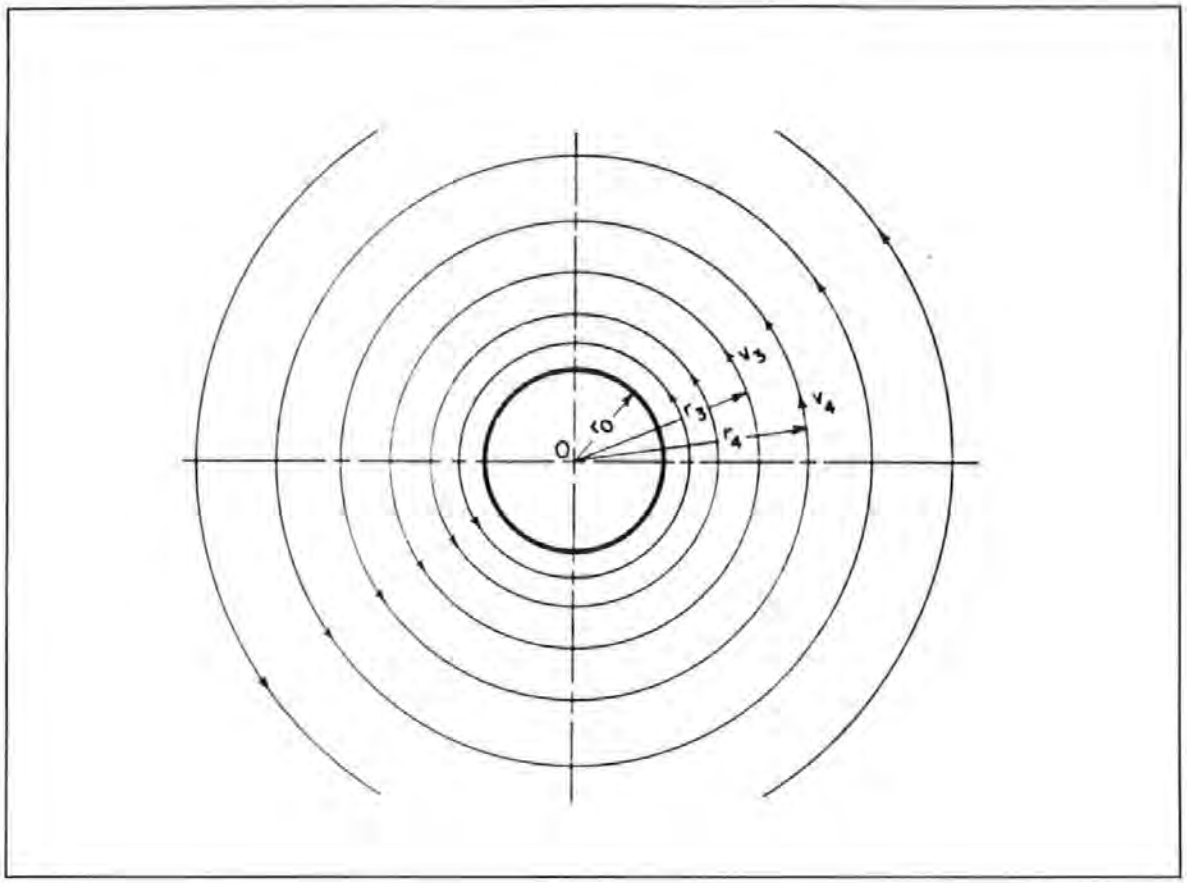


Figure 5.7. Circulation flow in a vortex, after Lewis (1988).

An inner streamline of radius r_o can be considered as representing the wall of a cylinder, whose axis is normal to the plane of the flow and around which the fluid circulates.

The circulation, Γ, can be defined as the line integral around a closed curve:

$$\Gamma = \oint v.ds \quad \text{.....(5.21)}$$

This type of flow is peculiar in that when the line integral along a closed curve in the flow field is calculated, the circulation is zero when the curve does not surround the origin, but has the constant value $2\pi c$ when the curve does surround the origin. The element ds is simply the circumference of the curve, $2\pi r$:

$$\oint v.ds = v_1(2\pi r_1) = v_2(2\pi r_2) = v_n(2\pi r_n) \quad \text{.....(5.22)}$$

therefore;

$$\Gamma = 2\pi c \quad \text{.....(5.23)}$$

The transverse lifting force per unit span acting upon the foil, with circulation in uniform flow, may be shown to be given by:

$$dL = \rho \Gamma V_R \quad \text{.....(5.24)}$$

where; ρ = the density of the medium,
$\Gamma = 2\pi c$ = strength of circulation flow,
V_R = resultant fluid velocity relative to the propeller blade.

Equation (5.24) is known as the *Kutta-Joukowski* equation, (Lewis 1988), and it applies to all bodies regardless of their shape, the shape factor being contained in the circulation factor Γ.

5.4.3 Application to Screw Propellers

Circulation theory is important in the design of marine screws as it can be used to calculate the fluid velocity relative to a particular blade section, corrected for induced velocities. This is significant as the angle of incidence of the fluid to the blade element governs the lift and drag characteristics of the blade, which in turn decide the final thrust and torque produced. The theory can be adapted to calculate the performance of a screw with given geometrical characteristics over a range of operating conditions, i.e. to make detailed screw performance calculations. It is this aspect that is of interest for propeller modelling.

In applying a simple circulation theory to a propeller, each blade is assumed to be replaced by a vortex line that extends from propeller axis to blade tip, O'Brien (1969). The vortex line rotates around the propeller axis and around the line there is a circulation. This line is called the bound vortex line, figure 5.8.

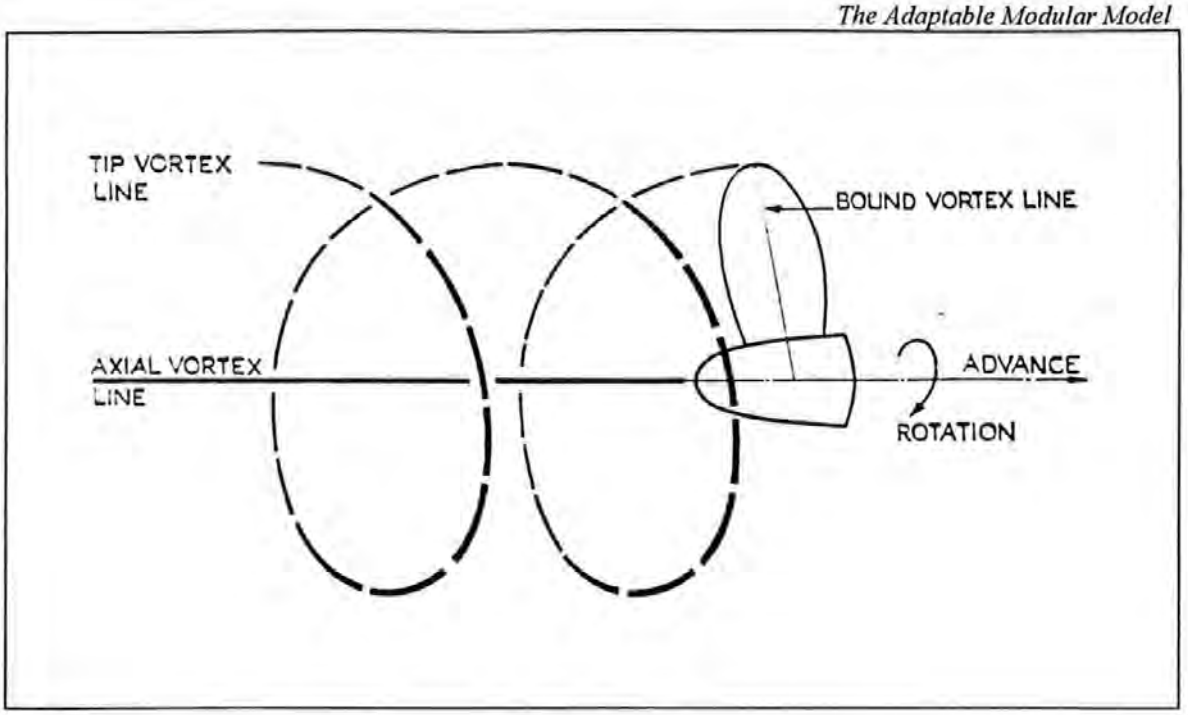


Figure 5.8. Tip and axial vortices.

The vortex line is terminated at the propeller axis and blade tip by two trailing vortex lines. The axial vortex line follows a path along the propeller axis and the tip vortex line follows a helical path. If the circulation varies radially, as it does for a propeller, then a system of trailing vortex lines of similar form to the tip vortex line are shed along the radial length of the blade, as can be seen in figure 5.9.

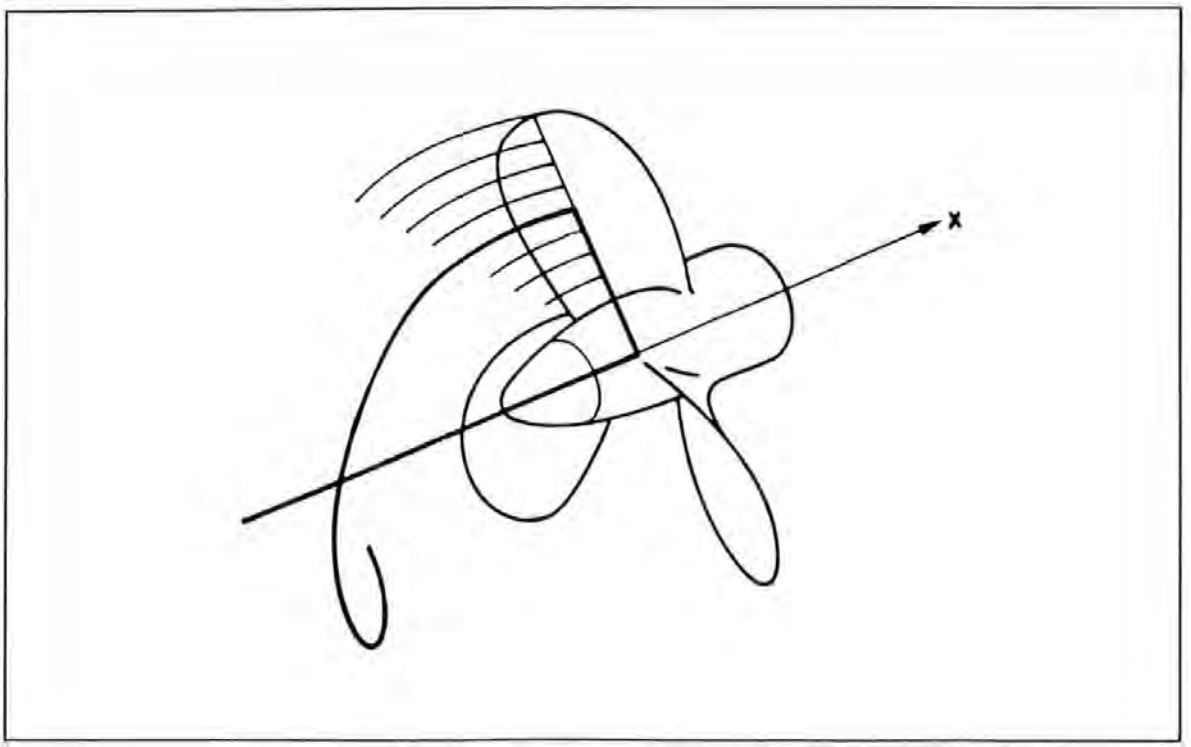


Figure 5.9. Vortex system, after Harvald (1983).

As a propeller in open water develops thrust, it induces three inflow velocity components, radial, axial and tangential. These are generally small compared with the speed of advance, V_a, but the axial and tangential component have a large effect upon the angle of incidence and must be accounted for.

The effect of trailing vortices is to induce at the bound vortices, a velocity component, U_n, normal to the resultant velocity: this velocity is due to the axial and tangential inflow components.

The radial inflow component is due to the contraction of the slipstream in passing through the propeller. It is small, in all but heavily loaded propellers, and is usually neglected.

Prandtl, O'Brien (1969), showed that along the vortex sheet, figure 5.10, from the lifting line, AA, to infinity to the right, the induced downward velocity varies from U_n at a very large distance from AA to a value of $U_n/2$ at AA. This can be proved by a theorem on vortex motions comparable to the law in electrodynamics that describes eddy current motions. (The Biot-Savart Law, Lewis (1988)).

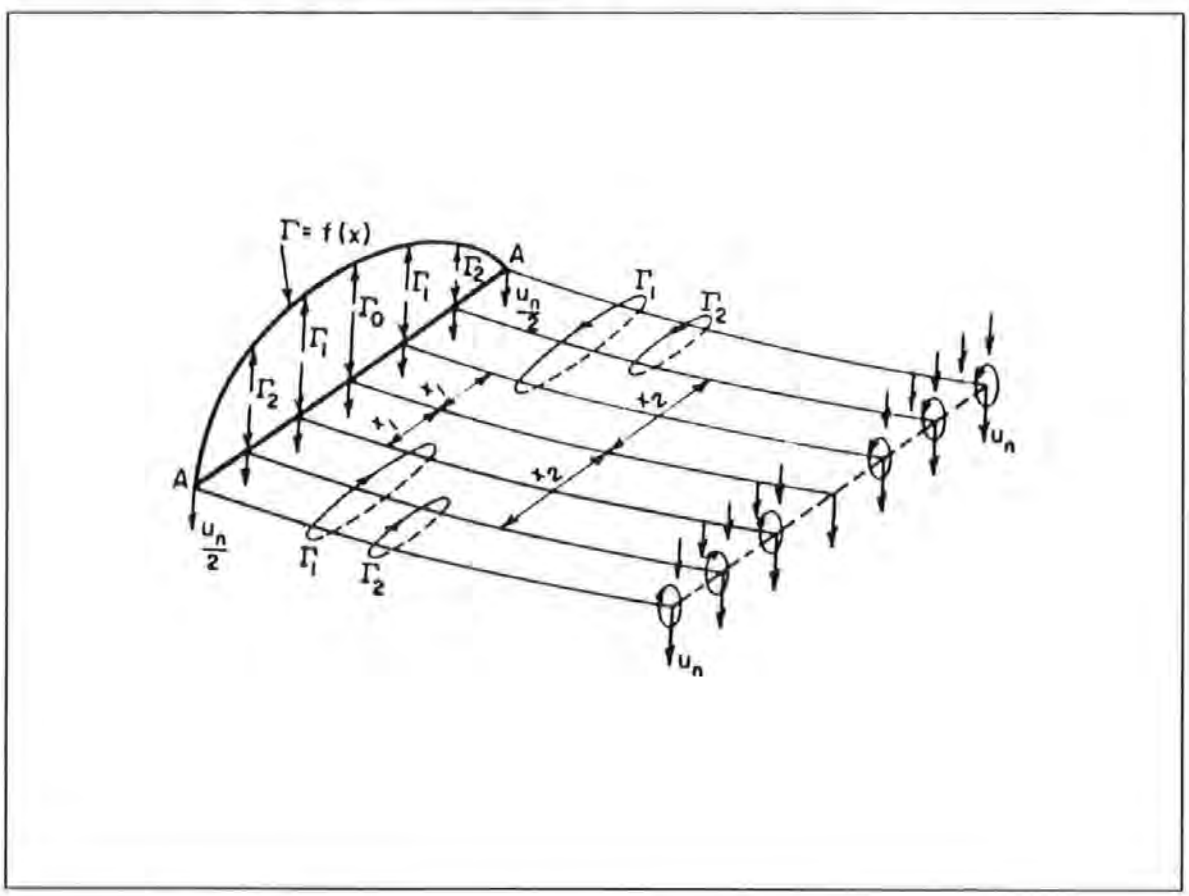


Figure 5.10. Vortex system over a finite foil span, after Lewis (1988).

The blade velocity diagram for a propeller operating in a non-viscous fluid, including the induced tangential and axial velocities, can be seen in figure 5.11.

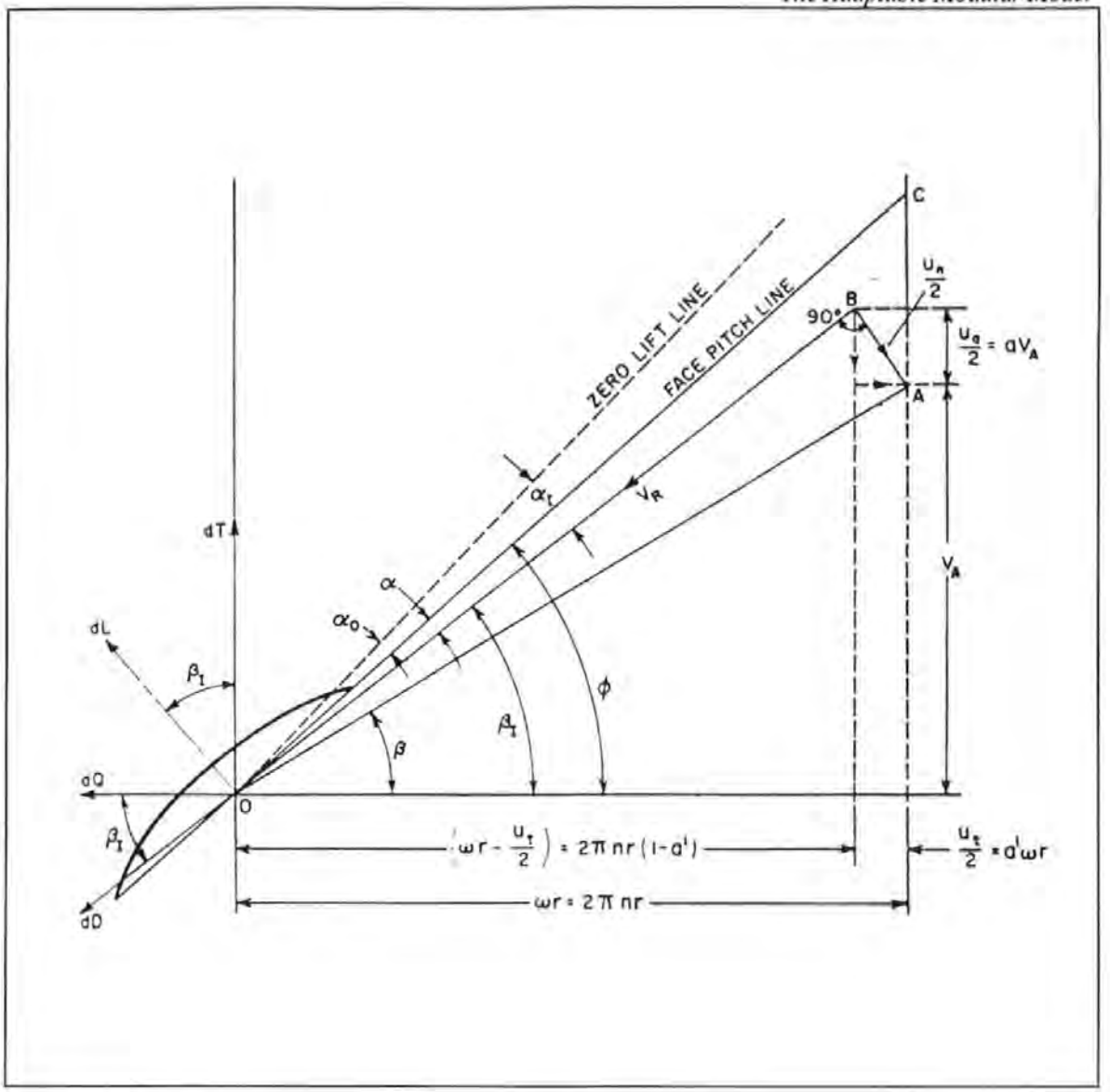


Figure 5.11. Blade velocity diagram, after Lewis (1988).

5.4.3.1 Correction Factors

Circulation theory makes various assumptions and correction factors have been adopted to account for them. There are three types of correction required:

1. *curvature correction;*
2. *tip correction;*
3. *blade number correction.*

Vorticity across a propeller blade is distributed, as opposed to being concentrated on a single vortex line as the circulation theory assumes. The resulting velocity field varies in direction and magnitude along each blade section as against the uniform resultant velocity at the bound vortex line. Due to this variable velocity field, the propeller will not produce the

same coefficient of lift that would be developed in a homogeneous inflow condition. Hill, (1949), applied a curvature correction, H_c, to compensate, figure 5.12,

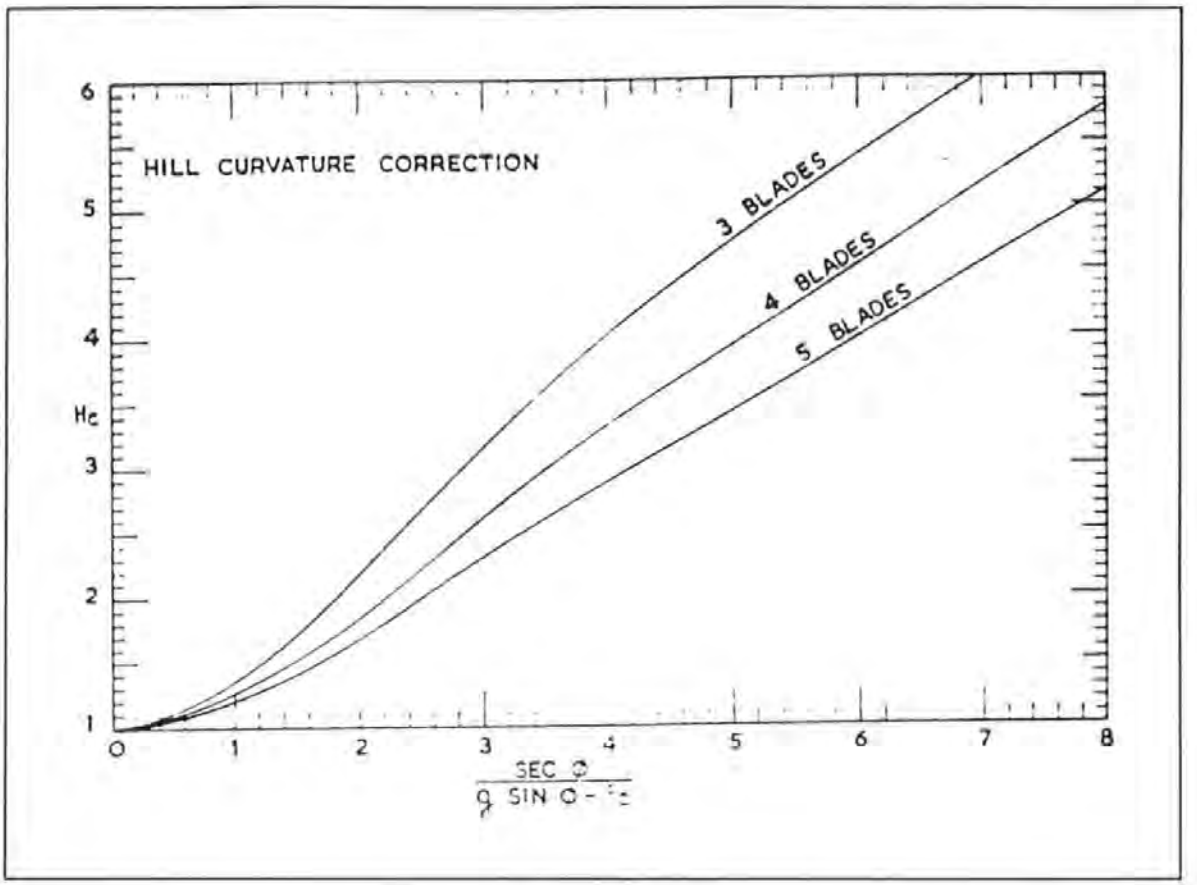


Figure 5.12. Curvature correction chart, after Hill (1949).

Where g is the gap factor;

$$g = \frac{\pi x}{Z C/D} \qquad \text{.....(5.25)}$$

As discussed previously, the difference between the pressure on the face and the back of the propeller blade produces fluid flow around the blade tips. This means an effective reduction of the lift produced at the outer blade sections which increases as the blade width and radius fraction increases. The tip correction, H_T, is a function of the mean chord ratio, C_m/D, taken between the blade tip and the blade section in question. It is given by;

$$H_T = \frac{C_m}{15R(1-x)} = \frac{C_m/D}{7.5(1-x)} \qquad \text{.....(5.26)}$$

The application of these correction factors to the lift coefficient will be shown later.

For a screw having a small number of blades, i.e. Z=5, the vortex sheets are widely spaced. Provided there are a large number of blades then the sheets will be closely spaced; close enough that the variation in velocity between the sheets is so small that it can be neglected. This assumption of a high value of Z means that an expression for the circulation can be derived and corrections applied to make an allowance for a small number of blades. Goldstein (1929) proposed the most accurate and widely used of the blade number correction factors, κ, which is a function of the number of blades, the radius fraction, $x = r/R$, and the induced advance ratio, λ_i. Tachmindji and Milam (1956) calculated these correction factors and represented them in a graphical format, figure 5.13. These factors are valid only for the case of zero circulation at the hub - generally considered as correct. They are also only strictly valid for a screw having a constant radial virtual pitch distribution.

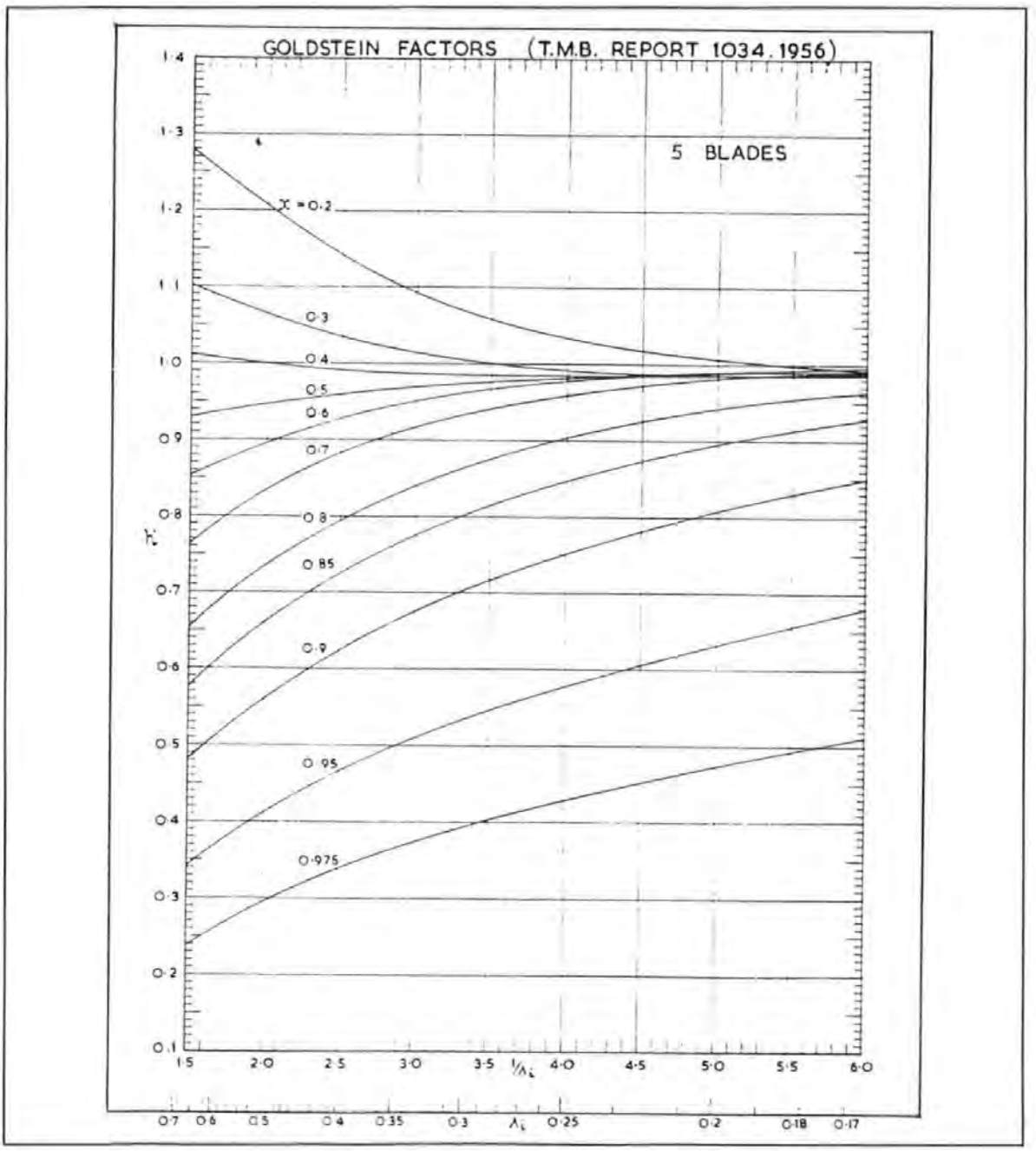


Figure 5.13. Goldstein reduction factors, after Tachmindji and Milam (1956).

5.4.3.2. Screw Performance Calculations

Betz (1919) established a minimum energy loss condition for a screw with a large number of blades which is operating in a homogeneous flow in a non-viscous fluid and under moderately loaded condition. This moderately loaded condition is described when the inflow factors a and a' are small and when the slipstream contraction can be neglected. It is reasonable to make this assumption for use in the adaptable mathematical model.

To satisfy the Betz condition, the circulation around a propeller blade can be given by:

$$\Gamma = \frac{2\pi r U_T}{Z} \qquad \text{.....(5.27)}$$

where, from figure 5.11, $U_T = 2a'\omega r$. Substituting and applying the appropriate Goldstein correction κ;

$$\Gamma = \frac{4\pi r^2 \omega a' \kappa}{Z} \qquad \text{.....(5.28)}$$

The tangential inflow factor, a', is the fraction of the tangential velocity that is induced as a tangential inflow component as the propeller advances. From figure 5.11:

$$a' = \frac{\tan\beta_i(\tan\beta_i - \tan\beta)}{1+\tan^2\beta_i} \qquad \text{.....(5.29)}$$

where β is the hydrodynamic advance angle and β_i is the hydrodynamic pitch angle corrected for induced velocities. The hydrodynamic advance angle is the ratio of the advance speed to the tangential speed of the propeller:

$$\tan\beta = \frac{V_a}{x\pi nD} \qquad \text{.....(5.30)}$$

and the hydrodynamic pitch angle can be determined from,

$$\tan\beta_i = \frac{p_h}{\pi x} \qquad \text{.....(5.31)}$$

where p_h is the hydrodynamic pitch ratio P_h/D and,

$$p_h = \pi\lambda_i \qquad \text{.....(5.32)}$$

$$\eta_i = \frac{\lambda}{\lambda_i} \quad \text{.....(5.33)}$$

where λ_i is the advance ratio corrected for induced velocities. Also, for the same condition, from the definition of the advance ratio;

$$\lambda = \frac{V_a}{\pi n D} \quad \text{.....(5.34)}$$

Combining this with equations (5.31) and (5.32):

$$\tan\beta_i = \frac{\lambda_i}{x} \quad \text{.....(5.35)}$$

Now an expression for $\tan\beta_i$ in terms of $\tan\beta$ and η_i can be derived, combining (5.30), (5.33), (5.34) and (5.35) as:

$$\tan\beta_i = \frac{\tan\beta}{\eta_i} \quad \text{.....(5.36)}$$

For each blade element the ideal thrust dT_i and ideal torque dQ_i can be determined as;

$$dT_i = Z.dL.\cos\beta_i \quad \text{.....(5.37)}$$

and,

$$dQ_i = Z(dL.\sin\beta_i)r \quad \text{.....(5.38)}$$

The ideal thrust and torque values do not account for the viscous effect of drag upon each blade element.

Previously an expression for the lift from the Kutta-Joukowski equation has been developed, equation (5.23), where the resultant fluid velocity relative to the blade is, from figure 5.11:

$$V_R = \omega r(1-a')\sec\beta_i \quad \text{.....(5.39)}$$

Combining this with equation (5.28) and substituting into equation (5.23), for the blade element *dr*:

$$dL = \frac{1}{Z} 4\pi\rho\kappa r^3\omega^2 a'(1-a')\sec\beta_i.dr \quad \text{.....(5.40)}$$

Now the lift for the blade section has been calculated it can be non-dimensionalised to give the coefficient of lift for the blade element foil section:

$$C_L = \frac{2dL}{\rho V_R^2 c.dr} \quad \text{.....(5.41)}$$

where c is the chord length and $c.dr$ is the effective area of the blade surface. Substituting the expression for lift from the Kutta-Joukowski equation into equation (5.41) gives;

$$C_L = \frac{4\pi\kappa a'}{Z\frac{C}{D}(1-a')\sqrt{(1+\tan^2\beta_i)}} \quad \text{.....(5.42)}$$

The dT_i value can be determined by combining equations (5.37) and (5.40),

$$\frac{dT_i}{dr} = 4\pi\rho\kappa r^3\omega^2 a'(1-a') \quad \text{.....(5.43)}$$

Substituting for the angular velocity, i.e. $\omega = 2\pi n$:

$$\frac{dT_i}{dr} = 16\pi^3\rho\kappa r^3 n^2 a'(1-a') \quad \text{.....(5.44)}$$

The dQ_i value can be determined by combining equations (5.38) and (5.40):

$$\frac{dQ_i}{dr} = 4\pi\rho\kappa r^4\omega^2 a'(1-a')\tan\beta_i \quad \text{.....(5.45)}$$

$$\frac{dQ_i}{dr} = r\frac{dT_i}{dr}\tan\beta_i \quad \text{.....(5.46)}$$

The ideal thrust and torque values are then given by:

$$T_i = \int_{r_B}^{R}\frac{dT_i}{dr}dr \quad \text{.....(5.47)}$$

$$Q_i = \int_{r_B}^{R}\frac{dQ_i}{dr}dr \quad \text{.....(5.48)}$$

where R = blade tip radius,

r_B = radius of the propeller boss.

The blade element values for ideal thrust and torque coefficients can then be expressed as:

$$K_{Ti}' = \frac{d}{dx} K_{Ti} = \frac{dT_i/dx}{\rho D^4 n^2} = \frac{R(dT_i/dr)}{\rho D^4 n^2} \quad \text{.....(5.49)}$$

Combining (5.44) and (5.49):

$$K_{Ti}' = \pi^3 x^3 \kappa a'(1-a') \quad \text{.....(5.50)}$$

Similarly:

$$K_{Qi}' = \frac{d}{dx} K_{Qi} = \frac{dQ_i/dx}{\rho D^5 n^2} = \frac{rR(dT_i/dr)\tan\beta_i}{\rho D^5 n^2} \quad \text{.....(5.51)}$$

which, by combining (5.44), (5.46) and (5.51), reduces to:

$$K_{Qi}' = \frac{x}{2} K_{Ti}' \tan\beta_i \quad \text{.....(5.52)}$$

$$K_{Qi}' = \frac{\lambda_i}{2} K_{Ti}' \quad \text{.....(5.53)}$$

The ideal thrust and torque coefficients are approximately constant across the whole operating range for the screw as they do not account for the lift and drag characteristics of the blade foil section. The angle of incidence of the blade will dictate the lift and drag produced varying with respect to each other, as can be seen in figure 5.14.

The coefficient of drag can be obtained from a 'standard series' chart for a particular foil type. Figure 5.15 shows a plot of the coefficient of drag against the thickness ratio, (*t/c*), for various angles of incidence. The chart is for a NACA[1] section a=1.0 mean line[2]. For inclusion in the model software a least squares fit was applied to the standard series data.

[1]NACA is the National Advisory Committee for Aeronautics.

[2]a=1.0 indicates the proportion of the blade chord over which the pressure is theoretically uniform.

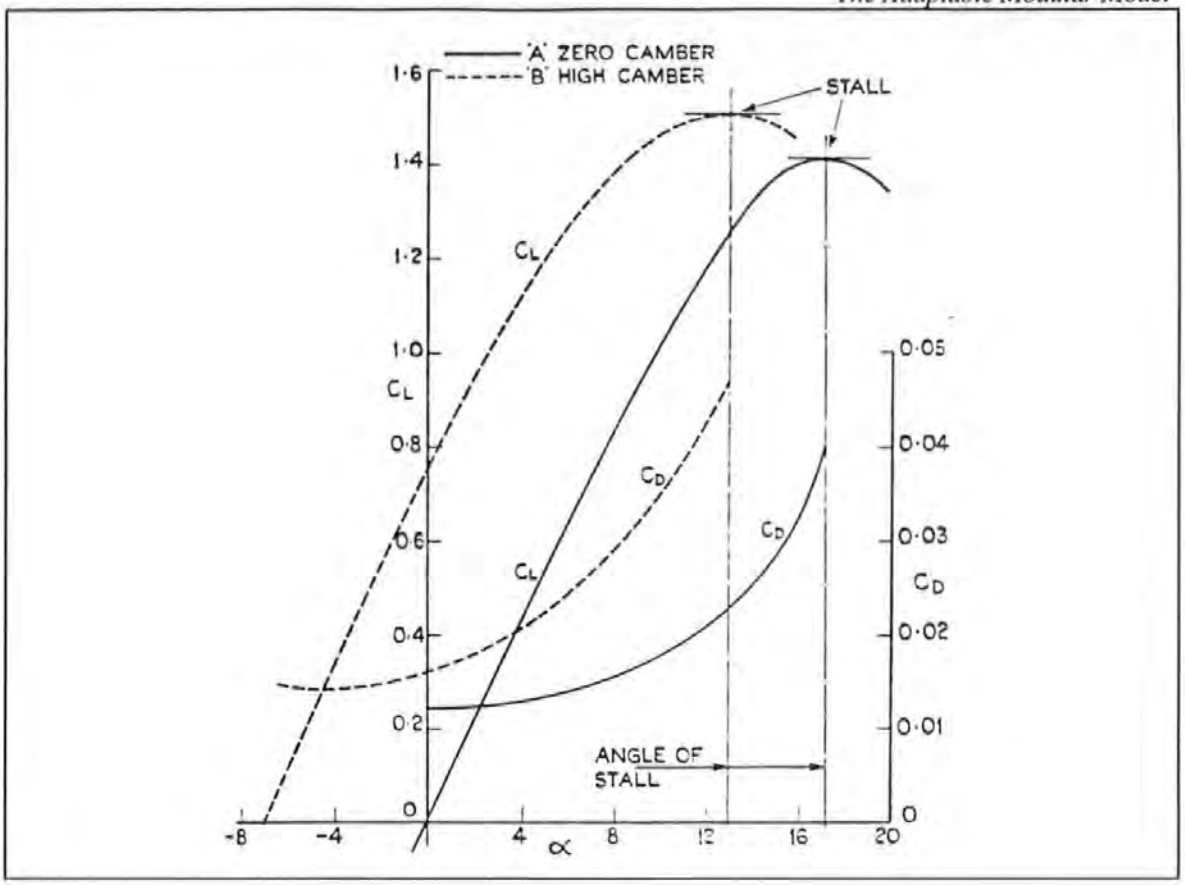


Figure 5.14. Lift and drag characteristics of a foil, after O'Brien (1962).

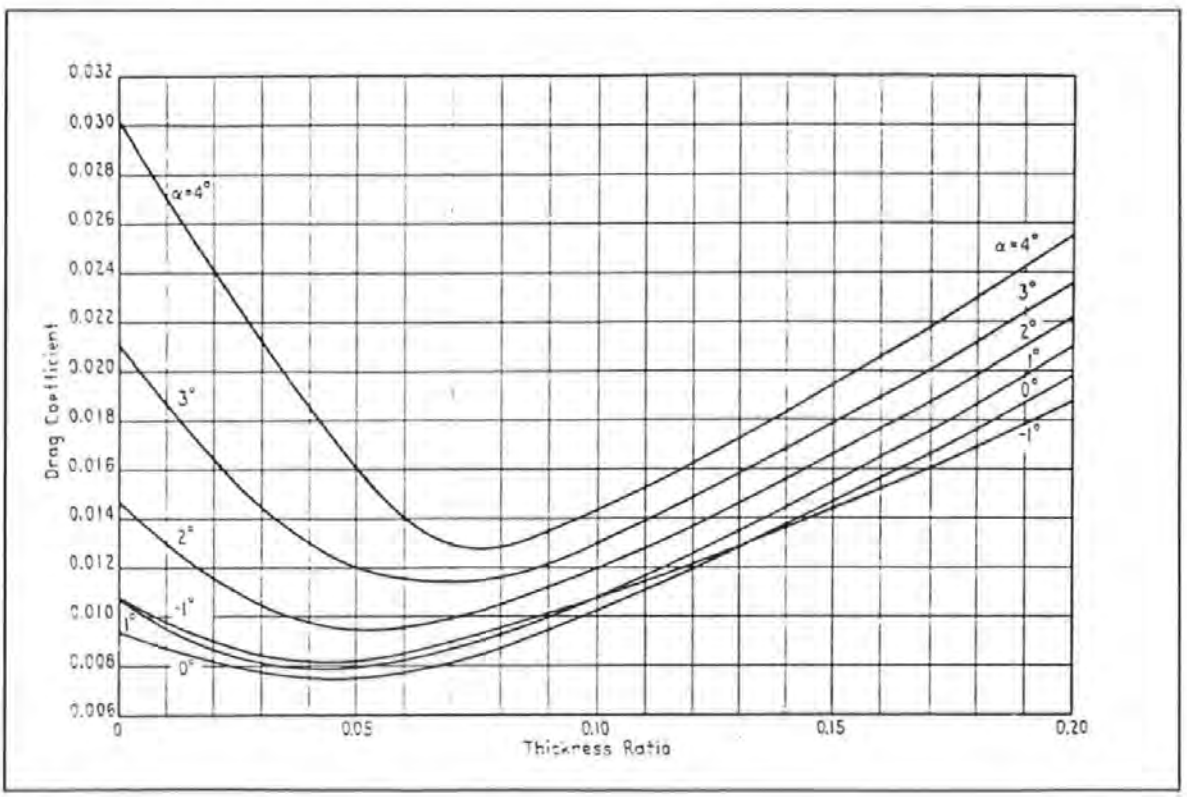


Figure 5.15. Variation of drag of airfoil sections with thickness ratio and angle of attack, after Hill (1949).

To obtain the real K_T and K_Q values, a correction is applied to each blade element:

$$K_T' = K_{Ti}'(1 - \varepsilon \tan\beta_i) \quad \text{.....(5.55)}$$

$$K_Q' = K_{Qi}'(1 + \varepsilon \cot\beta_i) \quad \text{.....(5.56)}$$

These expressions now account for lift, drag and incidence, giving;

$$\varepsilon = \frac{C_D}{C_L} \quad \text{.....(5.57)}$$

The values of K_T' and K_Q' are then integrated across the total blade length to determine the blade and hence the propeller K_T, K_Q values. This process can be repeated for any advance coefficient, J, at which the propeller is run.

5.4.3.3. Application of Calculations to a Screw

Applying the equations outlined in section 5.4.3.2 to screw performance is, in reality, complicated by the fact that the hydrodynamic pitch is not already known. In the design process, an ideal efficiency for the screw can be obtained from a Kramer (1939) chart and the hydrodynamic pitch angle can then be determined. Hill's (1949) prediction method overcomes this problem by assuming that the hydrodynamic pitch angle is found from the following relationship:

$$\beta_i = \varphi - \alpha_a \quad \text{.....(5.58)}$$

where α_a is a small assumed angle of attack. A range of these angles of attack are used and the hydrodynamic pitch angles are calculated for each one. The coefficient of lift is determined for each angle of attack and plotted, figure 5.16.

The required section lift coefficient is given by:

$$C_{Ls} = C_L(H_C + H_T) \quad \text{.....(5.59)}$$

However the actual section has a lift coefficient value for infinite aspect ratio, C_{Lc}, of $10f/c$ due to its camber. The angles of attack required to compensate for the difference between the section lift coefficients and the lift coefficient due to camber, are calculated using the fact that the resulting lift coefficient increases linearly with the angle of attack at the rate of 0.1097 per degree. These values of incidence are also plotted against the ideal lift coefficient, figure 5.16.

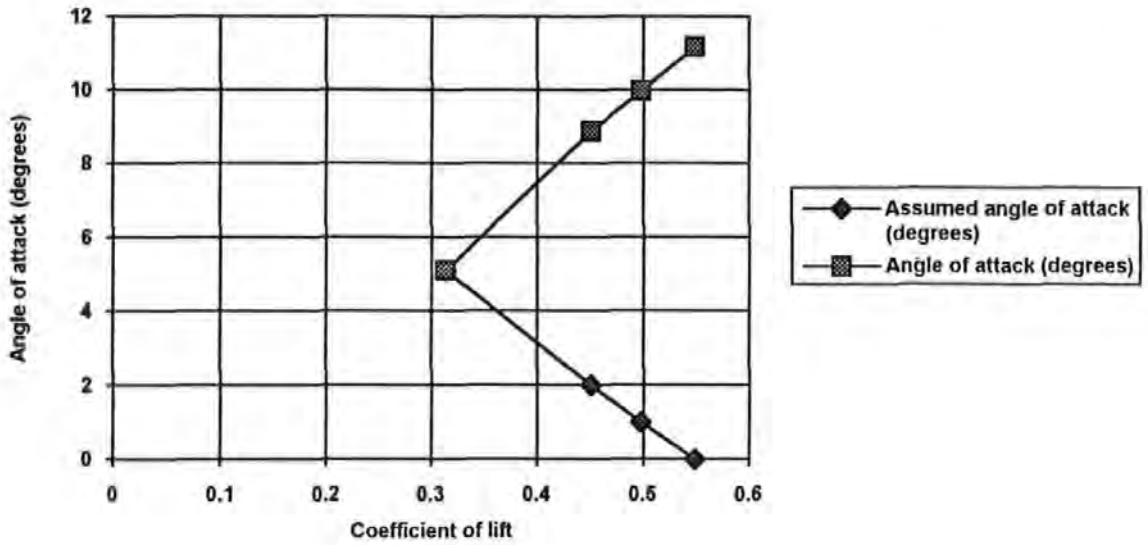


Figure 5.16. Determination of the angle of attack of the blade section.

The intersection of the two lines allows the angle of attack to be obtained, hence the hydrodynamic pitch angle can be calculated. At this point the *available* section lift coefficient is equal to the section lift coefficient *required* by the combination of the hydrodynamic pitch, the advance coefficient, tip correction and curvature correction.

The lift coefficient can now be determined for the final angle of attack, equation (5.42), and hence the thrust and torque values for the blade elements can be computed.

An example of the determination of the angle of attack for a propeller blade section[3] at x=0.7 and J=0.7 are shown in table 5.4.

The calculation for the thrust and torque loading for this section are shown in table 5.5.

[3]Details of the propeller geometry are given in appendix E.1.

Assumed angle of attack (degrees)		0	1	2
Geometric pitch angle		31.903	31.903	31.903
Hydrodynamic pitch angle β_i	*5.58*	31.903	30.903	29.903
$\tan\beta_i$		0.622	0.598	0.575
$\tan\beta$	*5.30*	0.318	0.318	0.318
Tangential inflow factor a'	*5.29*	0.136	0.123	0.111
Blade number correction factor κ	*5.60*	0.846	0.851	0.857
C/D ratio		0.517	0.517	0.517
C_L	*5.42*	0.549	0.498	0.451
H_c from correction chart		2.19	2.19	2.19
$H_c \times C_L$		1.20	1.09	0.988
$H_T \times C_L$		0.225	0.204	0.185
Section lift coefficient C_{Ls}		1.425	1.294	1.173
Lift coefficient due to camber C_{Lc}		0.20	0.20	0.20
Lift coefficient required by $\alpha = (C_{Ls} - C_{Lc})$		1.225	1.094	0.973
Angle of attack α (degrees)		11.167	9.973	8.869

Table 5.4. Determination of the actual angle of attack.
Numbers in italics refer to the corresponding equation number.

Pitch angle φ		31.903
Angle of attack		5.08
Hydrodynamic pitch angle β_i		26.823
$\tan\beta_i$		0.506
$\tan\beta$	*5.30*	0.318
Tangential inflow factor a'	*5.29*	0.076
Blade correction factor κ	*5.60*	0.878
K'_{Ti}	*5.51*	0.656
K'_{Qi}	*5.54*	0.116
Thickness ratio t/c		0.0311
Drag coefficient C_D		0.0310
Lift coefficient C_L	*5.42*	0.313
Drag-lift ratio ε	*5.57*	0.099
K'_T	*5.55*	0.623
K'_Q	*5.56*	0.139

Table 5.5. Determination of the actual performance data of the blade element.

The formulae outlined and polynomials representing the curvature and tip correction are included in the model program. To avoid using a look-up chart the blade number correction factor has been replaced by the following equation:

$$\kappa = \frac{2}{\pi}\cos^{-1} e^{-\left[\left(\frac{z}{2}\right)(1-x)\frac{\sqrt{(1+\tan^2\beta_i}}{\tan\beta_i}\right]} \qquad \text{.....(5.60)}$$

For screws with four or more blades there is no appreciable difference between the correction factors calculated by equation (5.60) and the Goldstein factors. Table 5.6 shows the complete performance characteristics calculated by the method outlined for the propeller in appendix E.1. The figures shown in table 5.6 are calculated for the following variables:

$$\lambda = 0.286 \quad J = 0.9 \quad V_a = 2.5ms^{-1} \quad n = 9.166$$

x	$\tan\beta$	$\tan\beta_i$	$\tan^2\beta_i$	λ_i	a'	1-a'	κ	$\pi^3 x^3$	K_{Ti}'	K_{Qi}'
0.2	1.432	1.646	2.689	0.328	0.092	0.908	0.939	0.248	0.019	0.0032
0.3	0.955	1.183	1.399	0.355	0.112	0.888	0.936	0.833	0.078	0.0138
0.4	0.716	0.945	0.893	0.378	0.114	0.886	0.926	1.984	0.186	0.0351
0.5	0.573	0.782	0.611	0.391	0.101	0.899	0.916	3.876	0.322	0.063
0.6	0.477	0.659	0.435	0.395	0.084	0.916	0.896	6.697	0.462	0.912
0.7	0.409	0.550	0.303	0.385	0.060	0.940	0.865	10.64	0.519	0.999
0.8	0.358	0.449	0.201	0.359	0.034	0.966	0.809	15.88	0.422	0.0757
0.9	0.318	0.346	0.119	0.311	0.008	0.992	0.692	22.60	0.124	0.019

x	α	C_L	C_D	ε	K_T'	K_Q'	SM	SMK_T'	SMK_Q'
0.2	3.760	0.108	0.0206	0.191	0.013	0.004	1	0.013	0.004
0.3	4.310	0.210	0.0176	0.084	0.070	0.015	4	0.070	0.015
0.4	4.320	0.244	0.0179	0.073	0.173	0.038	2	0.173	0.038
0.5	4.130	0.222	0.0248	0.112	0.295	0.072	4	0.295	0.072
0.6	3.650	0.195	0.0163	0.083	0.434	0.102	2	0.434	0.102
0.7	3.080	0.163	0.0146	0.089	0.490	0.115	4	0.490	0.115
0.8	2.330	0.120	0.0120	0.100	0.402	0.092	2	0.402	0.092
0.9	1.840	0.045	0.0099	0.221	0.121	0.033	4	0.121	0.033
								Σ5.935	Σ1.408

K_T=0.198 K_Q=0.047 Open water efficiency η_o=0.602

Table 5.6. Performance calculations.

5.4.4 Wake Distribution

Standard propeller model tests are undertaken in the open water condition and not in the 'behind hull' condition. When a propeller is placed behind the hull of a vessel conditions alter, the water in which the propeller is working has been disturbed by the hull and generally the water in the area of the stern has some forward motion. This forward moving water is called the wake and results in the propeller advancing at a speed V_a when the ship is advancing at a speed V_s.

The relationships between thrust, torque and revolutions in open water will now alter causing a change in the propeller efficiency as the inflow velocity is now not uniform.

As stated by Lewis (1988), the wake is due to three principal causes:

1. the frictional drag of the hull causes a following current which increases in velocity and volume towards the stern, and produces there a wake having a considerable forward velocity relative to the surrounding water;

2. the streamline flow past the hull causes an increased pressure around the stern, where the streamlines are closing in. This means that in this region the relative velocity of the water past the hull will be less than the ship's speed and will appear as a forward or positive wake augmenting that due to friction;

3. the ship forms a wave pattern on the surface of the water, and the water particles in the crests have a forward velocity due to their orbital motion, while in the troughs the orbital velocity is sternward. This orbital velocity will give rise to a wake component which will be positive or negative according to whether there is a crest or a trough of the wave system in the vicinity of the propeller.

From this it can be seen that as a propeller rotates, a section at any given radius passes through regions with varying wake contributions. Wake diagrams can be obtained for various ship types and after body forms, as shown in figure 5.17, and the average circumferential wake can be calculated for any particular radius.

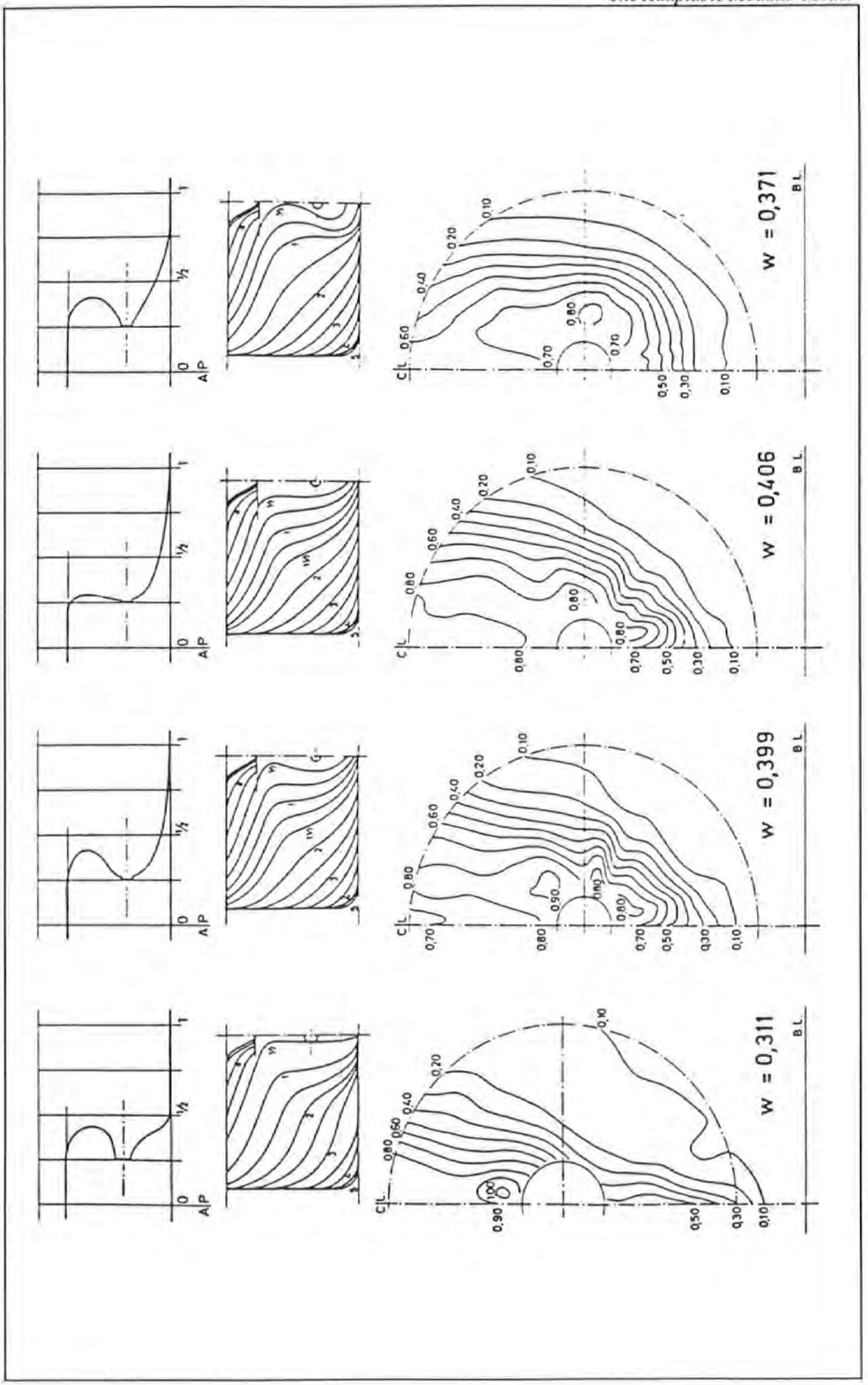


Figure 5.17. Wake distribution, after Harvald (1983).

These can be modified when the propeller is present and developing thrust. Thus from actual propeller performance and open water tests it is possible to obtain a wake factor which can remain constant, only dependent upon the ship speed and velocity of advance, and not taking into consideration the radius of the propeller. This method gives the effective wake fraction as:

$$\omega = \frac{V_s - V_a}{V_s} \quad \text{.....(5.61)}$$

For a mathematical model using the circulation theory this equation will not be accurate enough, so an equation involving the speed of the vessel, radius of the propeller and longitudinal velocity is required. One such equation was developed by Hadler et al (1964):

$$(1-\omega_x)R = \frac{2}{1-x_h}\int_{x_h}^{1} \frac{\overline{v}_x(x)}{v_s} dx \quad \text{.....(5.62)}$$

where:
- ω_x = wake fraction;
- x_h = hub radius coefficient;
- $\overline{v}_x$ = mean longitudinal velocity at x;
- x = non-dimensionalised radius;
- R = radius of propeller.

Applying this to the 'Esso Osaka' simulation of the turning circle in section 4.4, wake fractions were calculated for the initial approach speed where $v_s = 3.966 ms^{-1}$ and these values are shown in table 5.7.

Non-dimensional radius (x)	*Wake Fraction (ω_x)*
0.2	0.92
0.3	0.88
0.4	0.84
0.5	0.80
0.6	0.76
0.7	0.72
0.8	0.68
0.9	0.64
1.0	0.60

Table 5.7. Initial wake fractions for approach speed.

From equation (5.62) it can be seen that as the vessel speed changes then so will the wake fraction. Table 5.8 shows the value of the wake fractions for the 'Esso Osaka' when it has

completed the turning circle manoeuvre at a new speed of $v_s = 2.01ms^{-1}$. The wake fractions calculated are introduced to the propeller module prior to calculating the thrust coefficient, and are calculated by integrating over the whole propeller blade for any change of ship speed.

Non-dimensional radius (x)	*Wake Fraction (ω_x)*
0.2	0.860
0.3	0.796
0.4	0.727
0.5	0.689
0.6	0.590
0.7	0.522
0.8	0.455
0.9	0.390
1.0	0.320

Table 5.8. Wake fractions for final speed.

5.4.5 Validation of Circulation Theory

It was felt necessary that the circulation theory should be validated as assumptions are included in the method developed. The thrust and torque characteristics obtained using the circulation theory are to be compared with those obtained from open water tank tests. Two propellers will be used in the validation to show the adaptability of the method adopted:

1. comparison with a standard B-series screw;
2. comparison with a non B-series screw.

5.4.5.1 Presentation of Open Water Tests

Open water model tests of screw propellers are an important part of the process of determining the principle characteristics of the propeller.

Basic knowledge of non-dimensional groups is assumed; dimensional analysis can be found in relevant texts on the subject, Lewis (1988). The following groups are associated with open water tests:

- Thrust coefficient used to present and compare results.

$$K_T = \frac{T}{\rho n^2 D^4} \quad \text{.....(5.63)}$$

- Torque coefficient used to present and compare results.

$$K_Q = \frac{Q}{\rho n^2 D^5} \quad \text{.....(5.64)}$$

- Advance coefficient relates the screw advance speed to its tangential speed.

$$J = \frac{V_a}{nD} \quad \text{.....(5.65)}$$

- Open water efficiency the efficiency of a screw in open water.

$$\eta_o = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \quad \text{.....(5.66)}$$

In general the results of open water tests are given in the form of K_T and K_Q coefficients expressed as a function of the advance coefficient (J), figure 5.18.

5.4.5.2 Validation of a B-Series Screw

The chart shown in figure 5.17 was used to validate the B-series screw. The propeller chosen has the following principle features:

Diameter	21 in
Pitch	19 in
P/D	0.905
No. of blades	4
DAR	0.70

Detailed description of the propeller is given in appendix E.

The method outlined in section 5.4.3.3 was used theoretically to predict the thrust, torque and efficiency values of the propeller and these can be seen in table 5.9. The calculated values were then compared with those read from the B4.70 chart, figure 5.18, for the same advance coefficient. The results were plotted graphically and can be seen in figures 5.19-5.21.

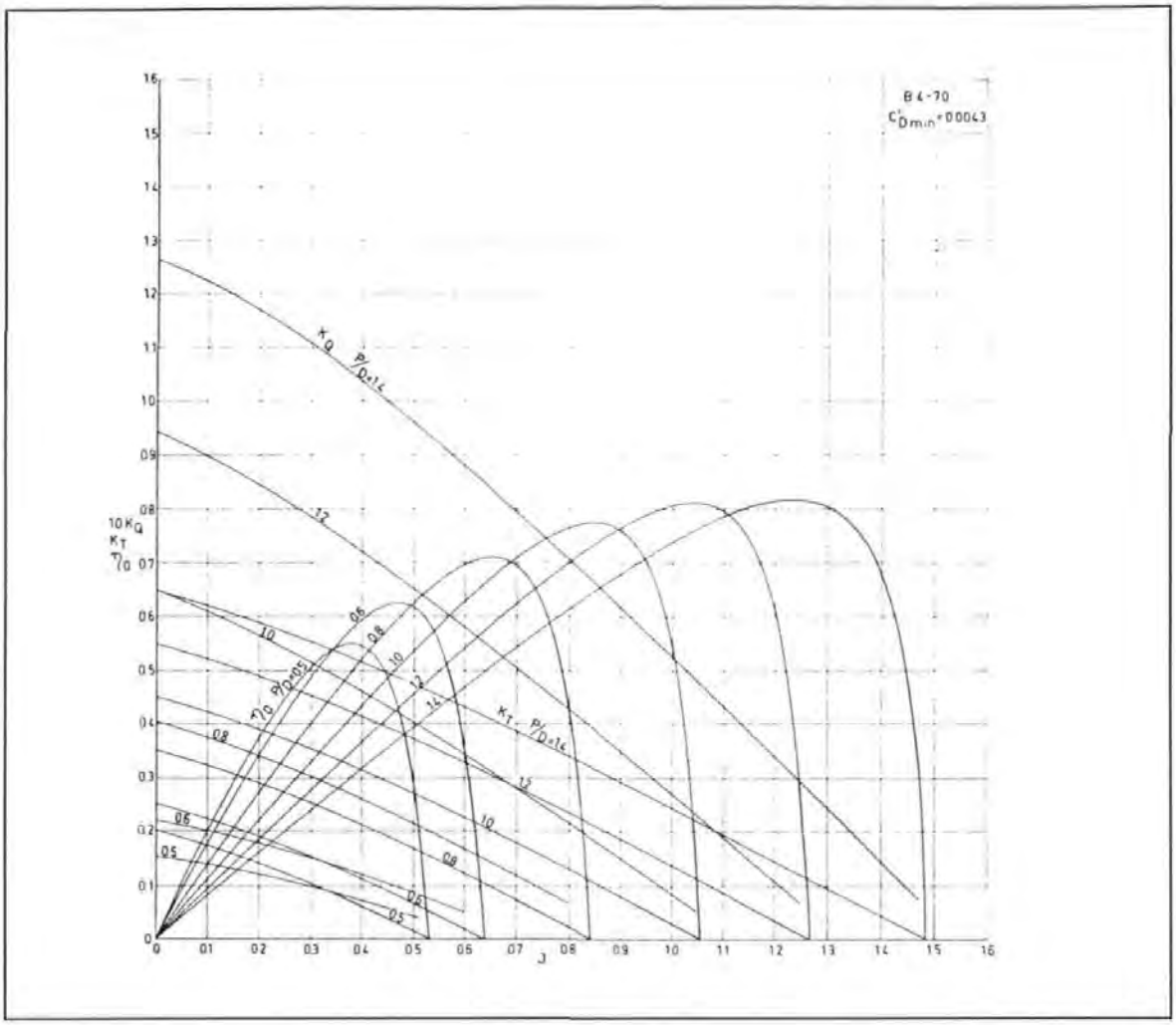


Figure 5.18. Open Water Test Results of B4.70 Screw Series, after Van Lammeren et al (1969).

J	$R_n \times 10^{-6}$	K_T	K_Q	η_o
0.300	10.4186	0.250	0.036	0.333
0.500	7.9398	0.185	0.027	0.537
0.700	6.9643	0.099	0.017	0.645
0.871	6.7738	0.020	0.006	0.425

Table 5.9. Theoretical prediction for the B-series screw.

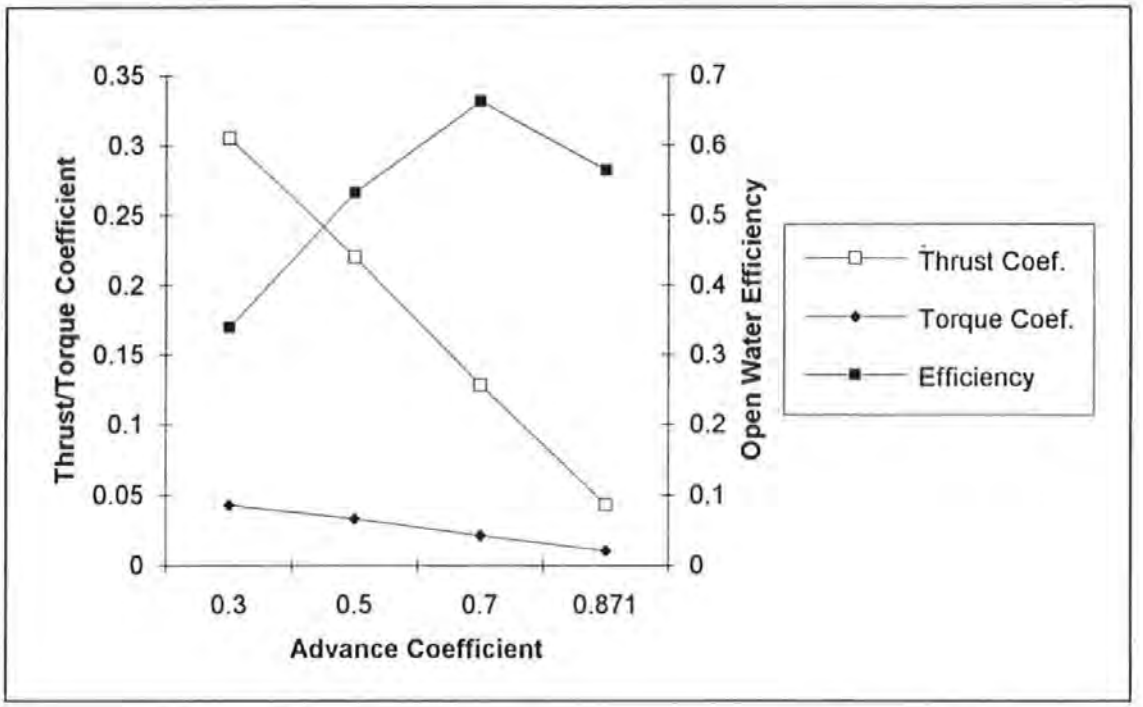


Figure 5.19. Operating characteristics for a B4.70 screw

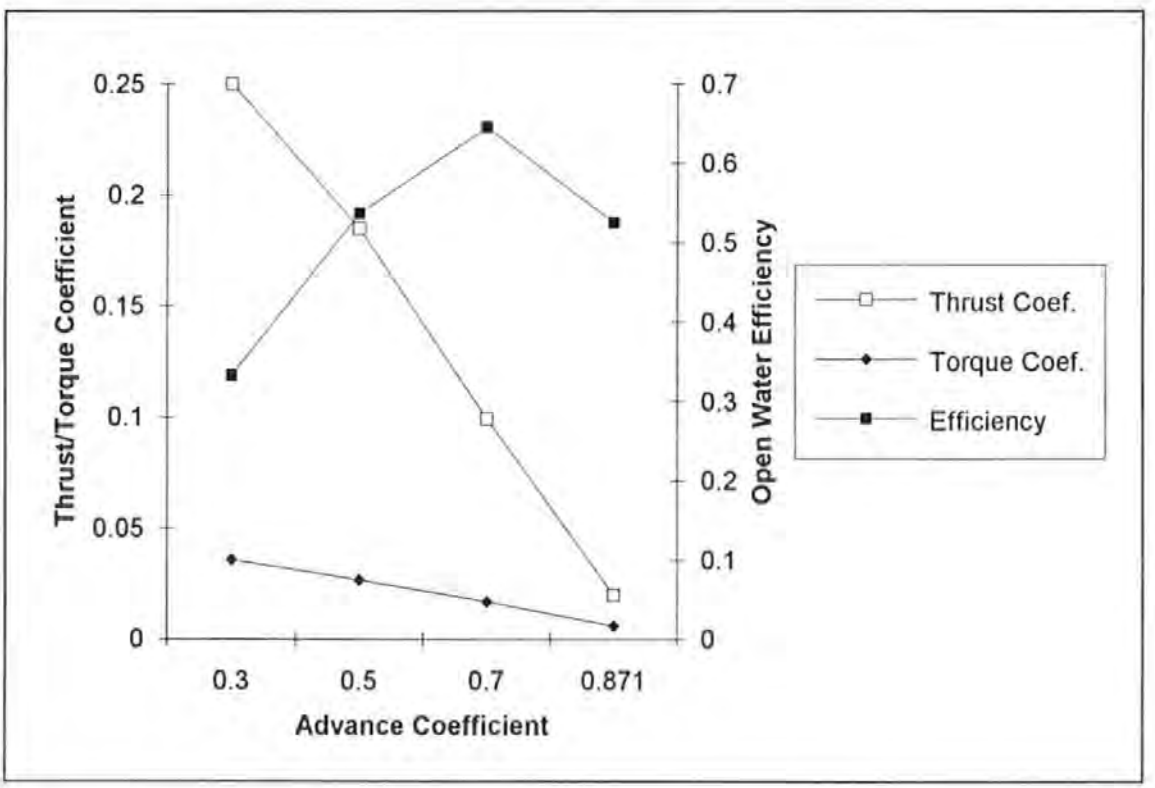


Figure 5.20. Theoretical operating characteristics for a B4.70 screw

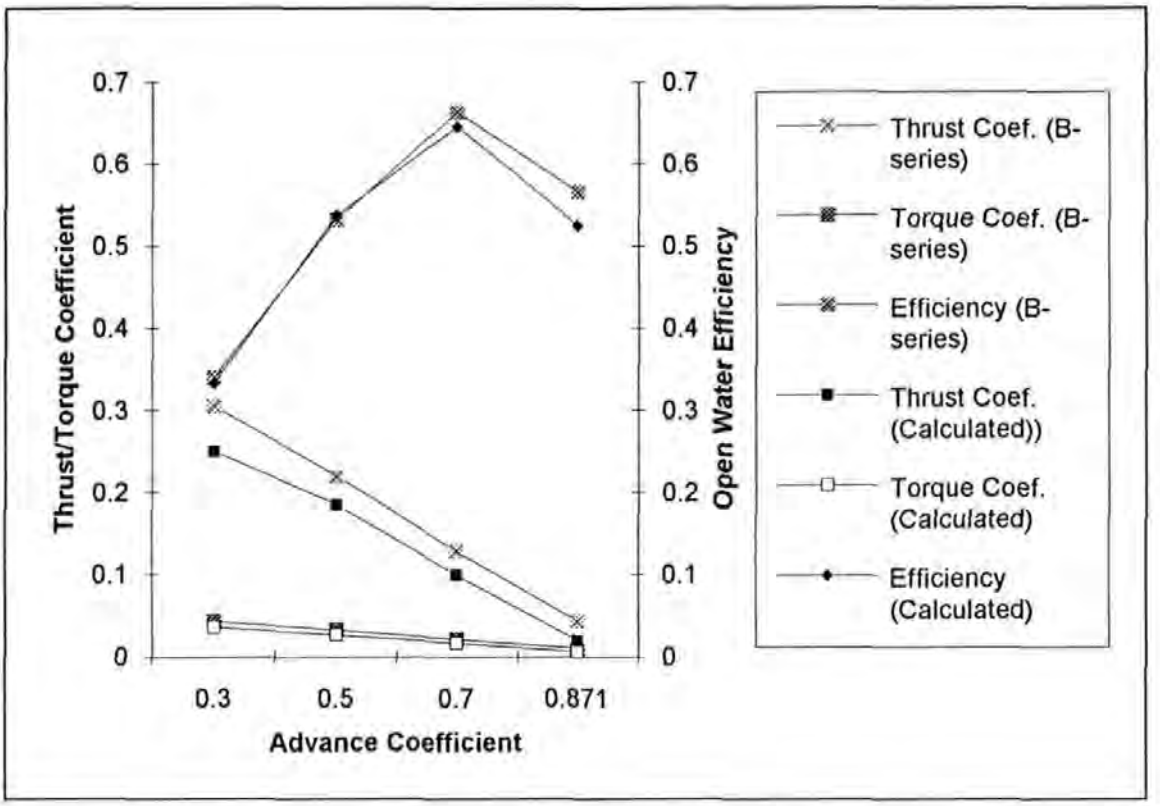


Figure 5.21. Theoretical and actual comparison for the B4.70 screw.

5.4.5.3 Validation of a Non B-Series Screw

Tank tests were carried out on a model screw, one twelfth scale, of a frigate propeller at the Royal Naval Engineering College (RNEC). Screw details are given in appendix E and tank tests are described in appendix F. By validating against this screw the mathematical model is shown to be truly adaptable. Plate 5.1 shows the underwater housing of the towing carriage, plate 5.2 the towing tank and table 5.10 shows the measured results.

The method outlined in section 5.4.3.3 was used to theoretically predict the thrust, torque and efficiency values of the propeller, these can be seen in table 5.11. The calculated values were then compared with those measured from tank tests for the same advance coefficient. The results were plotted graphically and can be seen in figures 5.22-5.24.

V_a	N	$R_n \times 10^{-6}$	J	T	Q	K_T	K_Q	η_o
1.9	530.78	0.619	0.7075	228.18	14.45	0.3451	0.0721	0.539
1.9	531.46	0.620	0.7079	228.46	14.42	0.3459	0.0720	0.541
1.9	530.78	0.619	0.7079	227.86	14.40	0.3458	0.0721	0.541
2.2	538.35	0.637	0.8091	200.11	13.15	0.2952	0.0640	0.594
2.2	537.74	0.637	0.8101	202.14	13.16	0.2989	0.0642	0.600
2.2	536.62	0.635	0.8118	197.20	13.03	0.2928	0.0638	0.593
2.5	522.54	0.632	0.9473	151.05	10.64	0.2365	0.0550	0.648
2.5	522.24	0.632	0.9475	150.36	10.60	0.2356	0.0548	0.648
2.5	522.16	0.632	0.4800	147.88	10.41	0.2319	0.0539	0.649
2.8	537.76	0.660	0.3090	133.14	9.74	0.1969	0.0475	0.680
2.8	530.65	0.653	1.0448	128.28	9.50	0.1947	0.0476	0.680
2.8	529.85	0.651	1.0463	122.36	9.23	0.1864	0.0464	0.669
3.0	520.29	0.651	1.1417	86.17	7.37	0.1361	0.0384	0.644
3.0	518.73	0.650	1.1451	85.97	7.18	0.1366	0.0377	0.660
3.0	518.39	0.649	1.1459	89.05	7.49	0.1417	0.0393	0.658
3.0	473.03	0.605	1.2557	37.70	4.14	0.0720	0.0261	0.551
3.0	472.99	0.604	1.2558	36.94	4.24	0.0706	0.0267	0.529
3.0	472.56	0.605	1.2570	38.18	4.42	0.0730	0.0279	0.523
3.0	439.96	0.573	1.3501	11.19	2.23	0.0247	0.0163	0.326
3.0	440.27	0.574	1.3549	7.25	2.21	0.0159	0.0162	0.212
3.0	438.40	0.572	1.3549	9.30	2.28	0.0207	0.0167	0.267

Table 5.10. RNEC Open water test results.

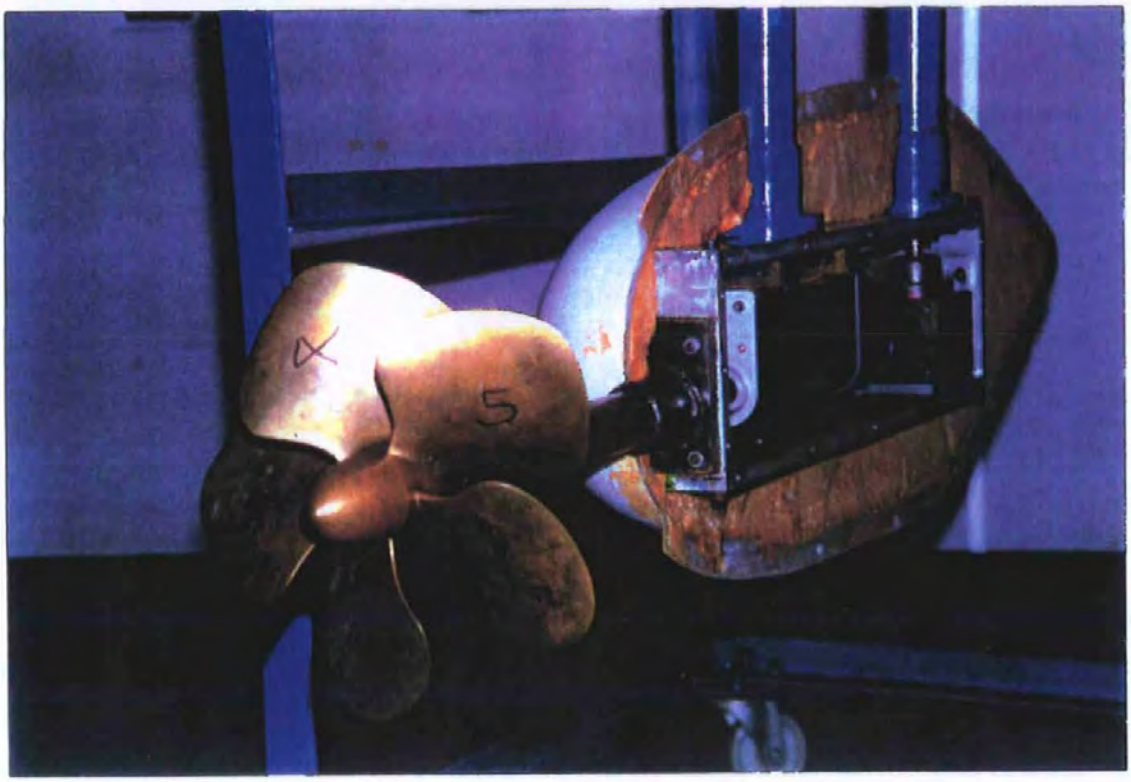


Plate 5.1. The underwater housing of the towing carriage.

Plate 5.2. Towing tank at the Royal Naval Engineering College.

V_a ms^{-1}	N	$R_n \times 10^{-6}$	J	K_T	K_Q	η_o
1.5	495	0.5699	0.600	0.330	0.072	0.438
1.9	534	0.6228	0.704	0.289	0.064	0.506
2.0	528	0.6197	0.750	0.268	0.060	0.533
2.2	541	0.6399	0.805	0.250	0.056	0.569
2.3	536	0.6380	0.850	0.224	0.051	0.589
2.5	550	0.6601	0.900	0.198	0.047	0.602
2.5	525	0.6345	0.943	0.187	0.044	0.632
2.5	510	0.6195	0.970	0.174	0.042	0.640
2.8	531	0.6529	1.044	0.137	0.035	0.650
3.0	519	0.6499	1.145	0.077	0.024	0.594
3.0	475	0.6071	1.250	0.017	0.012	0.268

Table 5.11. Theoretical prediction for the non B-series screw.

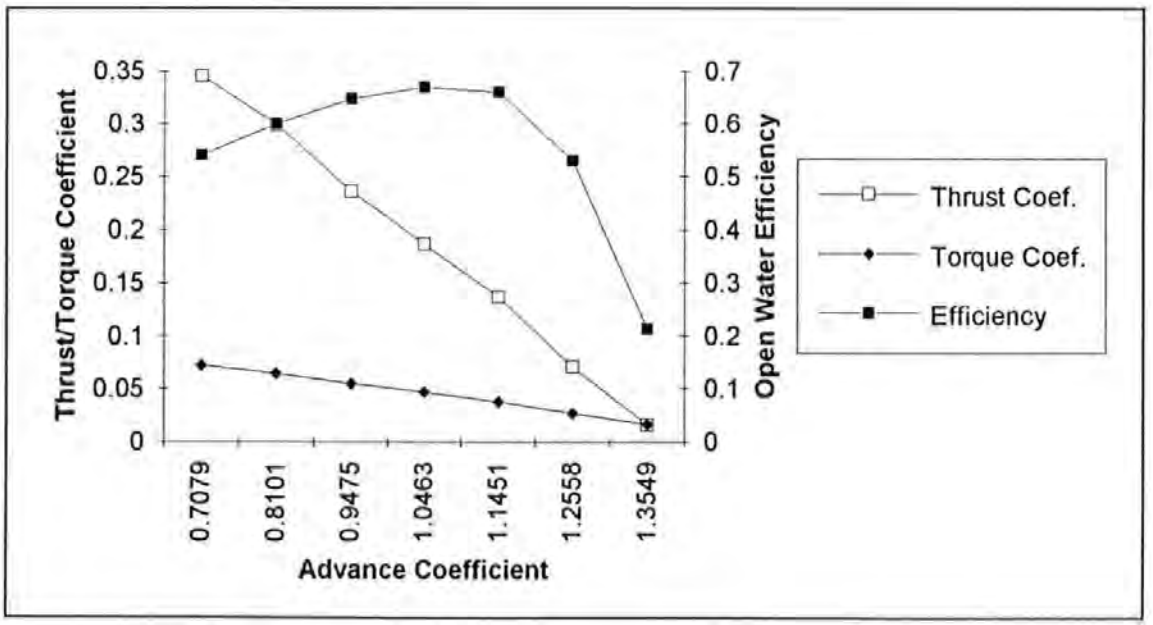


Figure 5.22. Operating characteristics from tank tests.

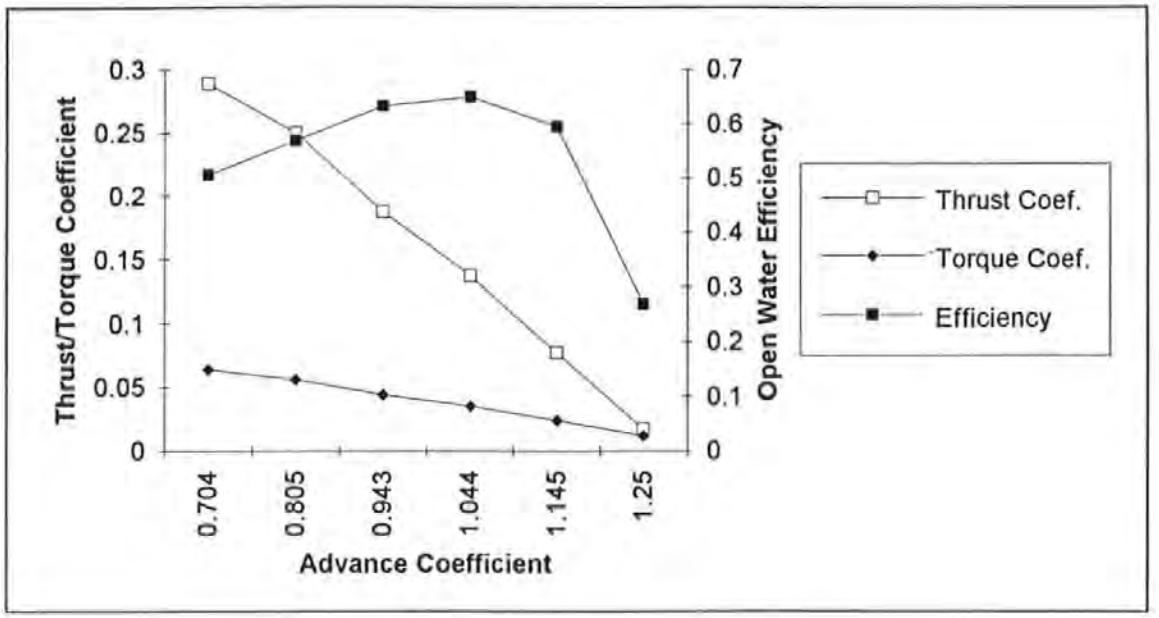


Figure 5.23. Theoretical operating characteristics.

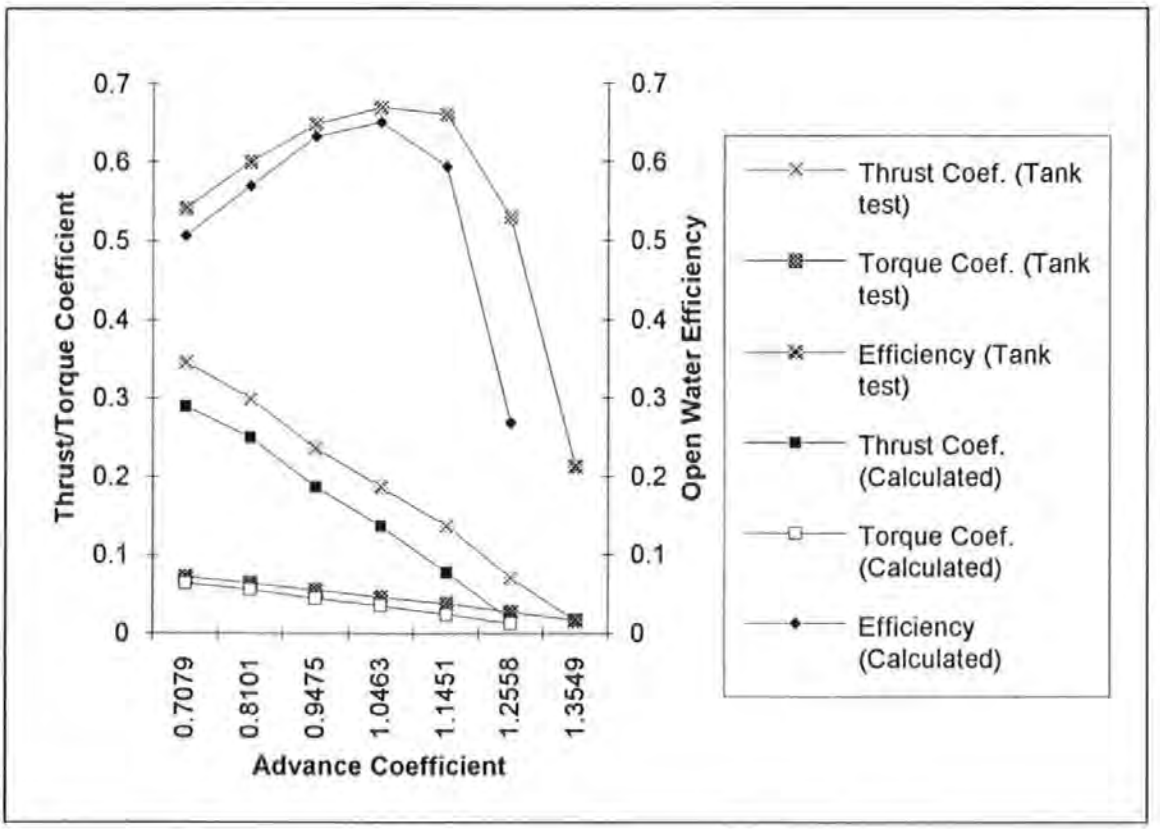


Figure 5.24. Theoretical and tank test comparison for the non B-series screw.

5.5 Propeller Forces and Moments

5.5.1 Surge Terms

It has already been seen in chapter 4.4 that the surge propeller component can be obtained from the following equation:

$$X_P = (1-t)T \quad \text{.....(5.67)}$$

The propeller thrust, T, for ahead motion, is obtained using the circulation theory as outlined in chapter 5.4.5. Although the circulation theory can be used for astern motion the flow characteristics in the stern area are very complex for any prediction method. For this reason the following formula was developed and was found to work adequately for the models purpose:

$$T = 0.5\rho A_o\left(0.11295\cos\varepsilon|\cos\varepsilon| - 0.69575\sin\varepsilon|\sin\varepsilon|\right)\left(up^2 + cp^2\right) \quad \text{.....(5.68)}$$

The thrust deduction fraction, t, can be calculated using the formula given by Holtrop (1984):

$$t = 0.25014\left(B/L\right)^{0.28956}\left(\sqrt{BT}/D\right)^{0.2624}/\left(1-C_P+0.0225lcb\right)^{0.01762} + 0.0015C_{stern}$$

.....(5.69)

The values for C_{stern} and lcb are as shown in section 5.3.1.1.

5.5.2 Sway and Yaw Terms

The sway and yaw propeller components have already been seen to be represented by the following formulae:

$$Y_P = Y_{nn}n^2$$

$$N_P = N_{nn}n^2 \quad \text{.....(5.70)}$$

The term Y_{nn} is a function of the "paddle wheel" effect, this is the condition when a propeller turning clockwise will cause the vessel to turn to port when there is no helm. Research was undertaken to produce a regression formulae based on a number of successful simulated vessels. Y_{nn} was found to be dependent on the pitch/diameter ratio and the number of blades, the greater number of blades the less the paddle wheel effect. The

disc area ratio of the propeller was found not to influence the value of Y_{nn} and was therefore not included in the formula.

$$Y_{nn} = \frac{((P/D) \times 2.18876 \times 10^{-5}) - 1.54996 \times 10^{-5}}{\text{No. of blades}} \quad \text{.....(5.71)}$$

Dependant on the handing of the propeller the following rule was found to apply:

RH	Y_{nn} + or −	N_{nn} −
LH	Y_{nn} + or −	N_{nn} +

N_{nn} can be obtained by, $Y_{nn}/2$, and adjusting the sign to suit the handing of the propeller.

5.6 Rudder Forces and Moments

The rudder forces and moments are modelled using the same method as described in chapter 4.4. However, for the model to be adaptable the following formulae were calculated using linear regression and added to the simulation program:

$$a_H = 0.6299 C_B - 0.1734 \quad \text{.....(5.72)}$$

$$t_R = 0.9798 - 0.002553 L \quad \text{.....(5.73)}$$

5.7 Additional Model Information

Additional inputs to the adaptable modular model program include the time sampling period and the rudder and engine response times. If these are not known they are calculated using the following formulae that were obtained after numerous vessel simulations.

$$t_{samp} = 0.0143624 L + 0.3322 \quad \text{.....(5.74)}$$

$$T_R = T_N = 0.0223415 L + 0.73898 \quad \text{.....(5.75)}$$

The vessels moment of inertia can be found from:

$$I_Z" = 0.00011255 L + 0.02592 \quad \text{.....(5.76)}$$

5.8 Discussion

The components of a new adaptable mathematical model have been presented.

The method adopted for calculating the total resistance of the model, section 5.3, has been used in other applications by the author and is known to be accurate and reliable. Applications have included finding vessel resistance at the design stage to calculate engine and propeller requirements. Many vessels, in service, have propellers designed by the author and no problems have been experienced using the method detailed.

The circulation theory is usually used in the design of wake adapted screws. However, it can also be used to calculate propeller performance. Comparative results have been shown for both the B-series and non B-series propeller types, figure 5.20 and 5.23, and from the diagrams it can be seen that the calculated thrust coefficient is consistently below that of the tank test result, (the B-series results are obtained from tank tests). The primary reason for this error is in the calculation of the drag coefficient. The drag coefficient is calculated for a NACA foil section a=1.0 but neither the B-series nor the selected non B-series screw has blades of this exact section. However, adaptability is the goal. In selecting the NACA foil section to calculate C_D, an acceptable level of accuracy can be achieved for the majority of propeller types. As will be seen in chapter 6 the accuracy of the model is not greatly affected by adopting the use of the circulation theory and reliance on standard series data is no longer required.

The propeller sway and yaw terms are now calculated with a newly developed formula, equation 5.71, that was created as part of the research, and is a function of the propeller pitch/diameter ratio and its number of blades. The disc area ratio was found not to significantly alter the propeller sway and yaw characteristics and was therefore not included in the formula.

CHAPTER 6

THE PC BASED SIMULATOR

6.1 Introduction

During the latter half of the 1980s there was an increase in the interest and use of PC based simulators, Anon (1989a), due primarily to the increased processor power available to the PC user, figure 6.1.

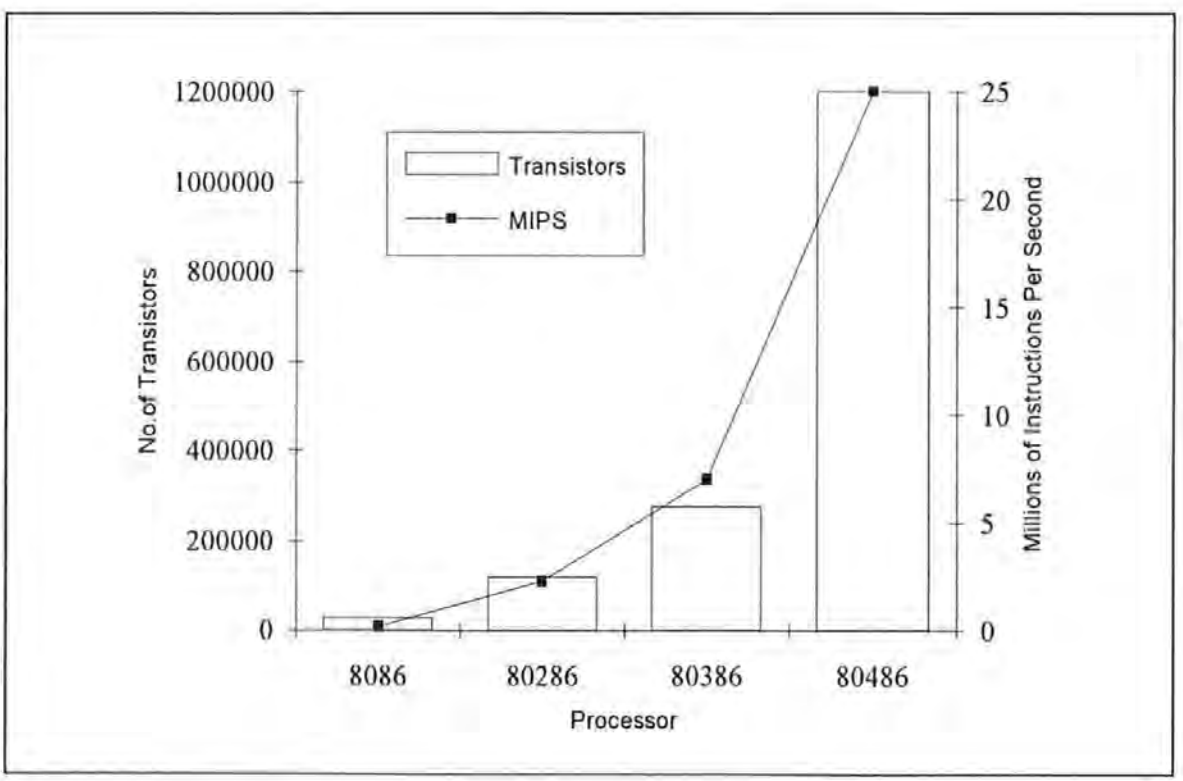


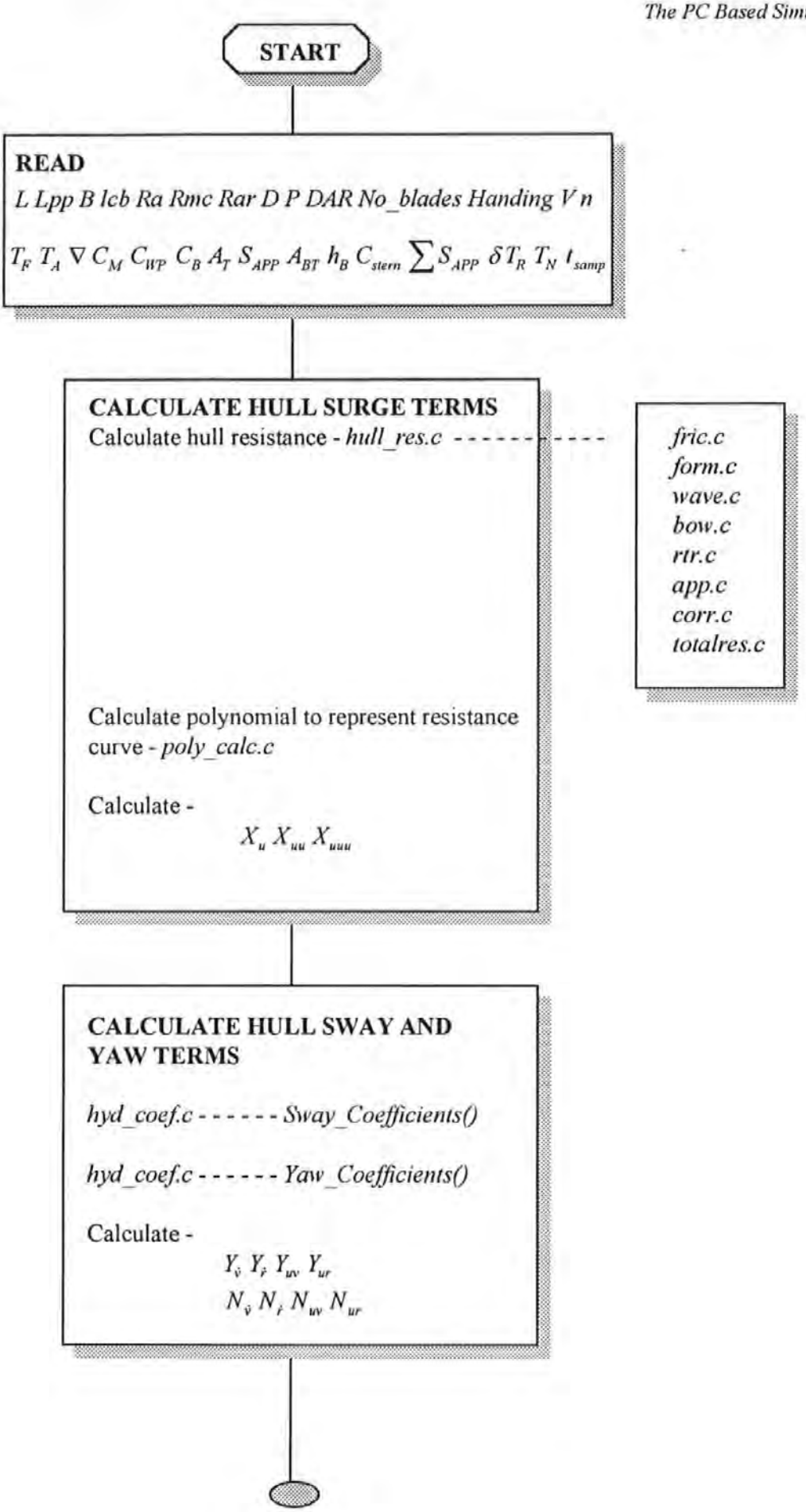
Figure 6.1. Intel Microprocessor Development.

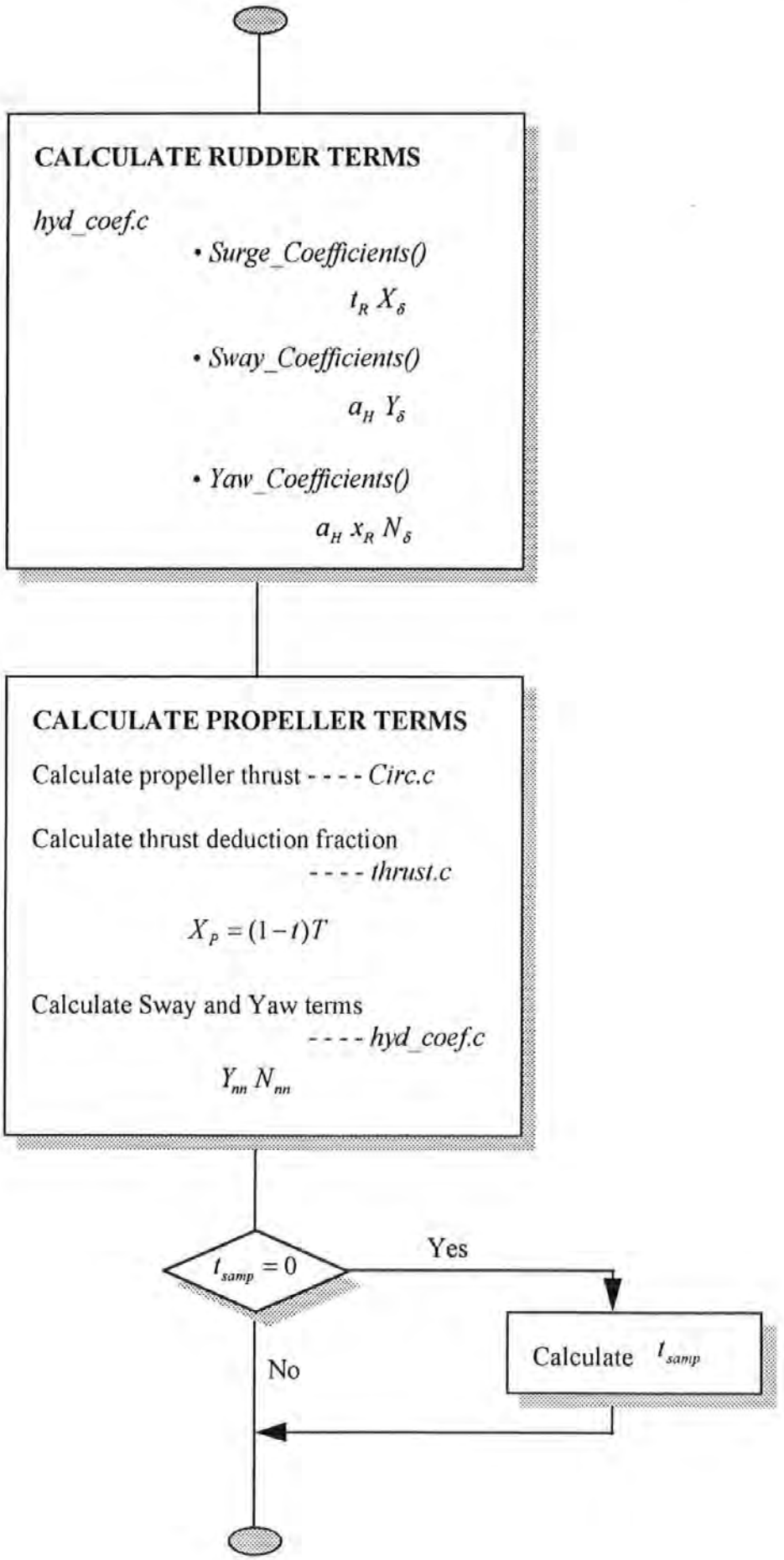
Increased processor power has enabled the programmer to move away from expensive mainframe computers and develop PC based simulation packages for the single user.

Forthcoming legislation, proposed by IMO[1] through MSC/Circ 389, will require all new ships greater than 100m in length to satisfy stringent manoeuvring performance standards. Due to the resources and finances that are required to build a modern ship, a designer will have to be able to evaluate the manoeuvring characteristics and powering predictions of a vessel before it is constructed. A simulator must use basic data from the preliminary design stage of the vessel and not rely on data obtained from scale model experiments and/or trial data. Therefore, at the heart of all simulators is the mathematical model used to predict the vessels manoeuvring characteristics. This is also the requirement of the adaptable mathematical model for use in the ACAS. Simulations will therefore be shown for various vessels and validated against actual vessel trials.

Figure 6.2 shows a flow diagram representing the part of the PC simulation program that calculates all necessary hydrodynamic coefficients and model data. Before the simulation can be run, all the hydrodynamic coefficients and associated data representing the proposed vessel must be calculated, as shown in chapter 5. The programs were written in *Microsoft C* and designed to run on a Viglen 486 33MHz PC with *Windows 3.1*. Windows is required as the results data file is interpreted in the spreadsheet *Excel for Windows*, thus a graphics routine is not required within the C program allowing a faster processing time.

[1]The International Maritime Organisation.


START
READ
L Lpp B lcb Ra Rmc Rar D P DAR No_blades Handing V n
T_F T_A ∇ C_M C_{WP} C_B A_T S_{APP} A_{BT} h_B C_{stern} $\sum S_{APP}$ δ T_R T_N t_{samp}
CALCULATE HULL SURGE TERMS
Calculate hull resistance - hull_res.c
fric.c
form.c
wave.c
bow.c
rtr.c
app.c
corr.c
totalres.c
Calculate polynomial to represent resistance curve - poly_calc.c
Calculate -
X_u X_{uu} X_{uuu}
CALCULATE HULL SWAY AND YAW TERMS
hyd_coef.c - - - - - - Sway_Coefficients()
hyd_coef.c - - - - - - Yaw_Coefficients()
Calculate -
$Y_{\dot{v}}$ $Y_{\dot{r}}$ Y_{uv} Y_{ur}
$N_{\dot{v}}$ $N_{\dot{r}}$ N_{uv} N_{ur}


CALCULATE RUDDER TERMS
hyd_coef.c
• Surge_Coefficients()
$t_R\ X_\delta$
• Sway_Coefficients()
$a_H\ Y_\delta$
• Yaw_Coefficients()
$a_H\ x_R\ N_\delta$
CALCULATE PROPELLER TERMS
Calculate propeller thrust - - - - Circ.c
Calculate thrust deduction fraction
- - - - thrust.c
$X_P = (1-t)T$
Calculate Sway and Yaw terms
- - - - hyd_coef.c
$Y_{nn}\ N_{nn}$
$t_{samp} = 0$
Yes
No
Calculate t_{samp}

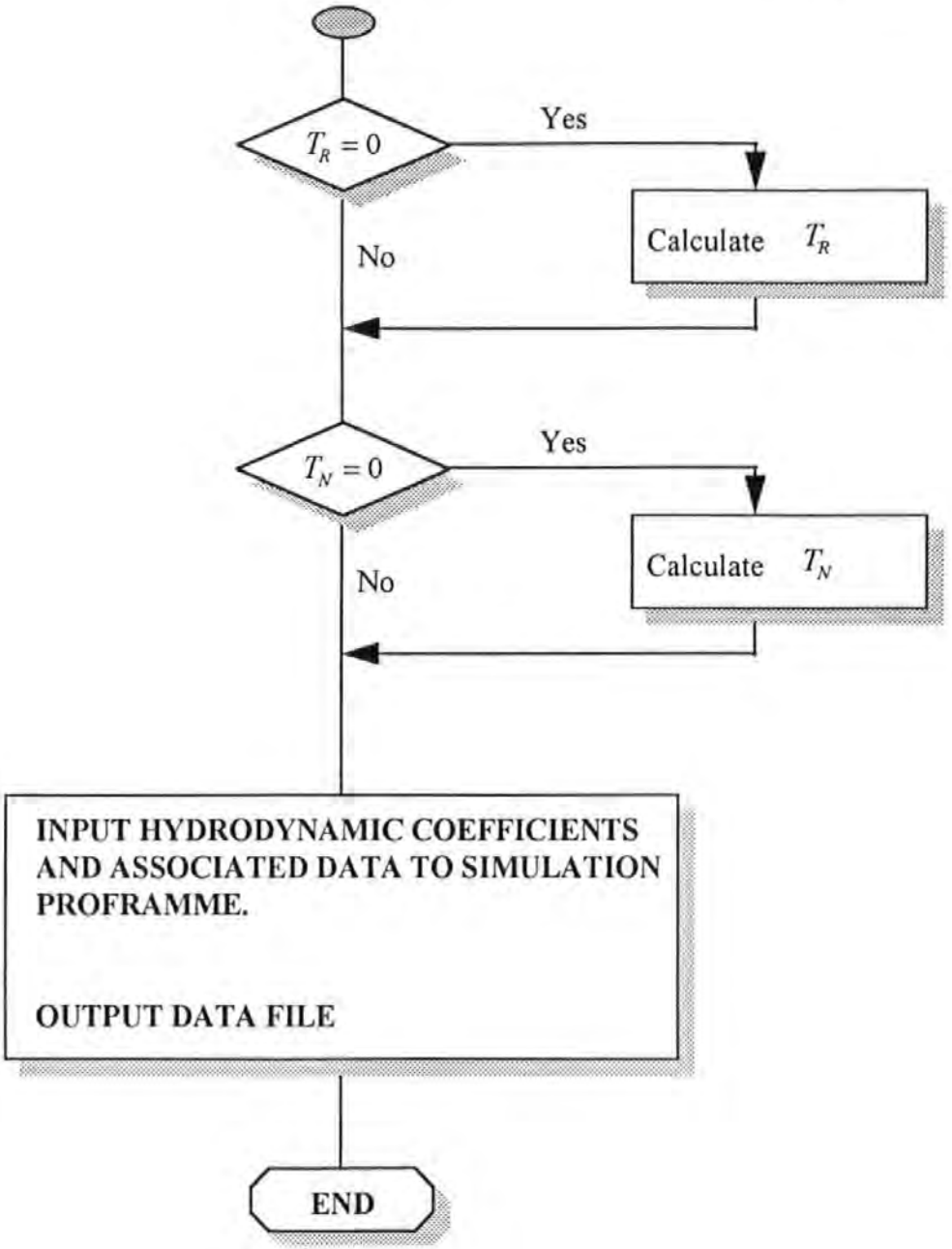


Figure 6.2. Flow diagram of model.c.

6.2 Vessel Trials

To be truly adaptable the mathematical model should be capable of modelling vessels of different size. Three vessels have therefore been chosen for validation and verification purposes, full details and principal dimensions are given in appendix D:

1. the '*Esso Osaka*', a 278000 dwt Oil Tanker. A full set of manoeuvring trials have been published by Crane (1979);

2. the '*Sand Skua*', a 63m converted sand dredger, now a 1850 dwt cargo vessel. By the kind permission of her owner trials were undertaken during a commercial voyage;

3. '*Picket Boat 9*', a 13m Navy training vessel; from now on referred to as PB9. Various trials were undertaken by kind permission of the Britannia Royal Naval College.

6.2.1 Sand Skua Trials

The 'Sand Skua', as shown in plate 6.1, is owned and operated by Trans Ocean Marine Associates Ltd, a company registered in Malta. Captain Mike Smith, Managing Director of Trans Ocean, allowed trials to be undertaken with the 'Sand Skua' on a scheduled voyage from Liverpool to Dundalk on 24th April 1990. The vessel was fully laden with coal. The weather was sunny, sea state was calm and there was no wind. The trials site was approximately 53°55'N and 6°5'W, Admiralty chart number 44, Howth to Ardglass.

There were no computers onboard to link with navigational aids to record position, speed or heading data, therefore these were recorded manually at 30 second intervals. The position was obtained using a Philips AP Decca Navigator. The following trials and manoeuvres were undertaken:

- log calibration check, resulting in the log under reading by 15%.

- 10° Port and Starboard turning circles.

- 20° Port and Starboard turning circles.

Unfortunately no other trials were undertaken due to time constraints. However, the author acknowledges that 'Sand Skua' is a commercial vessel and expresses his sincere thanks to Trans Ocean Associates Ltd for their invaluable assistance.

Figures 6.3-6.10 show the raw data collected during the trials, no correction for current or Decca errors has been applied. Appendix H shows the actual data collected in tabular format for future reference. A computer program was written to convert from Latitude and Longitude to Eastings and Northings (OSG36).

Plate 6.1. The 'Sand Skua'

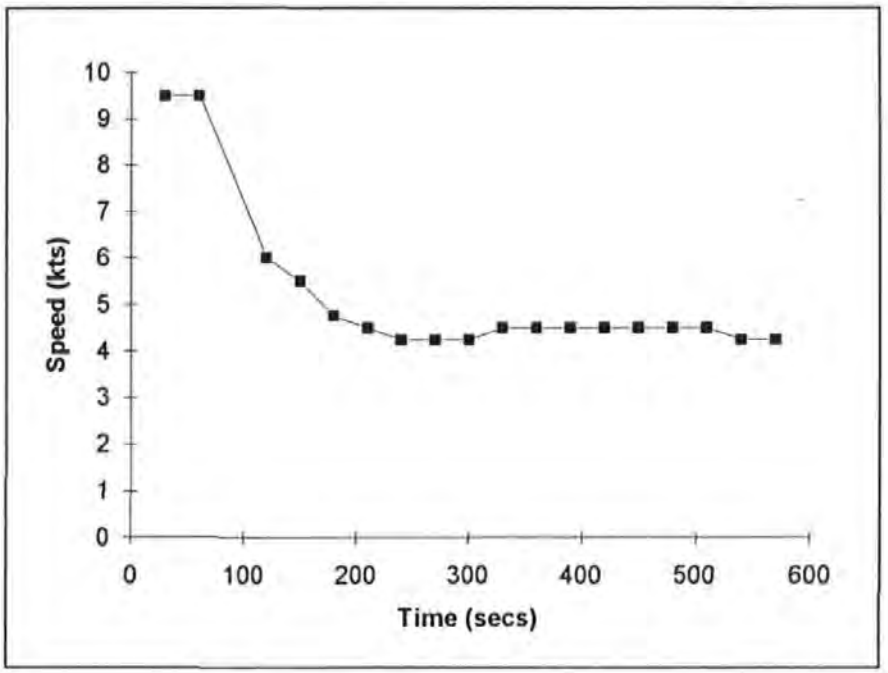


Figure 6.3. Speed reduction in a 20° Starboard turning circle for the Sand Skua.

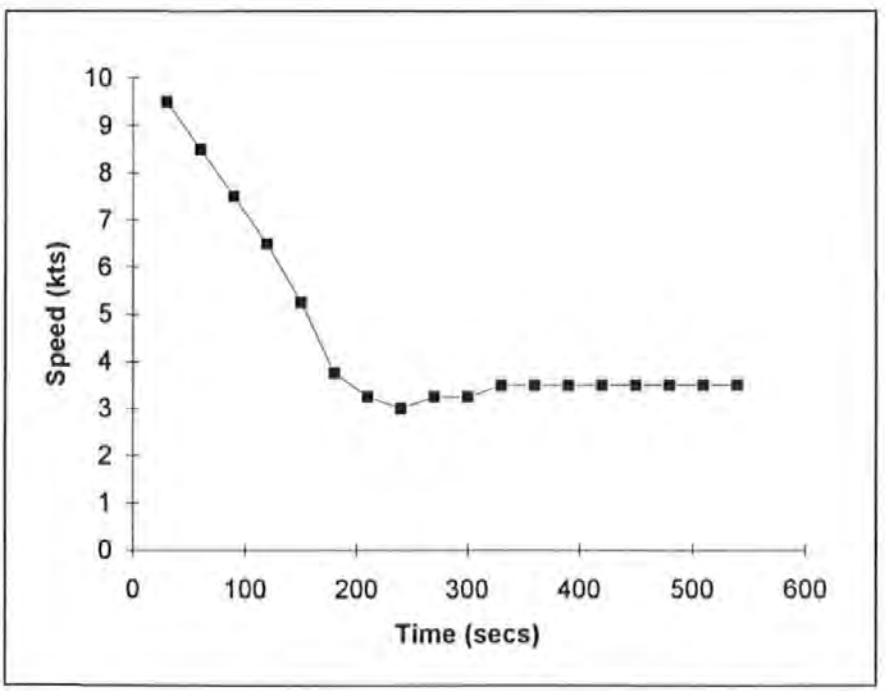


Figure 6.4. Speed reduction in a 20° Port turning circle for the Sand Skua.

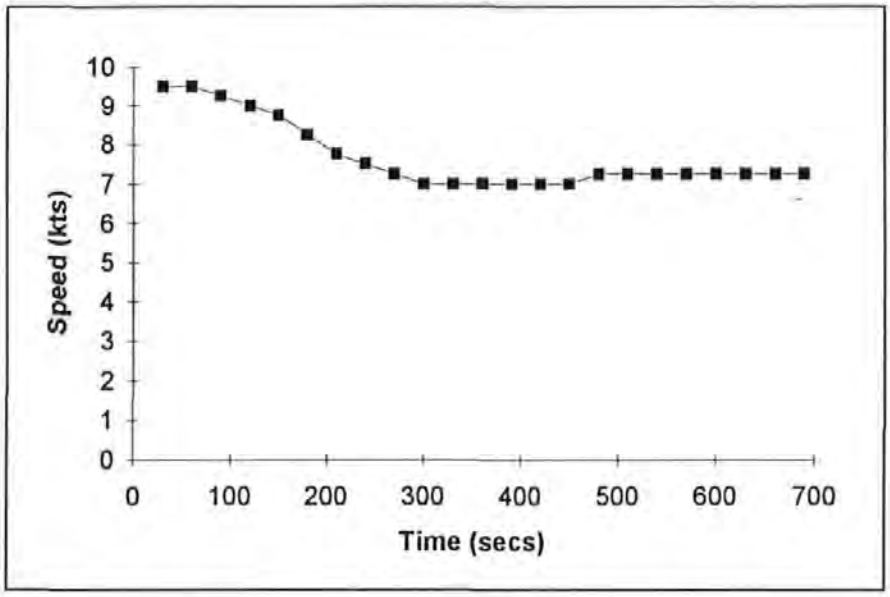


Figure 6.5. Speed reduction in a 10° Starboard turning circle for the Sand Skua.

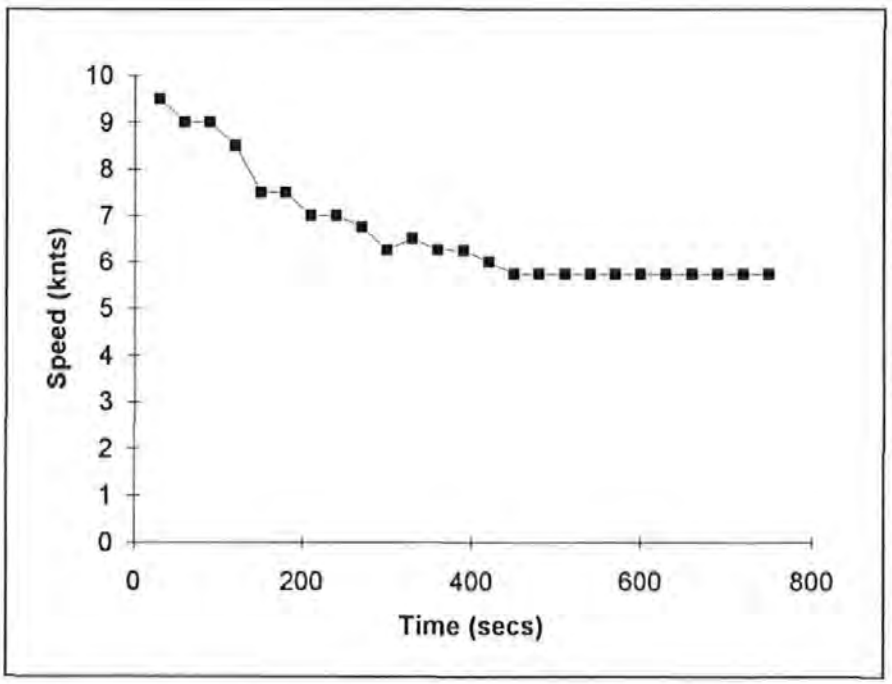


Figure 6.6. Speed reduction in a 10° Port turning circle for the Sand Skua.

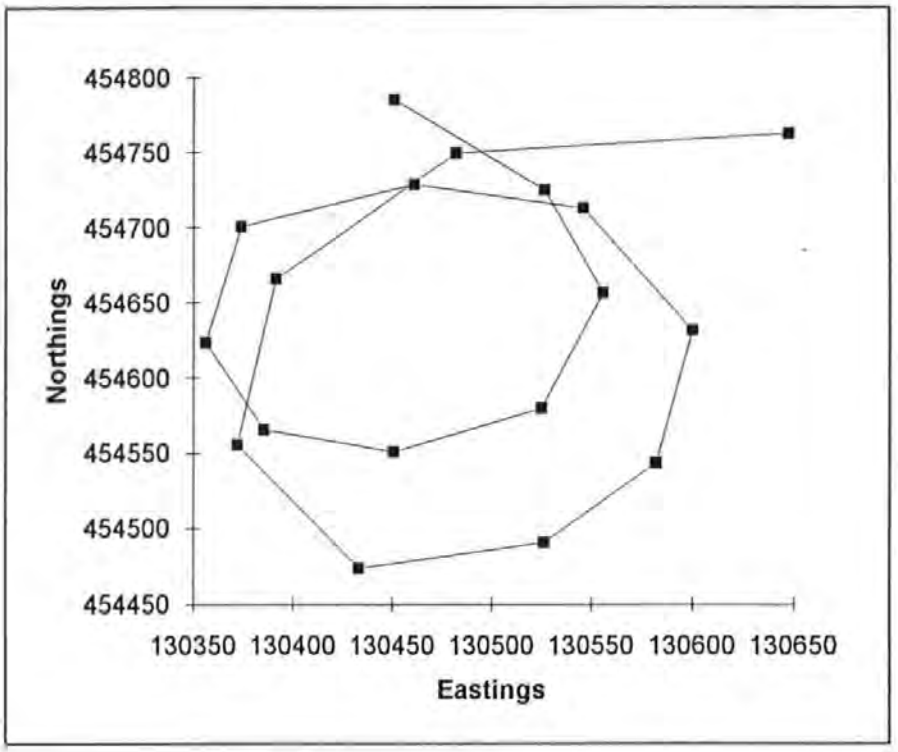


Figure 6.7. 20° Port turning circle for the Sand Skua.

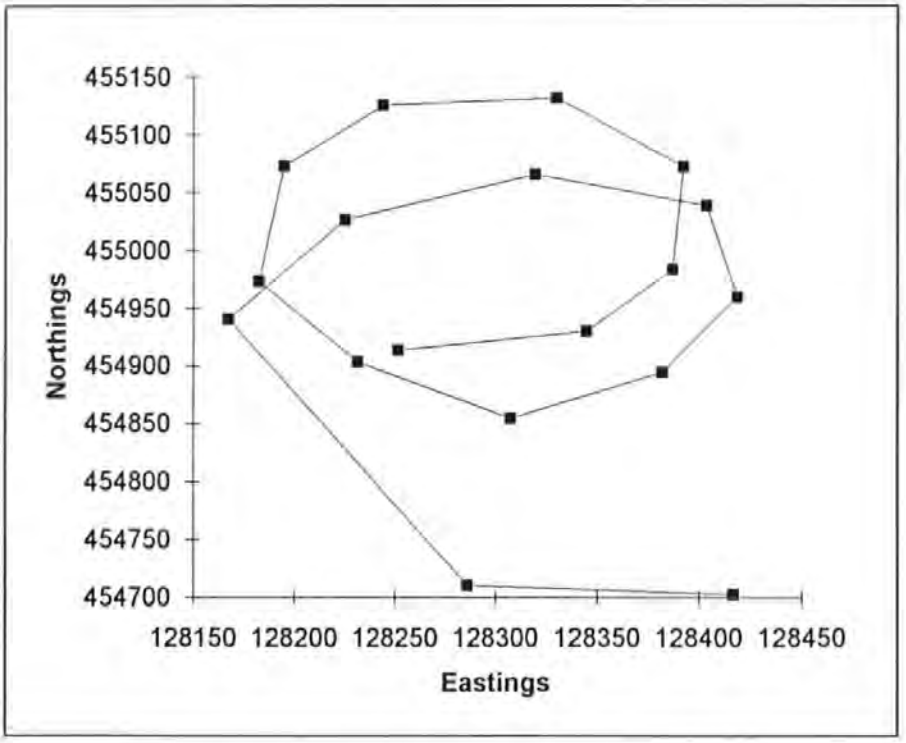


Figure 6.8. 20° Starboard turning circle for the Sand Skua.

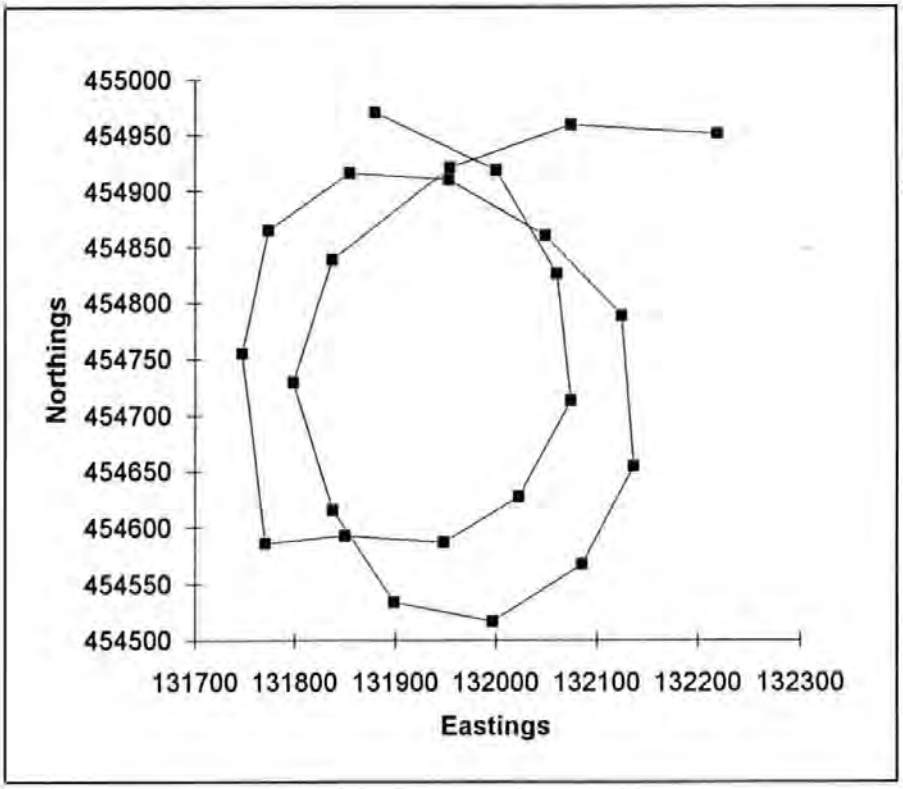


Figure 6.9. 10° Port turning circle for the Sand Skua.

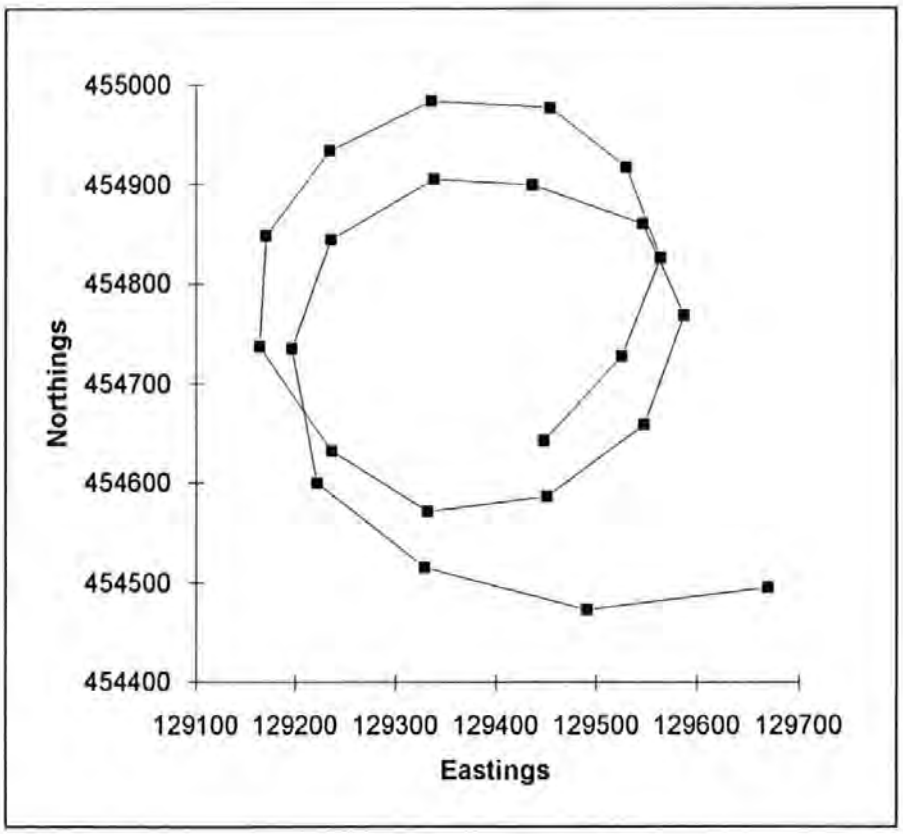


Figure 6.10. 10° Starboard turning circle for the Sand Skua.

6.2.2 Picket Boat 9 Trials

PB9, a Navy Training vessel, was recently refitted to include the following equipment, Mayo (1992):

- a 240V static invertor;
- a Rigel EC 0551 flux gate compass;
- an Autohelm ST50 paddle wheel log sender unit;
- two notch counter tachographs - one per shaft;
- a Navstar GPS position fixing device;
- a potentiometer fitted to the rudder;
- an Austin 286 16 bit micro processor with a PC30 AT expansion board to handle the data collection interface.

The initial software was written in Microsoft C, Mayo (1992), and interfaced with all the above hardware and collected data from each sensor at every time interval.

The trials were carried out in the River Dart, near Dittisham, in conjunction with Gill (1992). Standard ship manoeuvres were undertaken as laid down by the 10th International Towing Tank Conference, including basic trials such as turning circles, zigzag tests and spiral manoeuvres. More information on these trial manoeuvres is given in appendix G. Figures 6.11-6.12 show some of the raw data collected during the trials, no correction for current or GPS errors has been applied.

As PB9 is a twin screw vessel with contra-rotating screws, if both propellers are run at the same revolutions the port and starboard turning circles will be the same. This is due to there being no paddle wheel effect and hence no Y_P or N_P terms.

Plate 6.2 shows trials being undertaken on PB9.

Plate 6.2. 'Picket Boat 9'

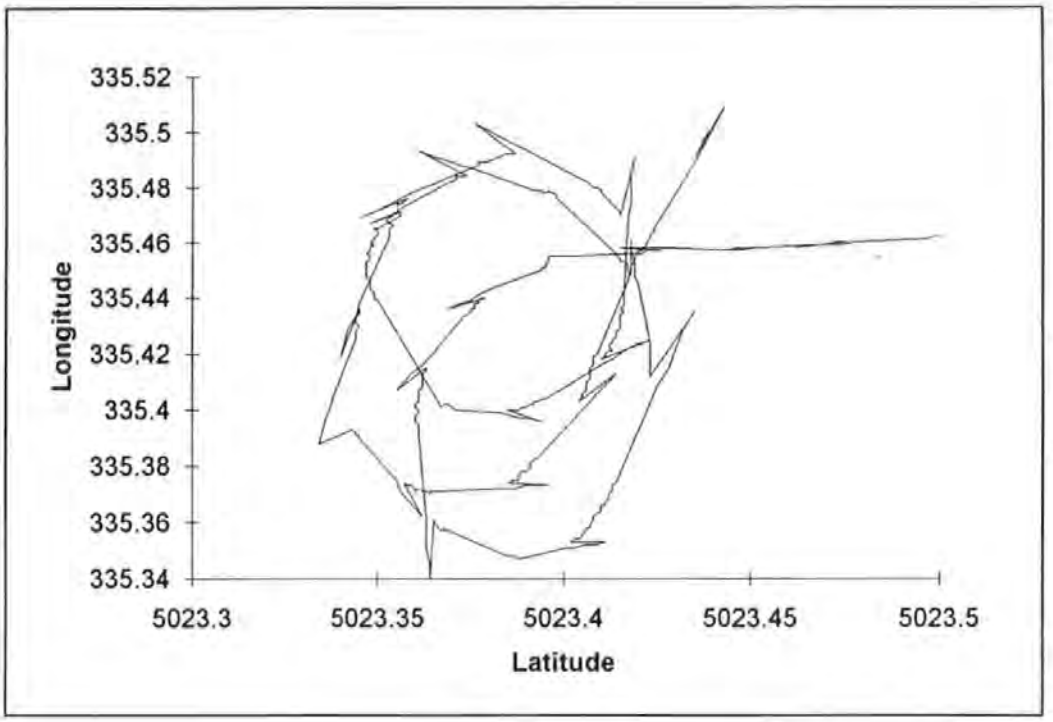


Figure 6.11. 5° Port turning circle for PB9.

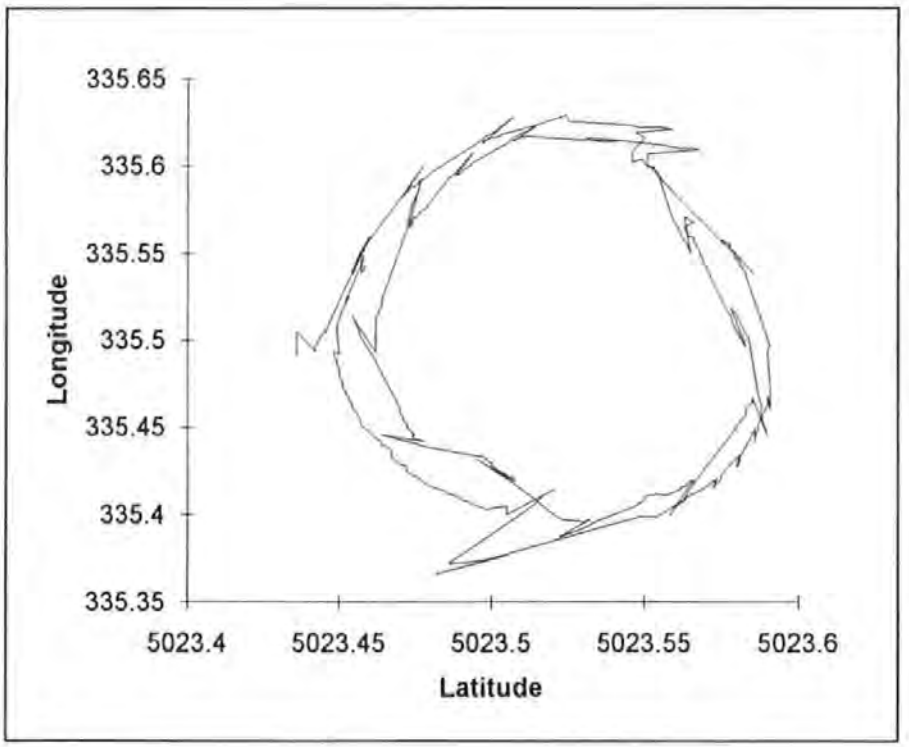


Figure 6.12. 2.5° Starboard turning circle for PB9.

The spikes present on the plots are caused by a linear filter within the GPS receiver, Mayo (1992). The positional estimates are filtered to give a straight line track, and when the

estimate shows an error beyond that acceptable the linear estimate is recalculated, resulting in the spike. The filtering is not configurable by the user and does pose a problem to data collection of turns on this small scale.

6.3 Comparison of Actual and Simulator Results

For each vessel and trial undertaken, as outlined in section 6.2, simulation runs were carried out. In general it will be seen that the results concur favourably with the actual vessel path, considering some inaccuracies are always present in trials data. It should also be borne in mind that all the vessel hydrodynamic coefficients and resistant data are calculated using the same program and no adjustments have been made, i.e. a truly adaptable model.

6.3.1 Sand Skua Results

Figure 6.13 to 6.16 show port and starboard turning circles for the 'Sand Skua'. It will be seen that the port turning circle is the smaller of the two, this is due to the paddle wheel effect of the right handed propeller. Diagrams of speed reduction, yaw rate and lateral speed have been included to show all the vessels turning characteristics. Figure 6.17 shows the simulated path for 0° rudder at a speed of 9.5 kts.

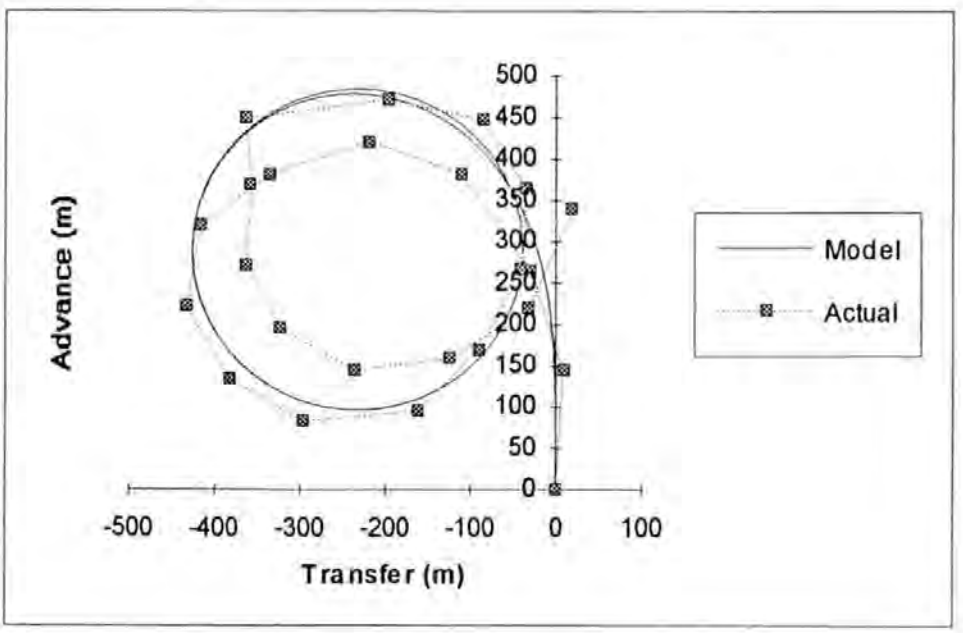


Figure 6.13a. 10° Port turning circle.

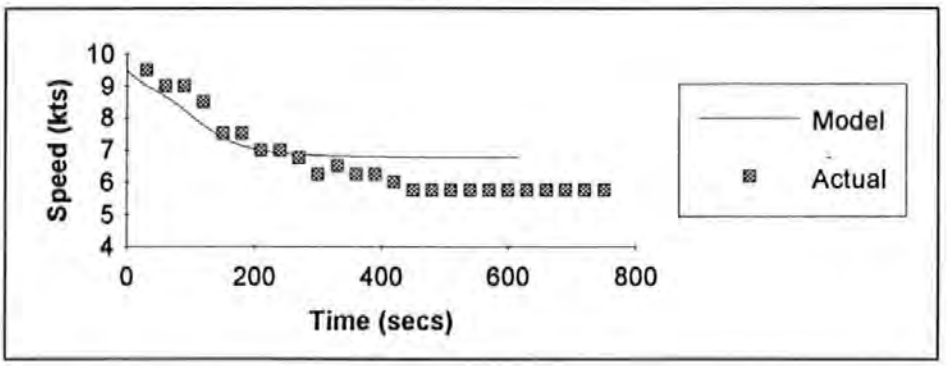


Figure 6.13b. Speed reduction.

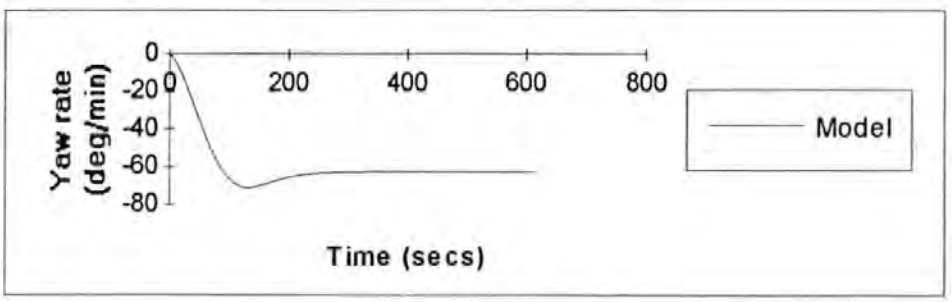


Figure 6.13c. Yaw rate.

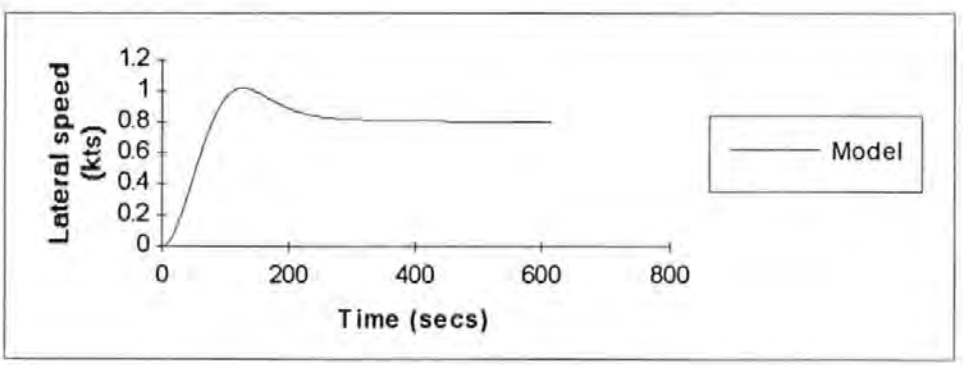


Figure 6.13d. Lateral speed.

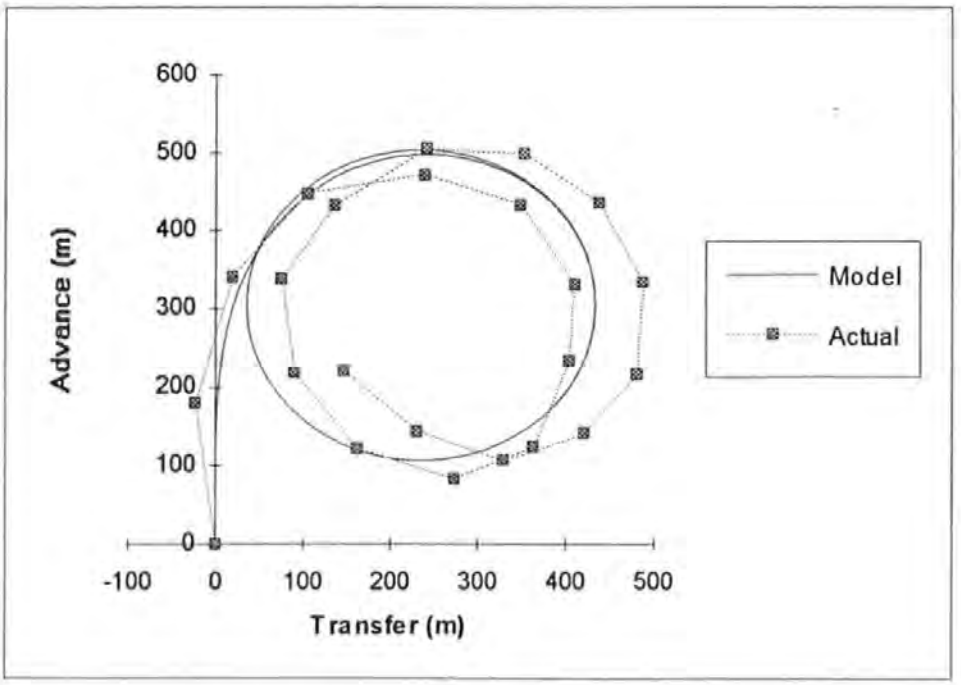


Figure 6.14a. 10° Starboard turning circle.

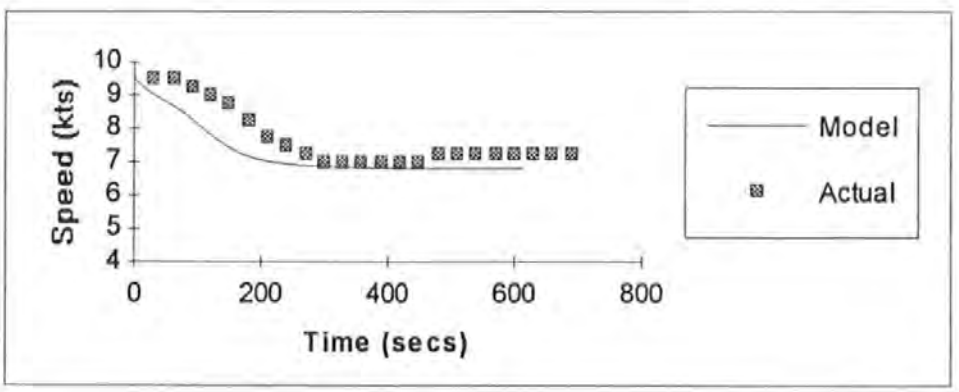


Figure 6.14b. Speed reduction.

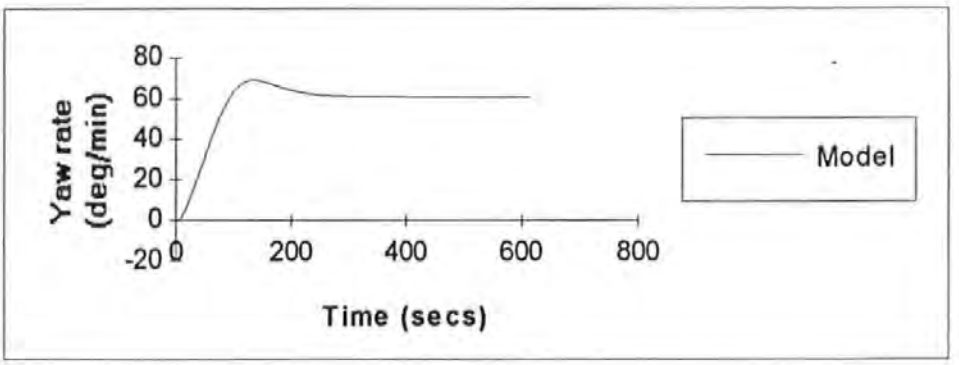


Figure 6.14c. Yaw rate.

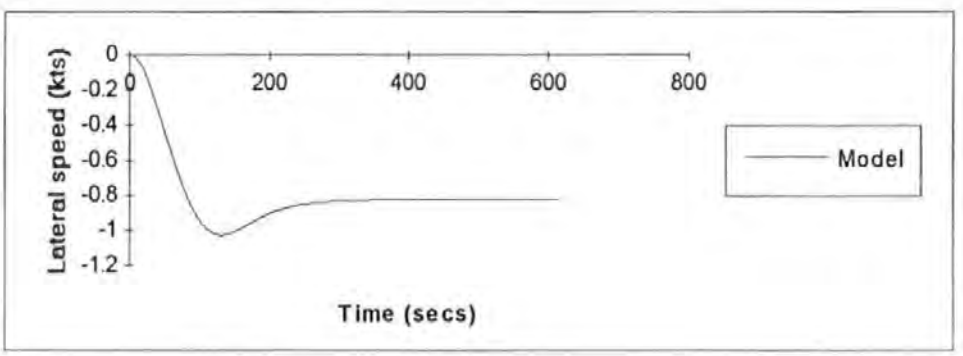


Figure 6.14d. Lateral speed.

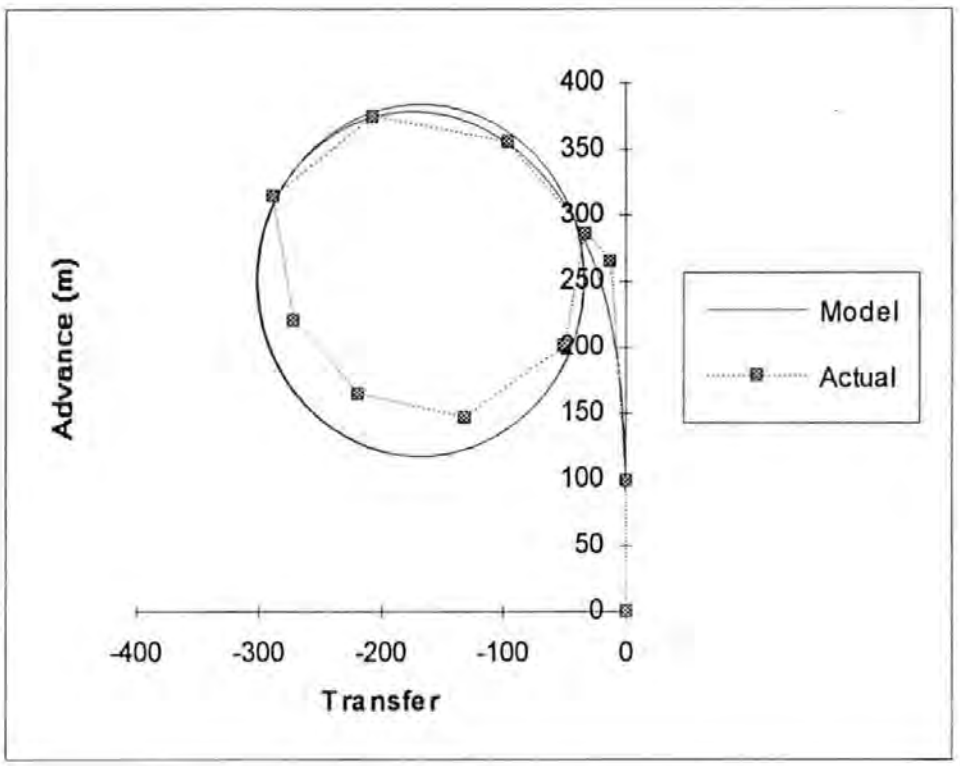


Figure 6.15a. 20° Port turning circle.

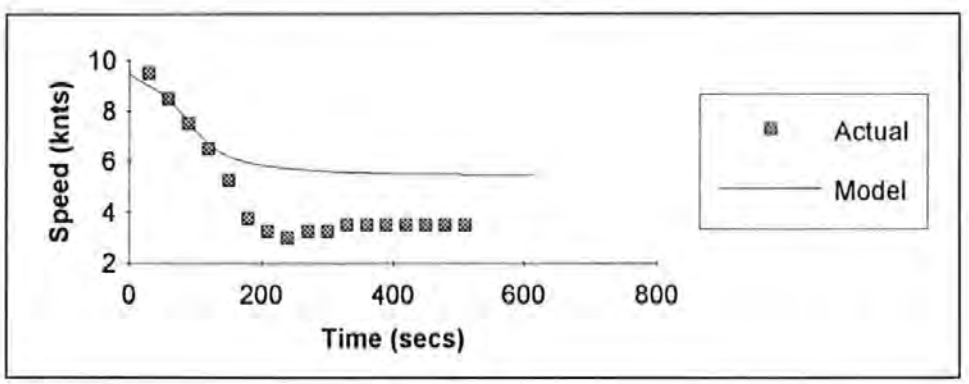


Figure 6.15b. Speed reduction.

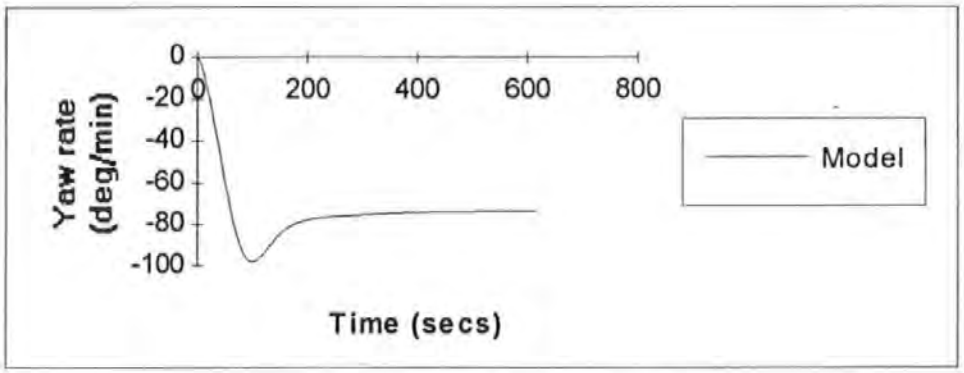


Figure 6.15c. Yaw rate.

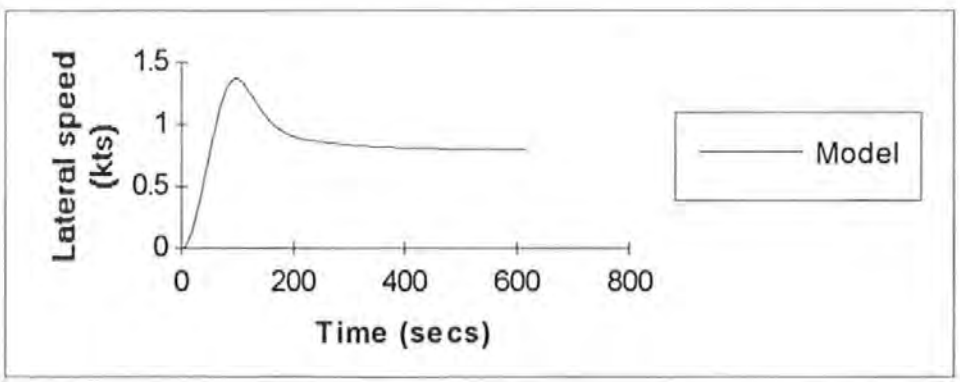


Figure 6.15d. Lateral speed.

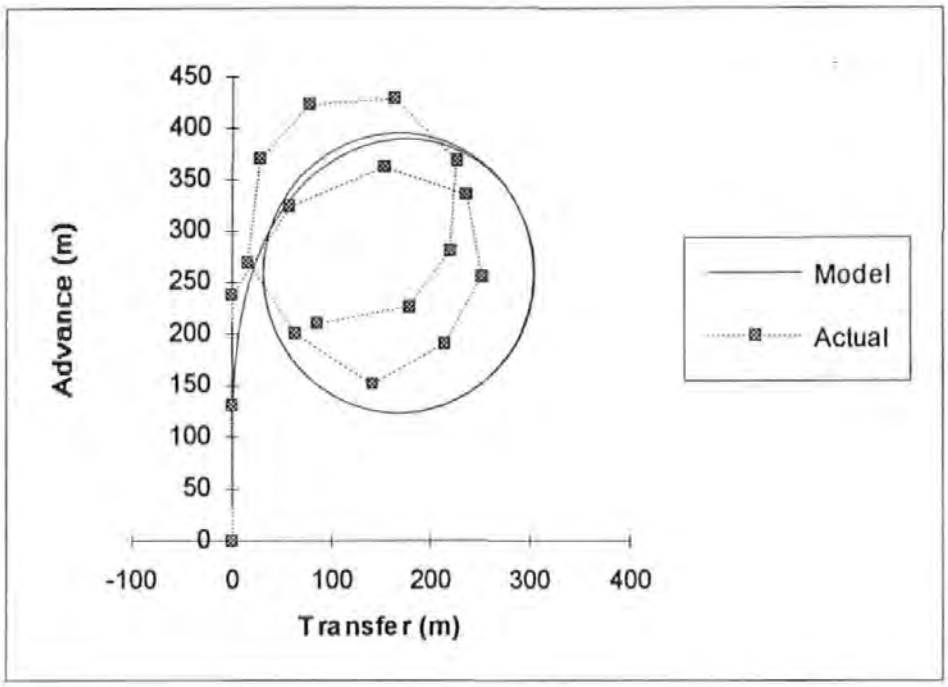


Figure 6.16a. 20° Starboard turning circle.

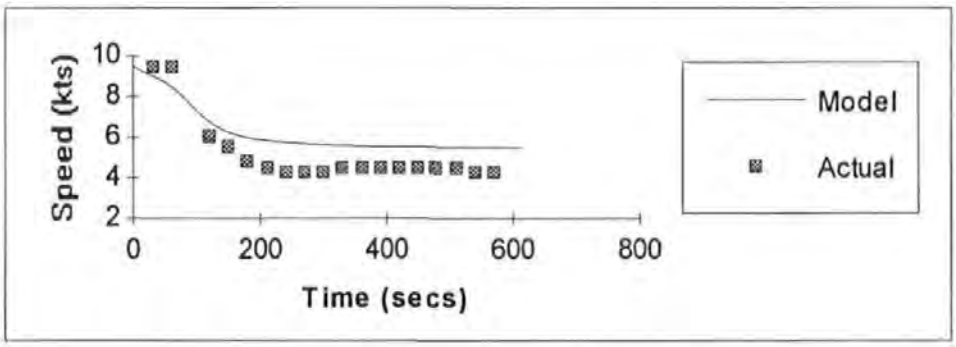


Figure 6.16b. Speed reduction.

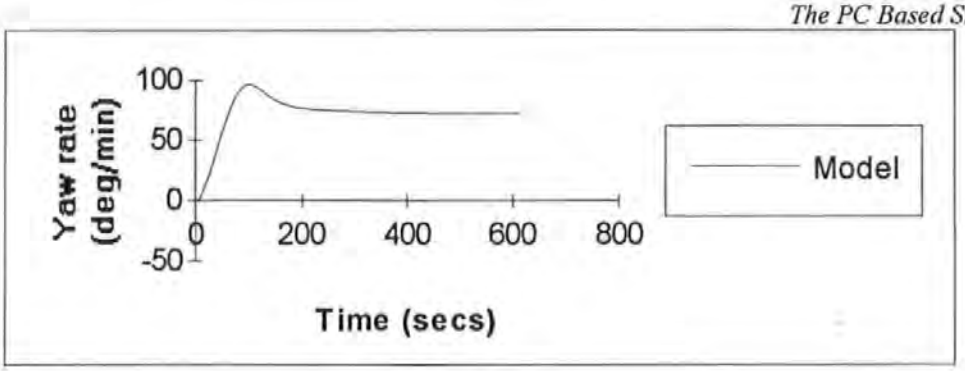


Figure 6.16c. Yaw rate.

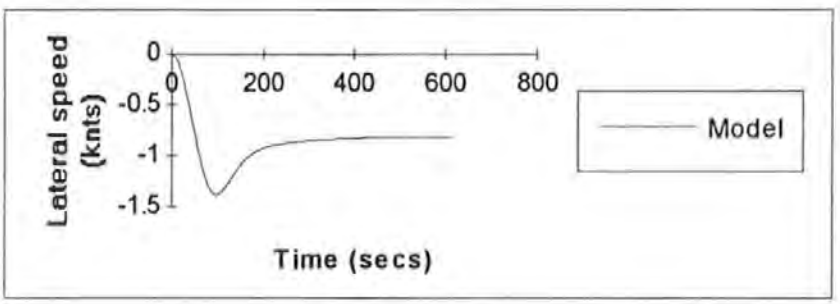


Figure 6.16d. Lateral speed.

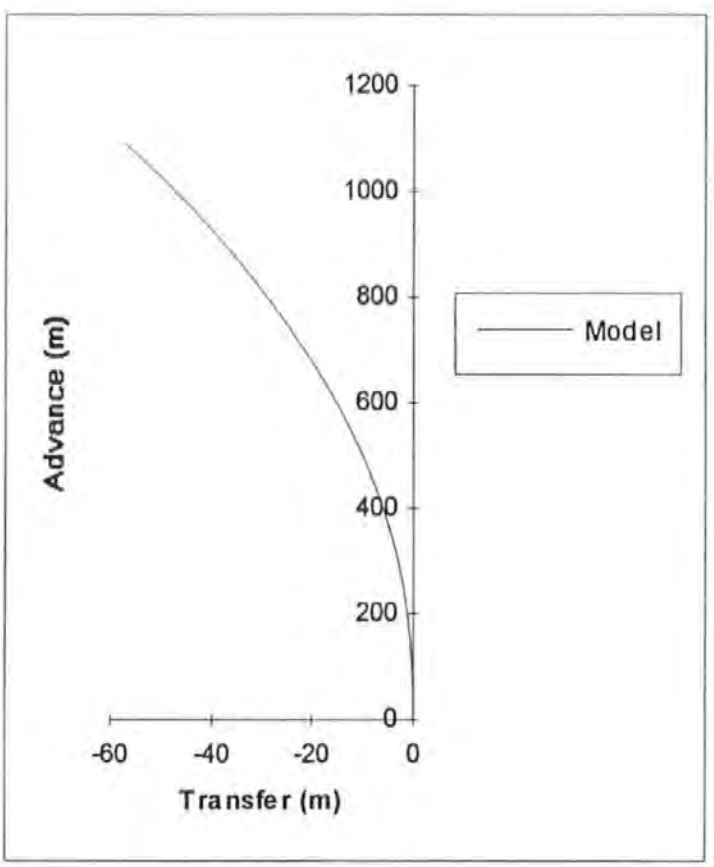


Figure 6.17. 0° Rudder angle showing "Paddle Wheel" effect.

6.3.2 Picket Boat 9 Results

Figure 6.18 to 6.19 show port and starboard turning circles for PB9. Only one either port or starboard turning circle have been shown for each rudder angle. This is due to there being no paddle wheel effect, and hence, no difference in the turning circle for each direction.

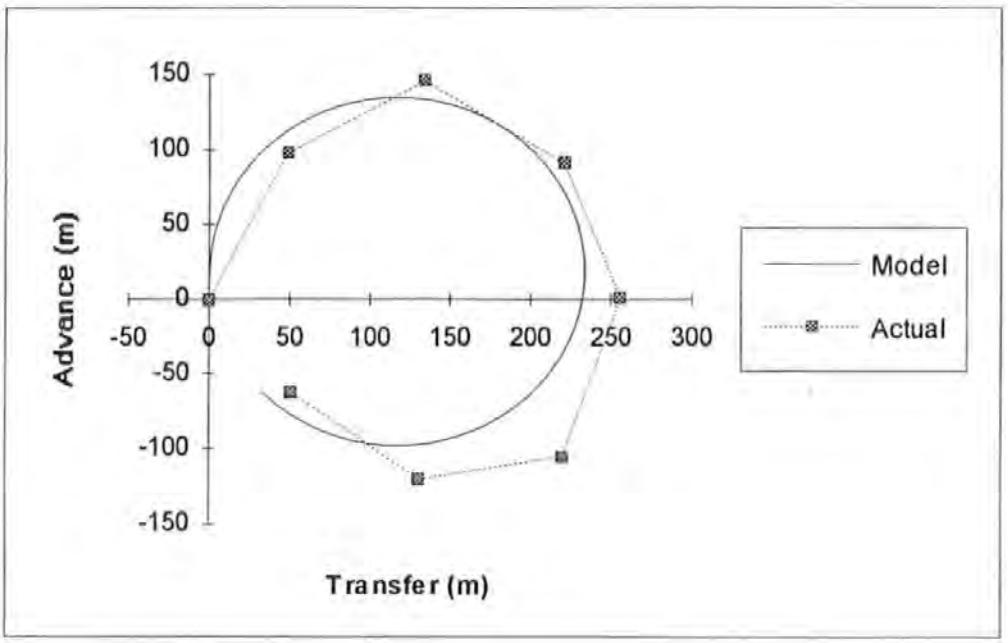


Figure 6.18a. 2.5° Starboard turning circle.

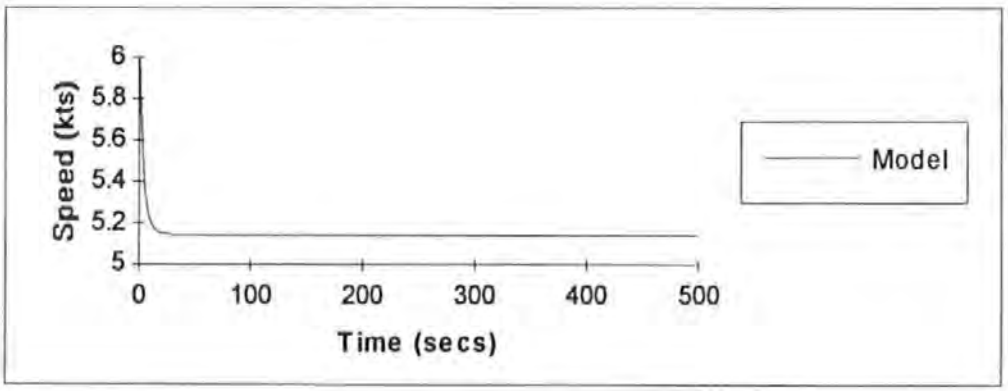


Figure 6.18b. Speed reduction.

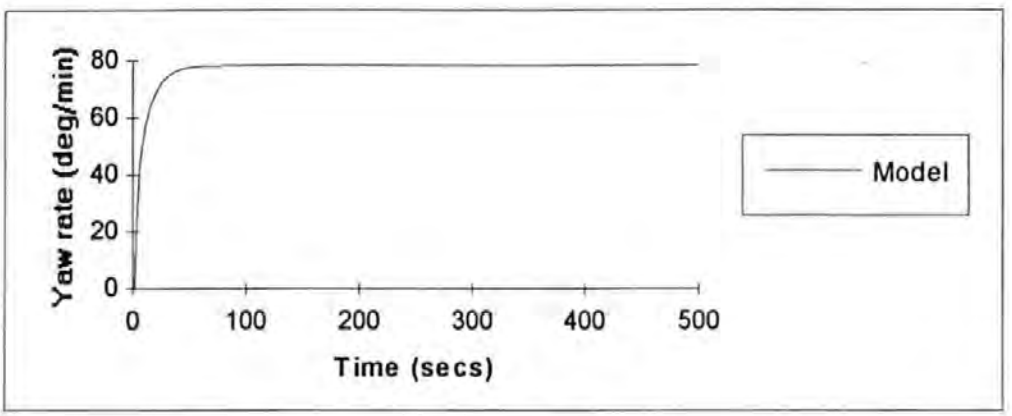


Figure 6.18c. Yaw rate.

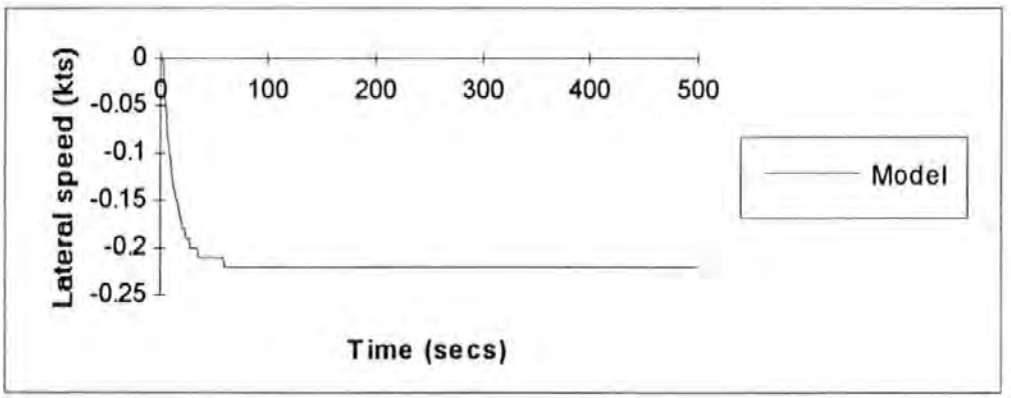


Figure 6.18d. Lateral speed.

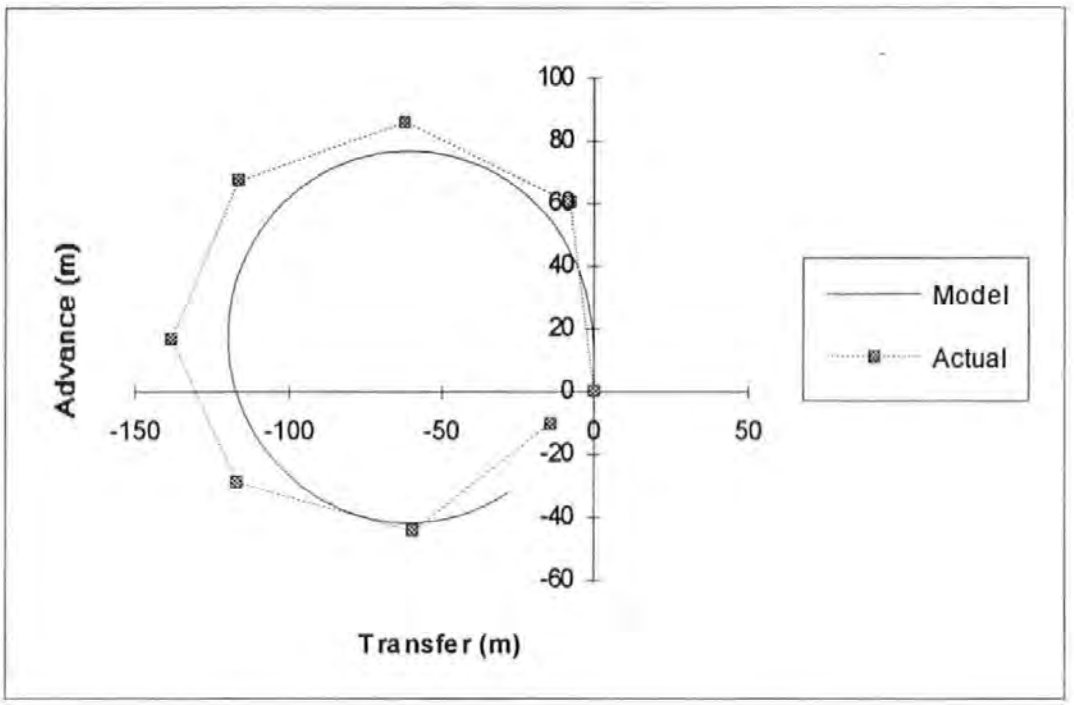


Figure 6.19a. 5° Port turning circle.

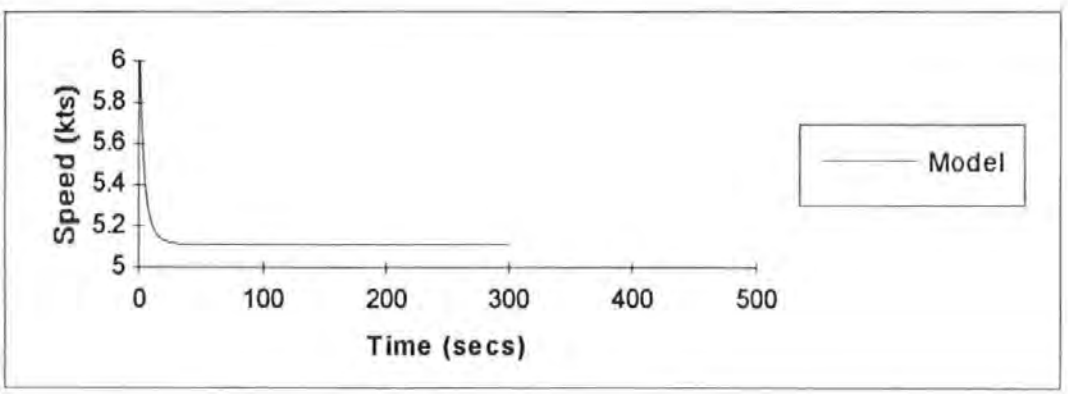


Figure 6.19b. Speed reduction.

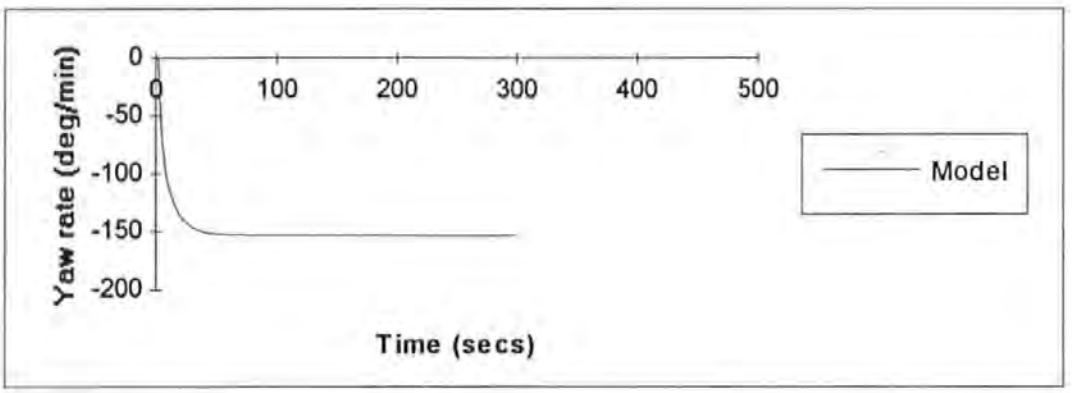


Figure 6.19c. Yaw rate.

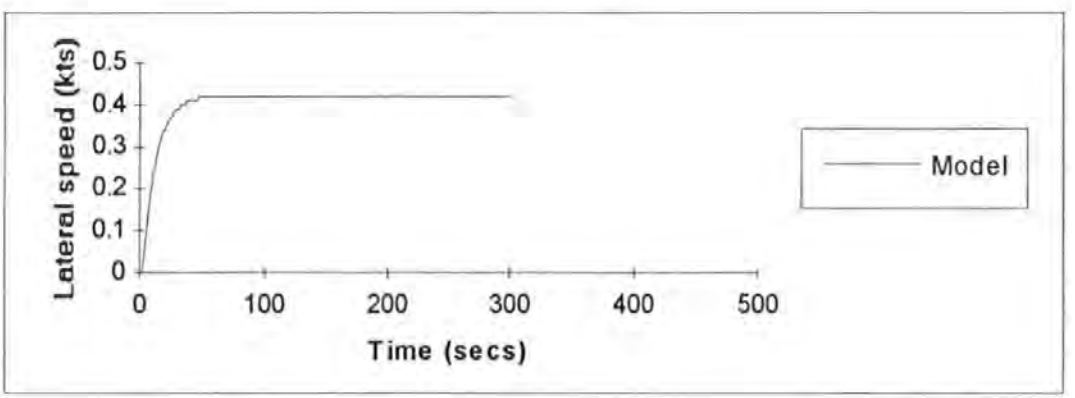


Figure 6.19d. Lateral speed.

6.3.3 Esso Osaka Results

Figure 6.20 to 6.22 show port and starboard turning circles for the 'Esso Osaka', the actual vessel path shown is for data supplied from sea trials, Crane (1979). Diagrams of speed reduction, yaw rate and lateral speed have been included to show all the vessels turning characteristics and the models accuracy. In comparing the 35° port and starboard turning circles it should be noted that the approach speeds vary by 2.3 kts. Figure 6.23 shows the simulated path for 0° rudder at an approach speed of 8 kts.

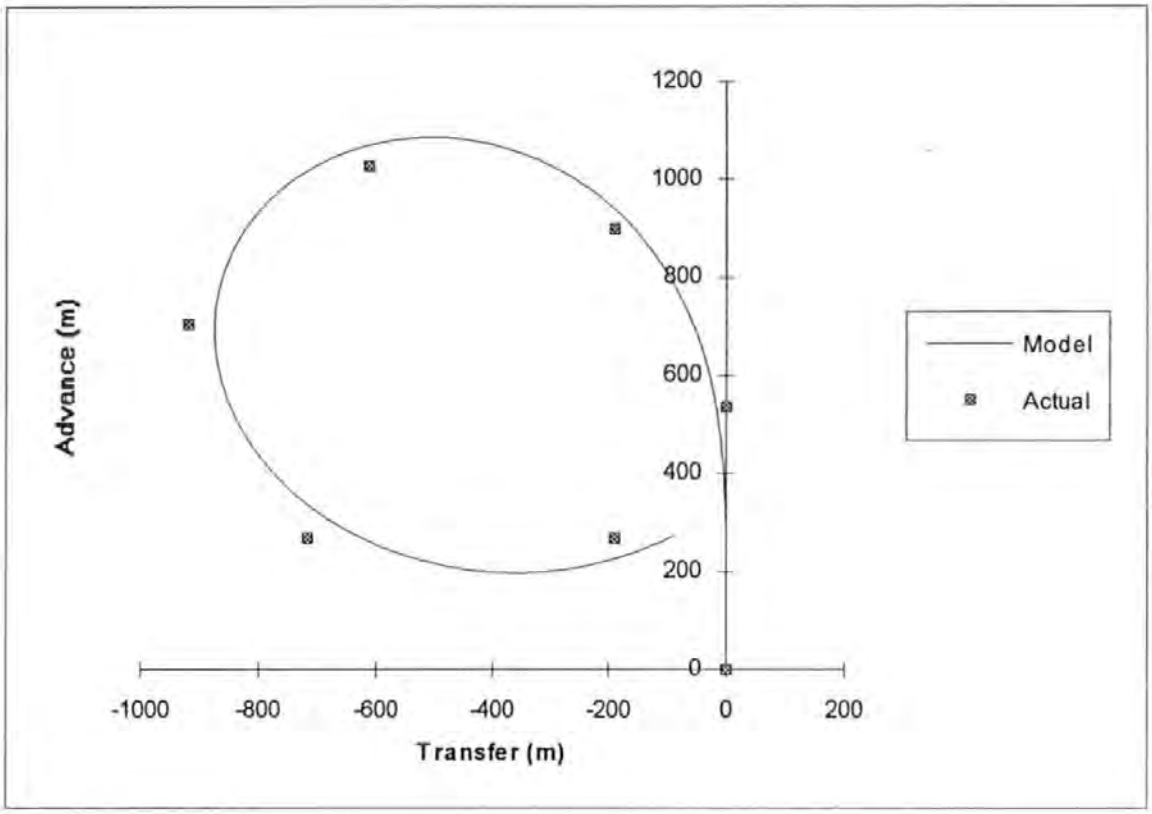


Figure 6.20a. 35° Port turning circle.

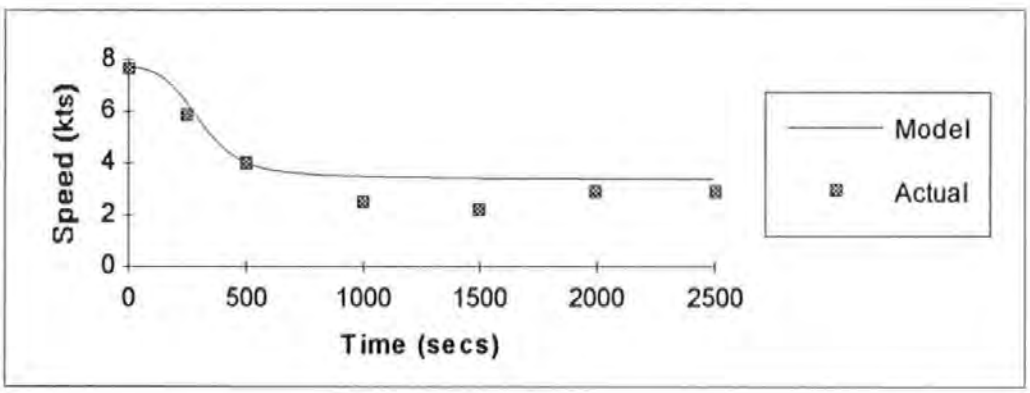


Figure 6.20b. Speed reduction.

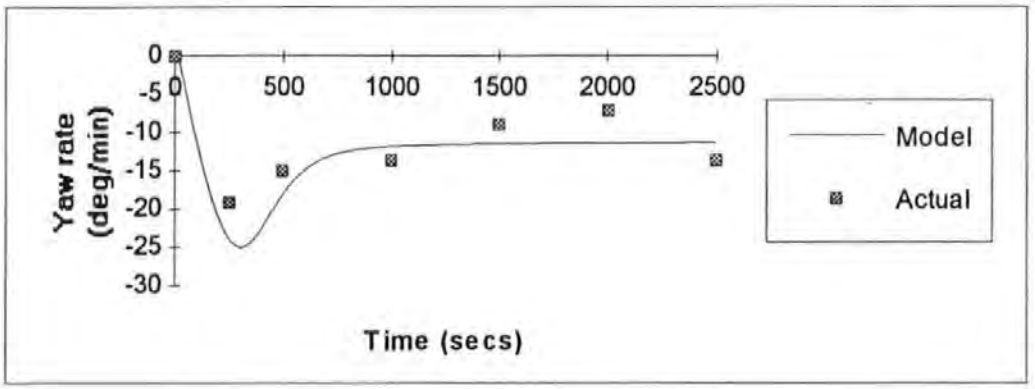


Figure 6.20c. Yaw rate.

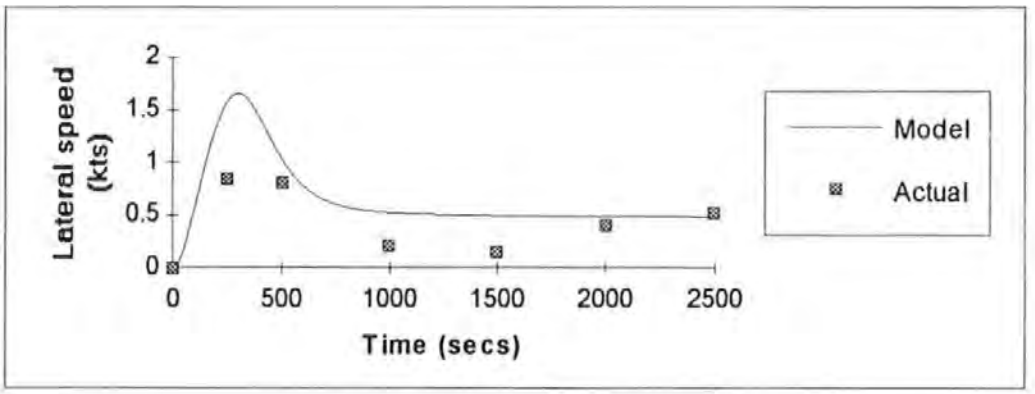


Figure 6.20d. Lateral speed.

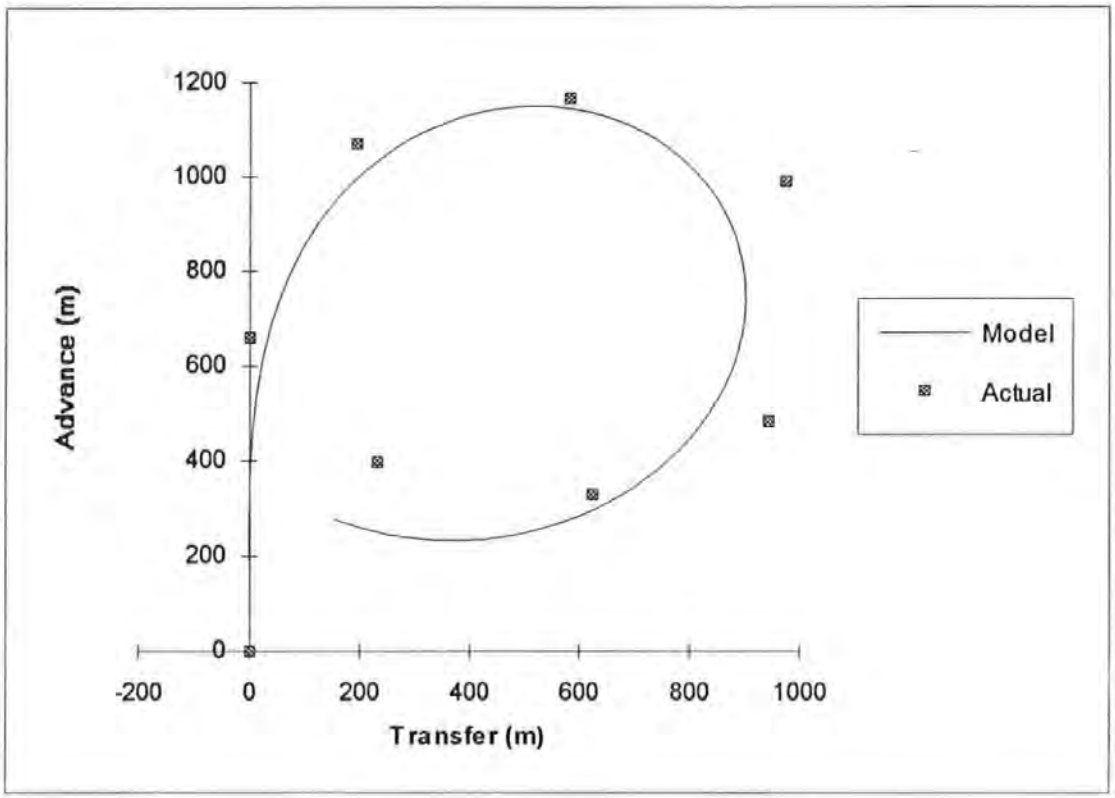


Figure 6.21a. 35° Starboard turning circle.

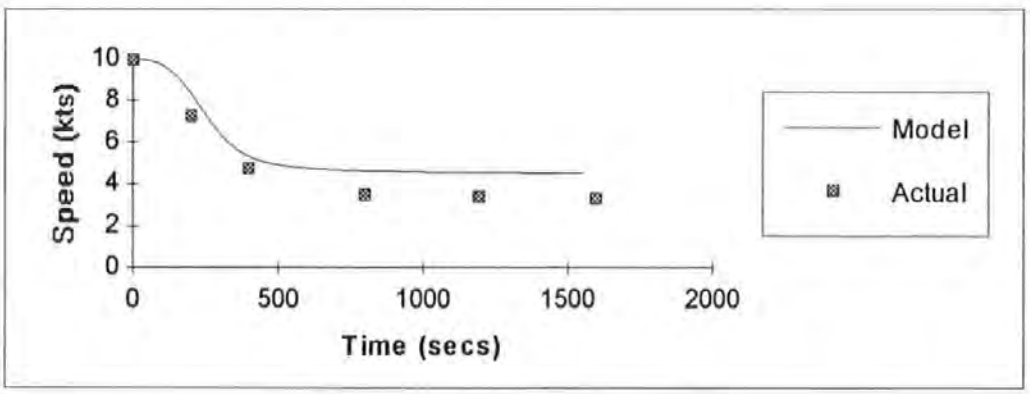
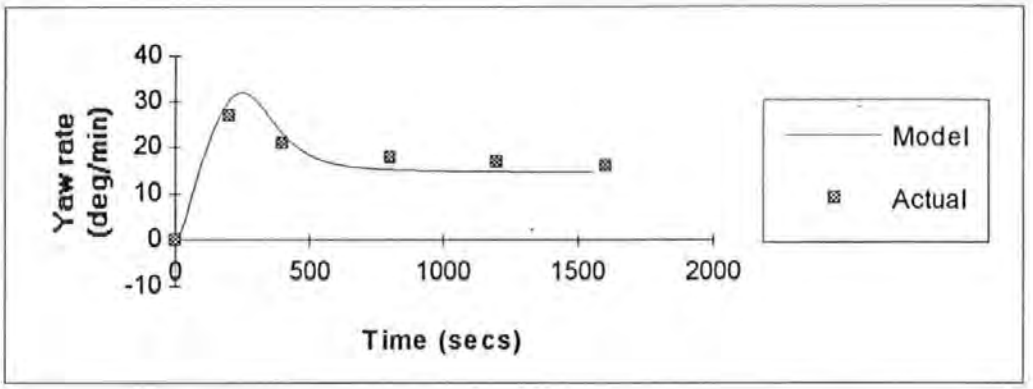
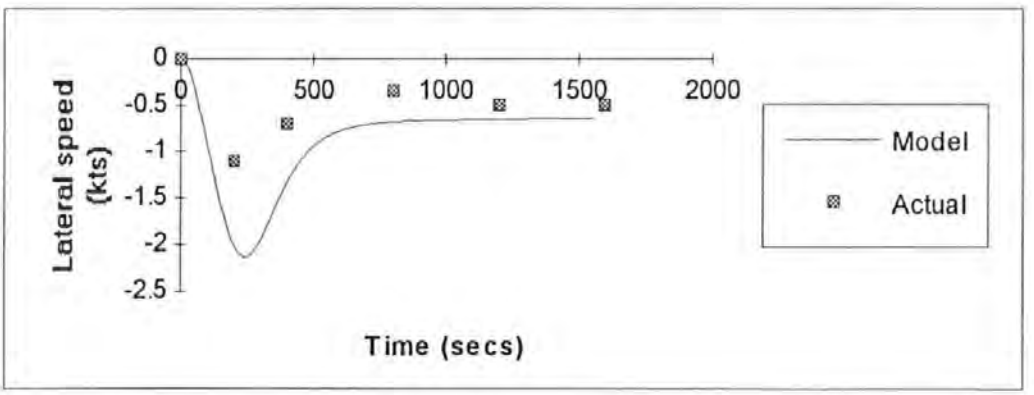


Figure 6.21b. Speed reduction.



6.21c. Yaw rate.



6.21d. Lateral speed.

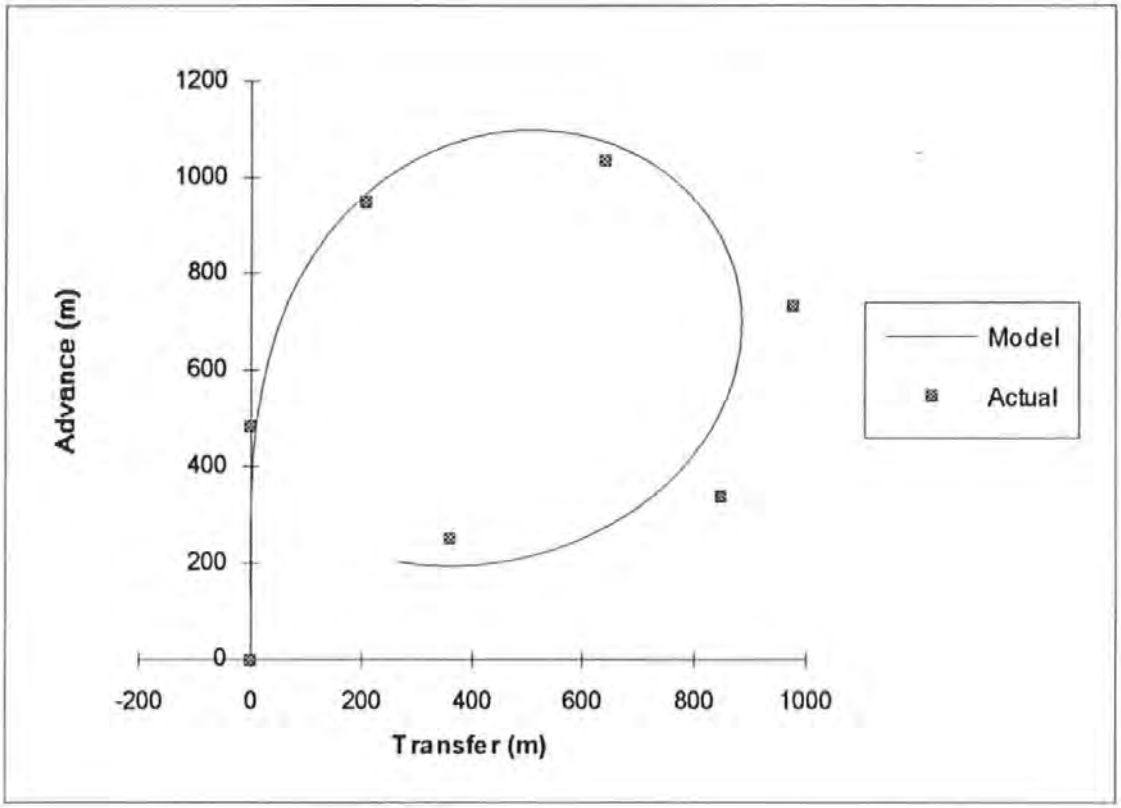


Figure 6.22a. 36° Starboard turning circle.

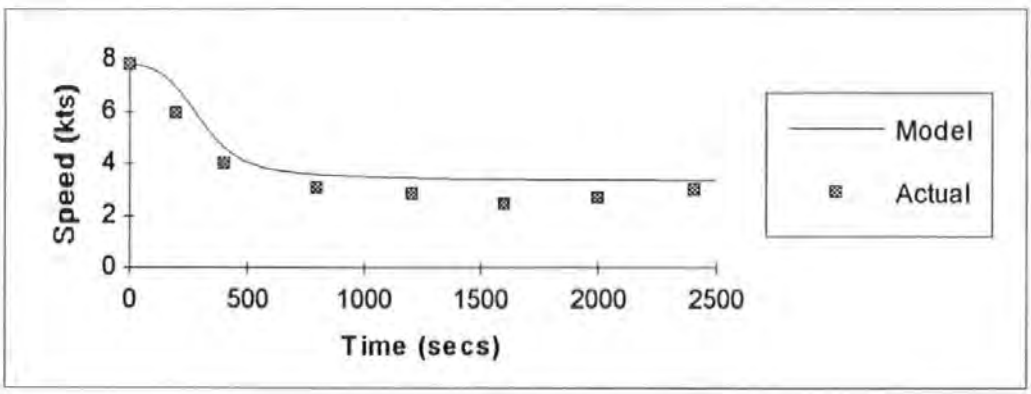


Figure 6.22b. Speed reduction.

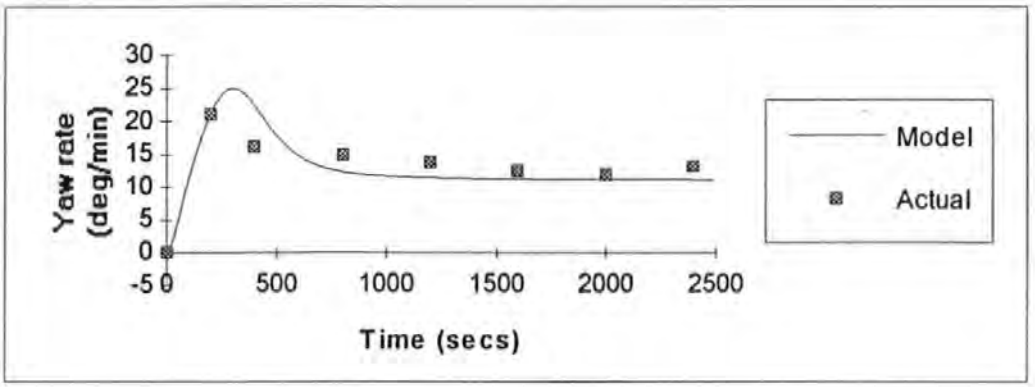


Figure 6.22c. Yaw rate.

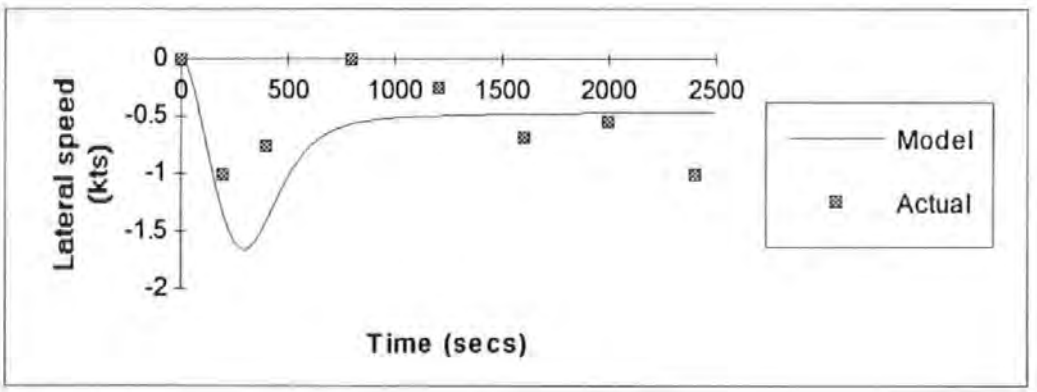


Figure 6.22d. Lateral speed.

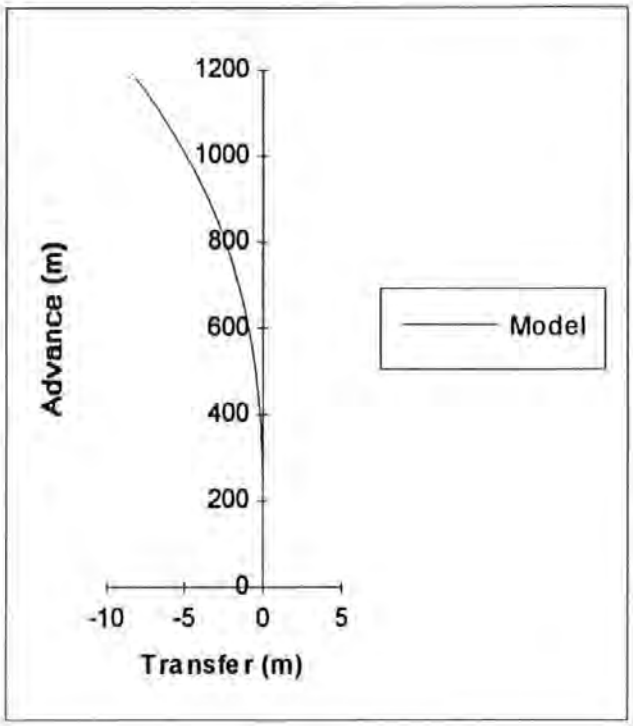


Figure 6.23. 0° Rudder angle showing 'Paddle Wheel' effect.

6.4 Discussion

Simulations have been shown for three very different vessels to validate the models adaptability as well as its accuracy. Each set of vessel simulations will now be discussed in turn.

6.4.1 Sand Skua

10° and 20° port and starboard turning circles were simulated and plotted on the same chart as the actual vessel trials data. The results compare favourably with those measured considering all the trials data had to be monitored manually and no current data was available or could be measured. Details of any error are shown in table 6.1.

Speed reduction in the turning circles are modelled with a good degree of accuracy with the exception of the 20° port turning circle, figure 6.15b, the error is in the region of 2 knots. One explanation could be that the rudder was over to port slightly more than 20° thus a greater speed reduction would be experienced. This reasoning is backed up by figure 6.15a where the simulated turning circle is slightly larger than the recorded trials data.

Rudder angle (°)	Error on transfer (m)	Error on advance (m)
10 Port	0	0
10 Starboard	50 (~11%)	0
20 Port	10 (~3%)	20 (~6%)
20 Starboard	Current error on actual data. Model error ~10%.	Current error on actual data. Model error ~12%.

Table 6.1. Sand Skua turning circle error.

The yaw rate and lateral speed diagrams would appear to be accurate although no comparison can be made with actual vessel trials. However, in comparing the diagrams with each other and those of the 'Esso Osaka' the correct trend is apparent in all the results.

6.4.2 Picket Boat 9

The 2.5° and 5° turning circles were simulated and plotted on the same chart as the actual vessel trials data. The results compare favourably with those measured considering no current data was available or could be measured; although to reduce this error trials took place at high tide. The overall error was <10%, details of which are given in table 6.2.

Rudder angle (°)	Error on transfer (m)	Error on advance (m)
2.5	15 (~6%)	30 (~11%)
5.0	15 (~12%)	<10 (~9%)

Table 6.2. PB9 turning circle error.

Speed reduction in the turning circles are modelled with a good degree of accuracy. During the sea trials the paddle wheel log was found to be in error so speed was measured with a trailing log. The speed reduction in the turn was measured as being approximately 1 knot for both turning circles. This is shown in simulation as being 0.8 knots for the 2.5° turning circle and 0.9 knots for the 5° turning circle.

The yaw rate and lateral speed diagrams would appear to be accurate although no comparison can be made with actual vessel trials. However, in comparing the diagrams with each other, and those of the other two vessels, the correct trend is apparent in all the results.

6.4.3 Esso Osaka

35° port and starboard and 36° starboard turning circles were simulated and plotted on the same chart as the published trials data. The overall error was <7%, details of which are given in table 6.3.

Rudder angle (°)	Error on transfer (m)	Error on advance (m)
35 Port	44 (~5%)	61 (~5%)
35 Starboard	66 (~7%)	96 (~8%)
36 Starboard	91 (~10%)	49 (5%)

Table 6.3. Esso Osaka turning circle error.

Speed reduction, yaw rate and lateral speed are all modelled to a good degree of accuracy and no discussion is necessary.

6.4.4 Conclusion

An adaptable modular model has been produced and shown to simulate manoeuvres using three very diverse vessel types of different size. A good degree of accuracy has been achieved for simulated versus actual data with a mean positional error of <7%. As a consequence, it is considered that any traditional mono hull vessels manoeuvring characteristics can now be simulated adequately, without any expensive tank tests or trials data being necessary to calculate the required hydrodynamic coefficients or other model data.

The adaptable modular model has also been verified against the modular model presented in chapter 4. Figure 6.24a-d shows the two models plotted against each other. The adaptable model could be argued to be not quite as accurate as the original modular model, however, the error is not that great and the adaptability is of considerable more importance.

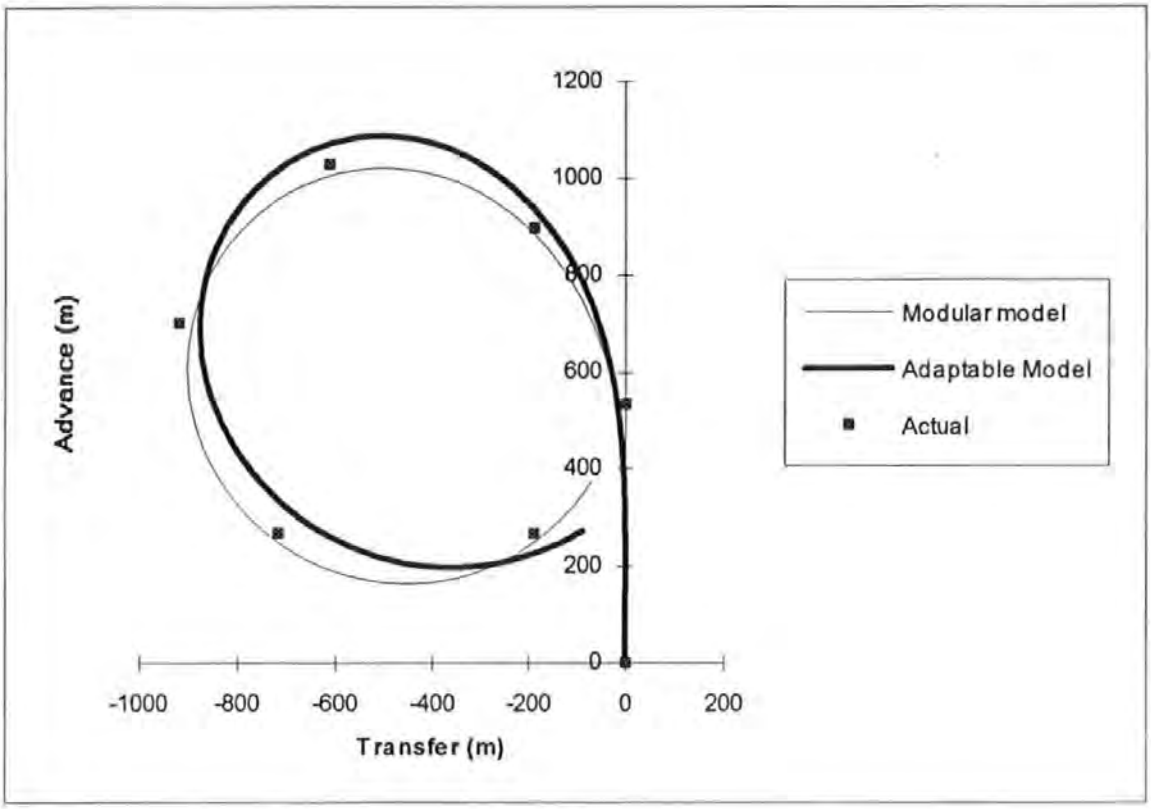


Figure 6.24a. 35° Port turning circle.

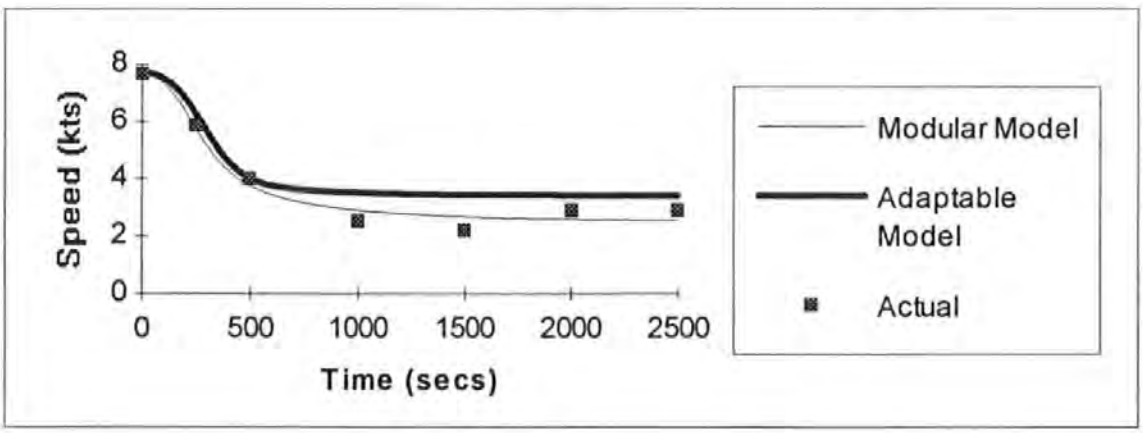


Figure 6.24b. Speed reduction.

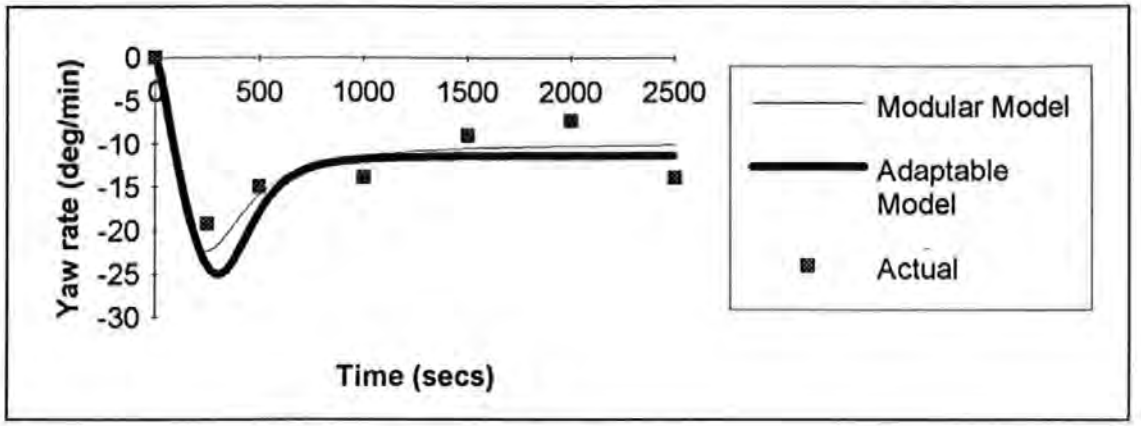


Figure 6.24c. Yaw rate.

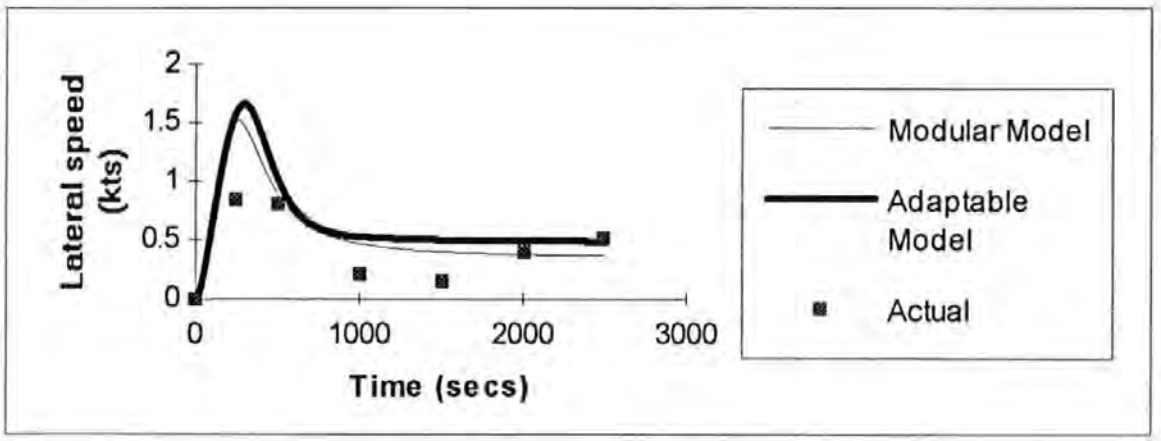


Figure 6.24d. Lateral speed.

With the adaptability required now achieved, chapter 7 will show the inclusion of the model into an automatic collision avoidance system.

CHAPTER 7

AUTOMATIC COLLISION AVOIDANCE SYSTEM (ACAS)

7.1 Introduction

The ultimate aim of the research being undertaken by various members of the MDRG is to investigate, design and develop an integrated navigation and collision avoidance system of which the model forms an integral part. The intelligent collision avoidance system is to be linked in with the options of either advisory or auto-control modes, using the ship model within the expert system to predict the consequences of alternative courses of action. The ACAS, fitted with a very simplistic model, has already been verified under sea trials and usage by sea-going personnel, Blackwell (1992).

One specific area in which automated expert support could yield significant benefit, as evidenced by numerous recent shipping disasters, is the recognition and avoidance of potential collisions or grounding. Given the relevant background information, and suitable input channels for continuously updating dynamically changing factors in the vessel's environment, an Intelligent Knowledge-Based System (IKBS) would maintain a continuous 'watching brief' on ships and other potential hazards in the vicinity. On detecting the need for alterations of course and/or speed to eliminate the danger of hazardous potential collision situations, a suitably tailored inference process would make recommendations of appropriate actions to ensure safety. This implies the development of an accurate model for the behaviour of the vessel undertaking such manoeuvres, and for the perception of a hazard at a sufficiently future time in order for the manoeuvre to be carried out. The hazard vessel should also be modelled as well as present technology allows.

7.2 An Intelligent Computer System for Collision Avoidance

Certain prerequisites for the proposed expert system are immediately evident:

1. it must be capable of receiving and processing all of the electronically sensed data which is normally displayed on the bridge instruments, plus any additional information which may be input by the user;

2. it must be cognisant, as is the ship's master, of performance characteristics of the vessel, plus any other relevant parameters - length, draught, etc.;

3. it must be conversant with the International Regulations for Preventing Collisions at Sea, IMO (1981), and the ramifications of those regulations in a multiplicity of situations;

4. it must be capable of arriving at a reasoned response to current circumstances, and presenting that response clearly, together with a succinct and unconfusing explanation of its reasoning if required;

5. it must be able to re-evaluate changing circumstances, and give its conclusions within a matter of seconds.

An initial framework for the rule base already exists, in the aforementioned anti-collision regulations. By themselves, however, these regulations are inadequate for such a task, since they leave the onus for certain major decisions with the mariner. Such phrases as 'in good time', 'a clear turn', and 'a safe distance' are open to a wide variety of individual interpretations, which may themselves vary with different contexts; sea state, nature of vessel and cargo, possible manoeuvring restrictions (such as coastal features or shipping lanes), traffic density, all affect decisions on collision avoidance manoeuvres. As with any competent human *personal assistant*, therefore, the electronic advisor would have to be conversant with that broader spectrum of 'rules' (i.e. situational responses) which derive from applied common sense and years of experience; such experience, gleaned from human experts, must be formalised into an inference structure which gives substance to the bare bones of the official regulations. Continuing the analogy, the system should be unobtrusive, providing information only as requested, in a meaningful way, but with the capability for drawing attention to matters in need of immediate action.

A graphical representation of the current scenario is clearly a prerequisite; a well planned display, invoking good use of colour and scale, would allow the immediate situation to be taken in by a cursory glance, without excessive detail. Such detail could be offered as 'optional extras', for example:

1. a status report, giving current speed and bearing , details of any current manoeuvre, plus any pertinent data on nearby ships or other hazards (notably, projected time to collision or near miss, if applicable);

2. an appraisal of the current situation, indicating advised course of action, with supporting rationale for such advice available on demand; in a real-time expert system,

that rationale would necessarily include reference to prior, and likely future, events - a dimension absent from most IKBS.

A desktop computer offering processing power hitherto associated with mainframes, providing a true multi-tasking environment, front ended by a sophisticated WIMPS (Window-Icons-Mouse-Pointer System) user interface and multi-colour graphics display, forms a readily-accessible environment for this type of application. Such options could be provided at the press of a button in a menu-driven WIMPS environment, with no requirement for keyboard dexterity or other new skills. Information would be to hand exactly as and when needed, without confusion or complication, particularly bearing in mind that this facility is likely to be most needed at times of greatest stress.

7.3 Previous Work

A customised expert system shell has been developed on an Acorn Archimedes RISC (Reduced Instruction Set Computer) system, Blackwell (1992), chosen on the basis of processing power at relatively low cost, good WIMPS and graphics facilities, and capability for a variety of input/output options. The RISC-OS multitasking environment, coupled to versatile I/O handling, are well suited to the planned integrated system.

The screen display is in the form of three windows, as shown in plates 7.1 and 7.2. A square graphics window, filling approximately half of the screen area, displays the tracks and positions of one's own vessel (own-ship) and any other vessels in the vicinity, with markers to show positions at corresponding times; own-ship is shown as a green track, others in various colours. At the current stage of development, only one other vessel (the most threatening) will be 'processed' by the rule structure as a potential hazard. The display in the graphics window may be enlarged by reference to a pop-up menu (invoked and actioned by mouse buttons), and any part of the scene studied in detail by scrolling the window horizontally or vertically. A second window optionally displays a review of the progress of the situation to date, including the decisions made by the expert system at various stages; this window may also be scrolled, or expanded over the graphics window temporarily, to display further detail of the stages of an encounter. A third window may be selected and de-selected as required, again by a mouse-operated pop-up menu. This window, appearing below the other two, displays data on the course, speed and current manoeuvring (if any) of own-ship, plus such data as is available (via radar) on any other vessel in the vicinity considered to be a hazard.

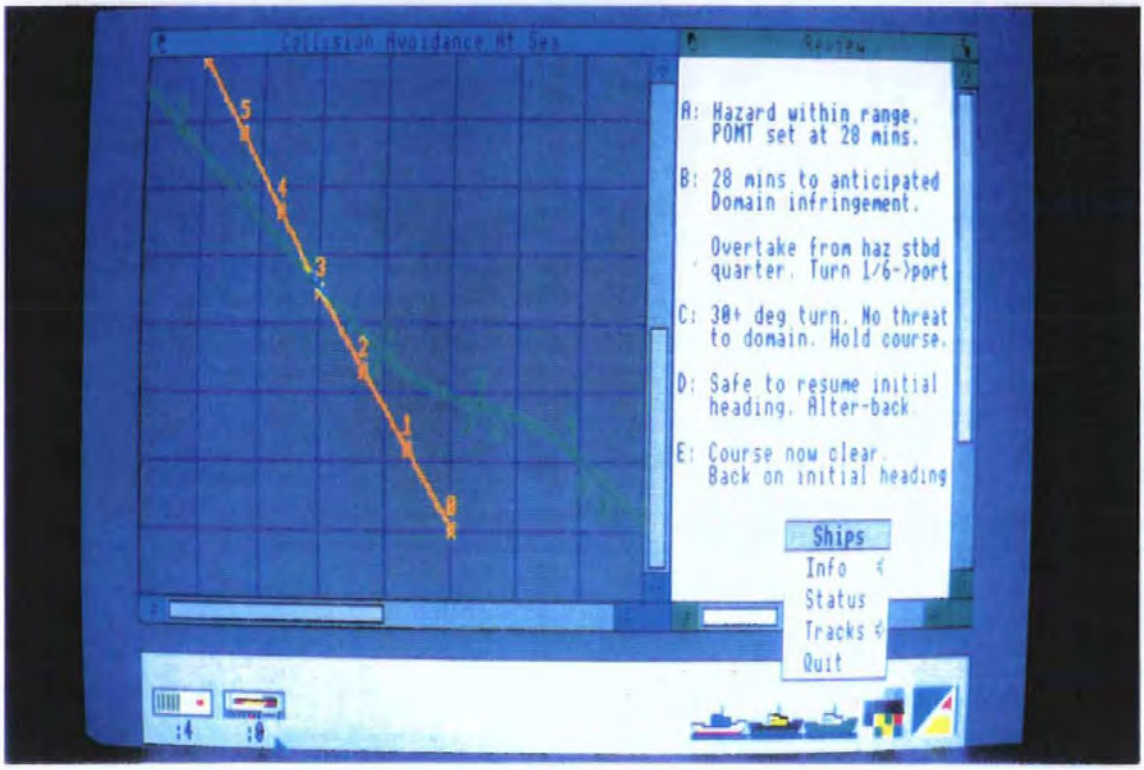


Plate 7.1. Expert system icon pop-up menu.

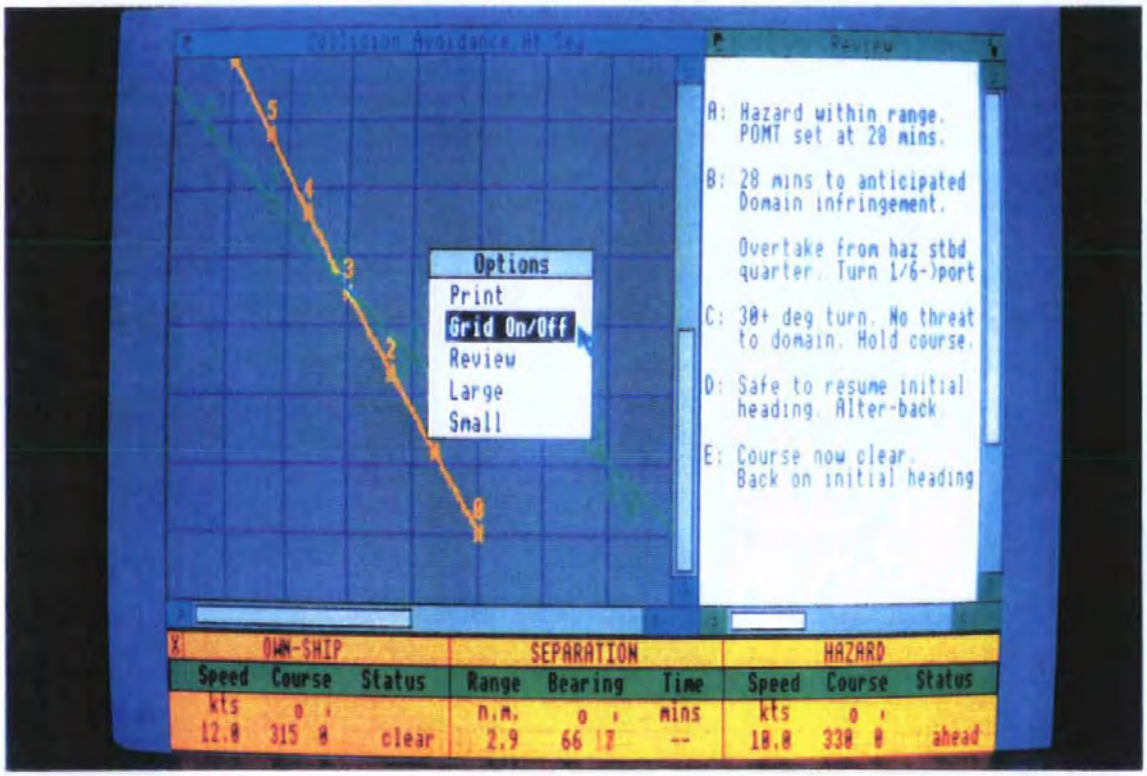


Plate 7.2. 'Tracks' window pop-up menu.

The current implementation is designed to operate in any of three modes, two being simulator trials, the third real data.

1. Hazard vessel and own-ship both simulated as additional tasks under the multitasking RISC-OS, on the same computer as the expert system; software communication channels between the tasks simulate radar data to and from hazard vessel, and sensor/control information between own-ship and expert system.

2. Hazard and own-ship are simulated in separate computers from the expert system computer; communications are via serial and parallel links respectively.

3. Inputs via serial and parallel ports are from genuine radar and sensors aboard own-ship.

The system, for present simulation exercises, runs under the multi-tasking RISC-OS on the same computer. Plate 7.3 shows the warning given if the operator tries to operate the expert system more than once. The three ships on the icon bar represent the expert system and ship simulator tasks:

- black ship - hazard ship simulator icon;
- green ship - expert system icon;
- white/red ship - own ship simulator icon.

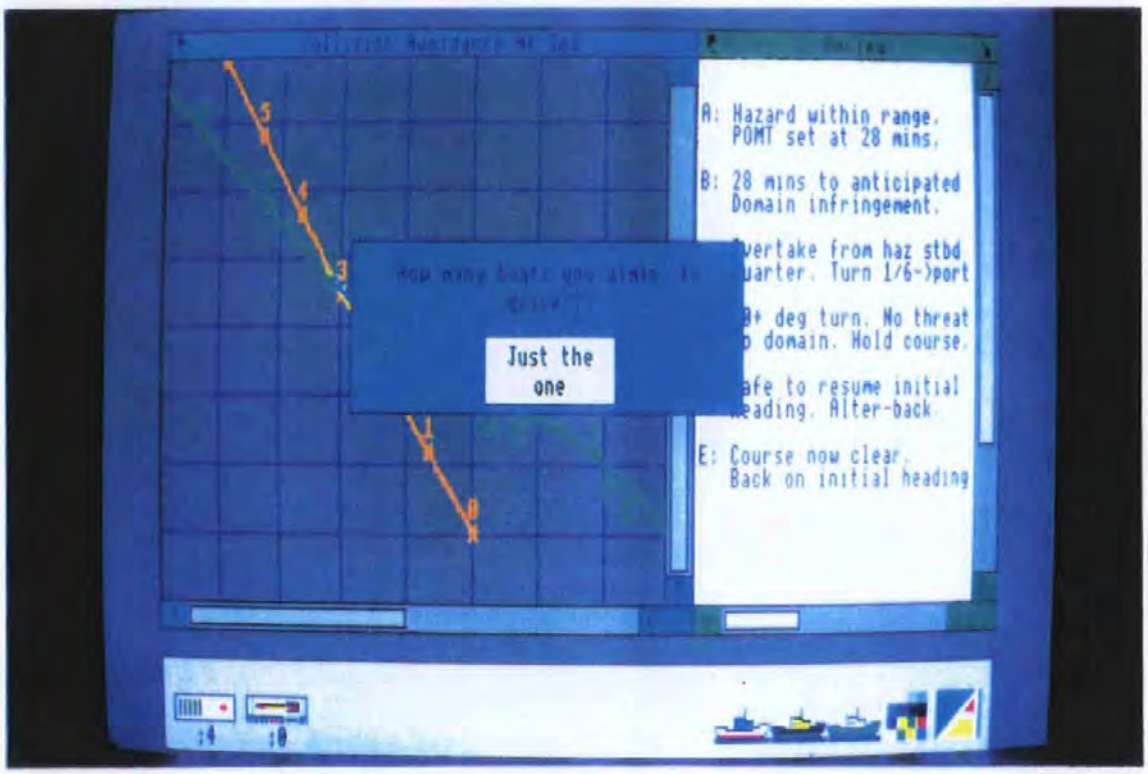


Plate 7.3. Response to repeated activation of expert system.

7.3.1 Criteria for Decision Making

The ultimate objective of any collision avoidance procedure is to avoid collisions; a secondary objective is to inform other mariners, through positive action, that the possibility of such an incident has been recognised and is being dealt with. Both of these aims are served by manoeuvres which seek to maintain a zone of clear water around one's vessel, generally referred to as the domain. This observed practice of experienced mariners, Goodwin (1975), has been taken as a prime objective of the expert system. A consequent concern is the distance at which another vessel or object should be considered as a potential hazard, evaluated as such, and appropriate avoidance action initiated if necessary, Davis et al (1980). Such proximity considerations were refined by Colley (1985) to a time-based criterion, the RDRR (Range-to-Domain/Range-Rate); a ship's master applying a 12 minute RDRR, for example (based on handling characteristics for his vessel), would evaluate a potential encounter 12 minutes before anticipated domain infringement, and implement appropriate action at that time.

Results from an early version of the system, Colley et al (1984), using the RDRR concept, indicate that such a fixed 'decision scheduler' is not appropriate to every encounter situation. A flexible time-constraint, matching decision time to interval needed for a safe manoeuvre, ensures optimum manoeuvring time: adequate, but not excessive. This Predetermined Optimal Manoeuvring Time (POMT) is found by simulating any projected encounter well in advance, for increasing RDRR values (starting from some pre-set minimum, say 10 minutes), until safe clearance is achieved. The simulation exercise is an integral element of the decision logic, and corresponds to a human appraisal of whether or not a situation requires particularly early remedial action. Figure 7.1 shows the principle of the look-ahead simulation used within the expert system to select an appropriate RDRR, i.e. the POMT, for any encounter. A fixed minimum RDRR is used in preference to a free-floating JIT (Just In Time) strategy, in recognition of the need to take action in good time, so as not to panic masters of other ships into emergency action.

The rule structure is designed to:

a) note the presence of a potential hazard, assess the threat in terms of expected time to domain violation (if applicable) and derive the POMT for avoidance action;

b) at POMT, identify the type of encounter; fix the status of own-ship and perceived status of hazard ship (give-way or stand-on) at this time in the encounter. Once decided, status is maintained throughout the encounter, unless circumstances change - the regulations rule out changes in status due solely to changes in relative positions through avoidance manoeuvres;

c) negotiate the stages of the encounter, with appropriate safety margins.

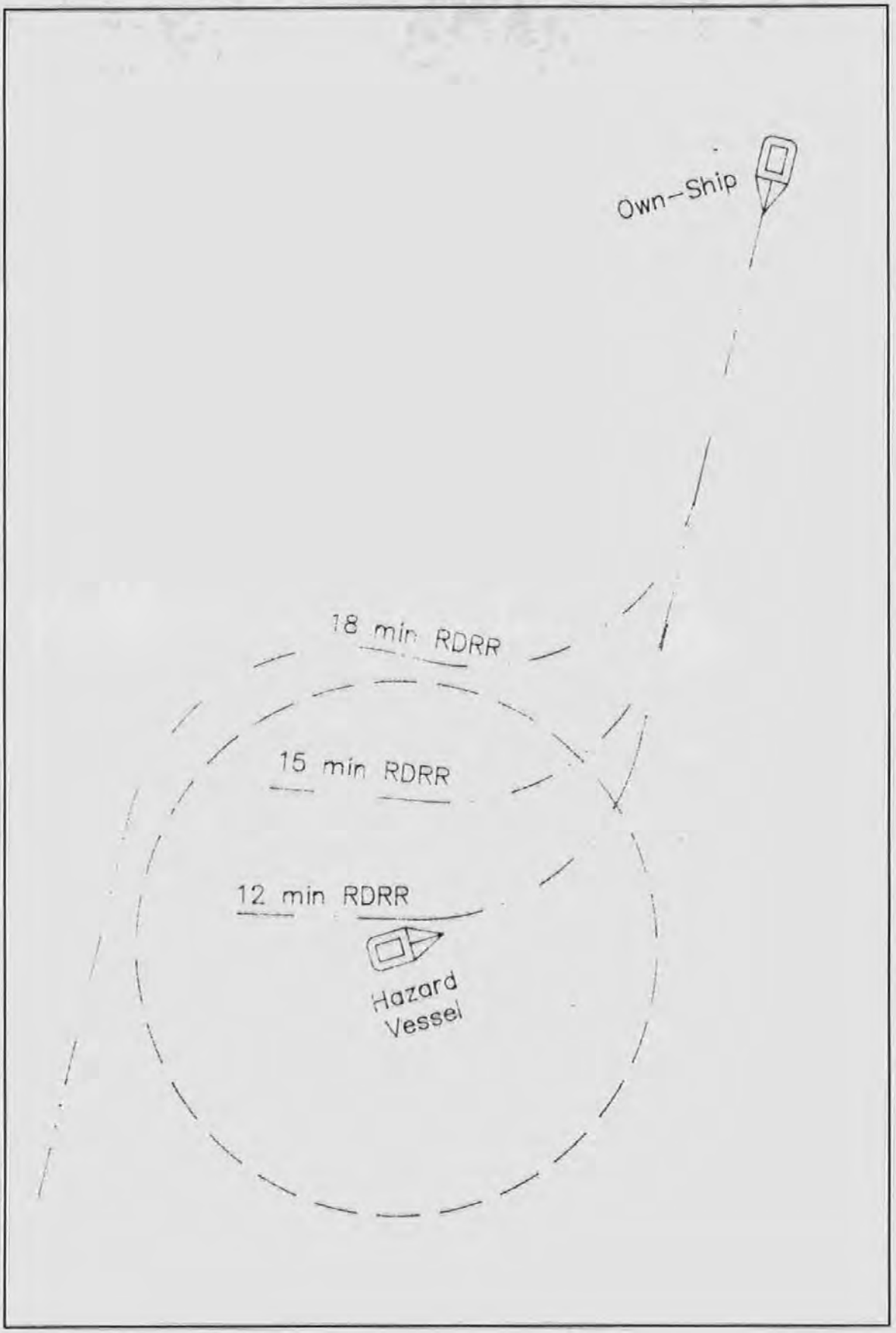


Figure 7.1. Multiple look ahead simulation, after Blackwell (1992).

It is anticipated that (c) will be extended to incorporate the possible need for a change in strategy in response to untoward action by other vessels, including emergency manoeuvres. Such additional rules may be edited into the existing rule base.

The rules embody the International Regulations for Preventing Collisions at Sea, plus clarification of specific practical detail as noted by Colley (1985) and used most effectively in an earlier simulation.

7.3.2 Inference Engine and Rule Structure

The inference engine operates on a discrete time interval of 20 seconds. At each step the inference engine will:

a) take dynamic information via communication channels from radar and own-ship sensors (or simulators); from these parameters (speed, course and position) it will generate secondary data, i.e. relative bearing and relative velocity components, for use in rule evaluation;

b) apply the appropriate rule to these data, to ascertain the new situation;

c) trigger display and control/simulator outputs in response to any change in status; invoke any new rules indicated by such a change, until a 'defer' flag is reached, inhibiting any further action on the rule base until the next time step.

The rule base is a hierarchical structure, based on a binary tree, but with considerably more flexibility in links to left and right 'sub-trees'. In this rule structure, links may lead to any other node, up or down; two or more links may lead to a common node; a link may loop back to a node at a higher level. Figure 7.2 shows a schematic of this structure, illustrating part of the initial rule base.

The rule base is also in effect a state table, each node representing a possible state of own-ship: no encounter currently in progress, second stage of a 'parallel-up' overtaking encounter, etc. Each node contains:

1. left and right links to other nodes (or looping back to the same node) in the rule structure; one of these links will be followed at every decision step (i.e. every time step);

2. a mathematically-based decision function, used to determine which link is followed at each stage;

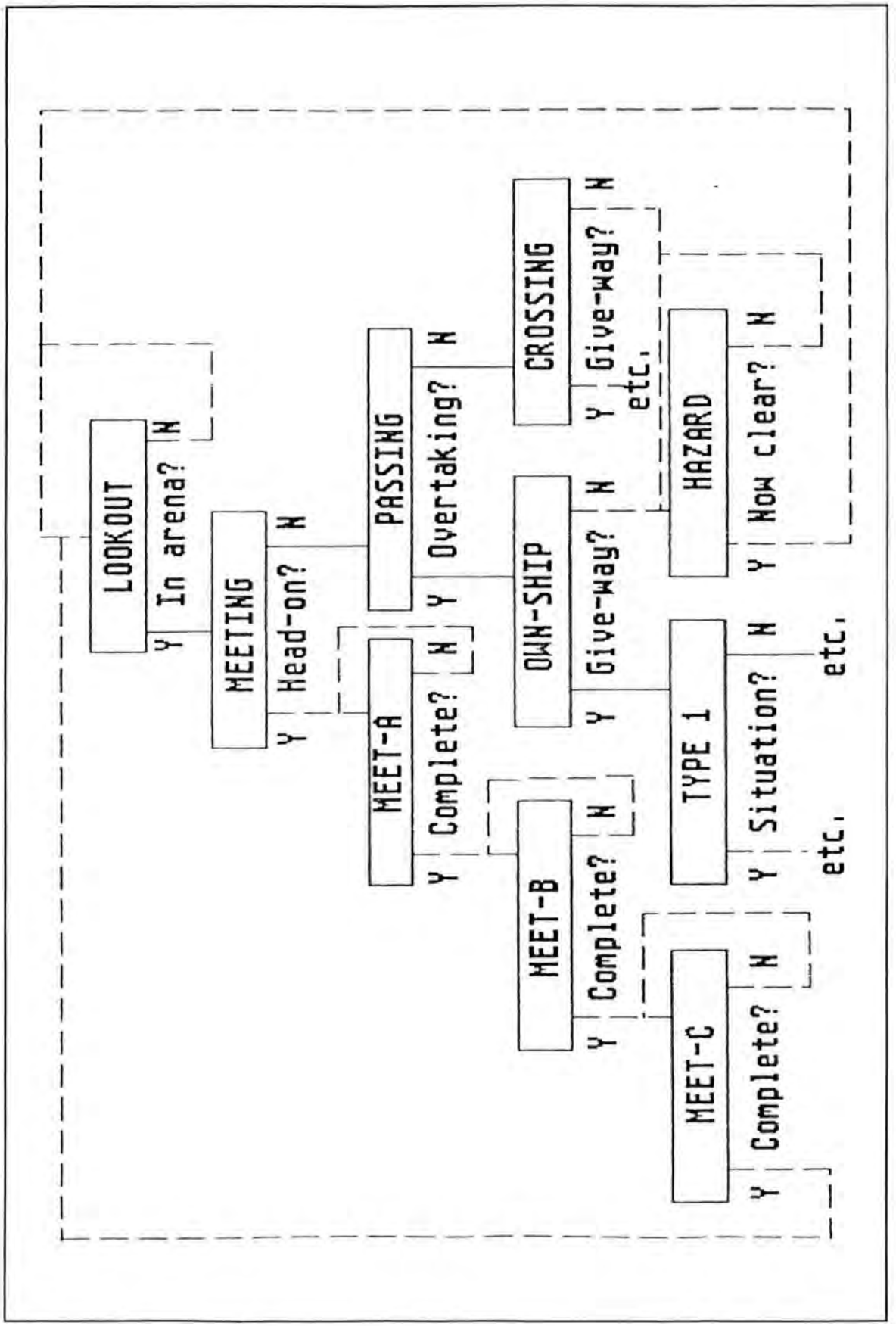


Figure 7.2. Collision avoidance decision network, after Blackwell (1992).

3. an 'immediate/defer' flag for each link, indicating action time for the next rule;

4. ship status flags, to pass display and control information.

Each rule incorporates a Boolean function, using inequality tests on combinations of displacement and velocity vectors. The bulk of processing is thus centred on evaluation of trigonometric functions. This factor becomes increasingly dominant as situations increase in complexity - a major consideration in choice of language and form of rule structure for a time-critical system.

Extension of the rule base is achieved by creating the relevant new nodes and resetting the necessary links to insert them at the appropriate points in the structure. It is envisaged that a software utility will ultimately simplify this task for the non-computer specialist.

7.4 Ship Modelling in Collision Avoidance

The nature and complexity of ship models incorporated in collision avoidance systems depends primarily on whether one is concerned with shore-based Vessel Traffic Control (VTC) or bridge-based advisory systems.

A shore-based advisory/control system requires a working knowledge of the performance characteristics of all vessels under surveillance at any time, since the ability to give helpful directives presupposes a capability to accurately predict the likely outcome of manoeuvres by one or more vessels. In general, those vessels will each fall into one of three categories:

1. known vessel, for which hydrodynamic coefficients are documented in detail, and for which an accurate model may be defined;

2. known or unknown vessel, for which hydrodynamic coefficients are not available but which may be fitted into one of a number of 'classes' of ship, and thus matched approximately to a less tightly defined model;

3. unknown vessel for which little or no performance data is available (apart from immediate observation), and which must therefore be judged on a very broad basis, with a wide margin for error allowed around any assumptions which have to be made.

Such considerations lead naturally to the need for:

1. a file of 'modelling' data for all vessels for which data is available, and which frequent the waters under surveillance;

2. a library of 'standard' vessel types, to which the majority of ships may be fitted with reasonable accuracy;

3. a rule base which, in so far as is possible, avoids the need for suppositions about any ship not susceptible to handling by (1) or (2) - this may well mean preferential treatment for such vessels, on the basis of 'when in doubt, keep clear'.

Shore-based VTC, with its requirement for detailed modelling of a number of ships simultaneously, demands substantial computing power to operate effectively in real-time. In most other respects the problems of shore-based collision avoidance, and the function of ship models therein, mirror those of bridge-based systems as considered further in the paper. Further references to this topic are to be found in Colajanni (1990), Degre (1987), and Bootsma and Poldermann (1987)

The requirement for ship models in the shipboard Collision Avoidance System (CAS) is twofold: firstly, the expert system logic must be able to model ship behaviour in order to predict likely outcomes of manoeuvres; secondly, the development of a simulated environment in which own-ship and the various hazard vessels are represented by appropriate computer models.

7.4.1 Modelling of Hazard Vessel

In a simulation environment all of the vessels may be represented as accurately as current modelling techniques permit. There is no problem of 'unknown identity', since vessels for the simulation exercise may be chosen from those for which full sets of hydrodynamic coefficients are available. The only hindrance is the collection of a suitably representative cross-section of single ship data, as outlined in chapter 4. However, in the absence of specific data, parameters for a 'typical' ship of a specific type are adequate for such a task - as proposed above for 'standard vessel types'. The question of adequate computing power for such a task need not present a problem, since separate vessels may if necessary be simulated on separate processors; such a technique has been shown to have various benefits at certain stages of development, Blackwell and Stockel (1989). Alternatively, a multitasking environment with substantial processing power (using one or more processors) yields comparable benefits; such as the set-up described earlier. A less satisfactory solution is to run the simulation slower than real-time to circumvent processor limitations.

For the 'real' situation much consideration was given to the modelling of the hazard vessel. Until when (and if!) it becomes possible to recognise a vessel by using ARPA, then and only then, will it become feasible to model the hazard vessel with any 'real' accuracy: This will only happen if all vessels were to carry, and emit, RACON signals. At present the best scenario is to have a range of simple linear ship models and for the mariner to select, from experience, the vessel type.

Due to computation time involved in multi-target situations, it may be better to use recognised regression type formulae, as published by Barr et al (1981), to predict the hazard vessels manoeuvring performance. Equation 7.1 shows the formula for calculating the tactical diameter of a vessel.

$$D_T = \frac{D' \times 35 \times L_{PP}}{\delta_r} \quad \text{.....(7.1)}$$

where;

D_T = tactical diameter in metres,
D' = non-dimensional tactical diameter,
L_{PP} = length between perpendiculars,
δ_r = rudder angle in degrees.

δ_r can be obtained from table 7.1.

Ship type	Number of manoeuvres	Mean curve D'	Standard deviation
All ships	483	$3.21 - 1.62 \times 10^{-6} \Delta^{@@}$	0.84
Tankers	373	$3.03 - 0.87 \times 10^{-6} \Delta$	0.67
Bulk carriers	56	$3.32 - 4.61 \times 10^{-6} \Delta$	1.12
Cargo ships	29	$3.72 - 2.05 \times 10^{-6} \Delta$	1.25
Container ships	6	$2.58 + 148 \times 10^{-6} \Delta^{@}$	0.45
Other ships	19	$2.65 + 31.4 \times 10^{-6} \Delta^{@}$	0.27

Δ is ship displacement in metric tons.

@ these results are not based on sufficient data to be considered meaningful.

@@ this relationship is not particularly meaningful since combined effect of all ships should be used for comparison only.

Table 7.1. Value of D' for various ship types, after Barr et al (1981).

This method produces acceptable results when compared with actual and mathematical model data. The following example is for the Esso Osaka:

Esso Osaka	L_{PP}	325 m
	Δ	278000 dwt
	Δ @ trials	319400 dwt

Results for 35° port turn;

D_T calculated	894 m
mathematical model	900.2 m
actual	915 m

After validation, as shown above, and consideration that it offered the best solution at present, this method was adopted for modelling the hazard vessel.

To accurately predict the expected behaviour of the hazard vessel does, however, pose a very real pragmatic question: given that one cannot read (still less guide) the thoughts of the master of another vessel, what benefit may be derived from assessing the consequences if a specific control were applied at a specific time on that vessel? The situation is very different from shore-based VTC, where advice (or directives) may be communicated to any vessel, in the manner of air traffic control. At best, one may take into account the perceived manoeuvrability of the other vessel, and thus its ability to resolve a tricky situation; at worst, one has to admit the possibility of an adverse manoeuvre on his part. Until proven otherwise (by unreasonable procrastination or other 'rogue' action), it may be reasonably assumed that the other vessel will conform with the 'rules of the road'; but any attempt to model the other vessel's likely avoidance manoeuvres would be purely speculative, and should not form the basis for action on the part of own-ship.

Given the above caveats, the modelling of a hazard vessel has little part to play in the expert system logic, other than consideration of continuation of current course and speed. Turning action may be observed, and intent to avoid possibly inferred, but the extent of the manoeuvre may not be prejudged in detail. Any attempt to model the behaviour of another vessel, beyond constant velocity projection, is based on untested assumptions and therefore of dubious value.

7.4.2 Modelling of Own Vessel

The mathematical model described in detail in chapter 5, and validated in chapter 6, has been included into the 'own' ship system of the ACAS, this model accurately describes the vessels manoeuvring characteristics. The adaptability and modular structure of the model allows the ACAS to be implemented on any vessel and also allows refit changes of propeller or rudder.

7.5 System Validation

Prior to using the described mathematical model for modelling own vessel the turning manoeuvre was modelled by a simple arc, this may seem crude but worked exceptionally well. The system, with the simplistic approach of modelling the own vessel as an arc, has previously been validated and approved, Blackwell (1992). Three methods were adopted.

1. Simulating one thousand randomly generated encounter situations and measuring the separation at the closest point of approach, CPA, without, and then with, collision avoidance directed by the expert system. Figure 7.3 shows the results of this exercise.

2. Presenting a variety of simulated encounter situations to groups of experienced mariners, and analysing their responses to the system's handling of those situations. The results of this exercise support the opinion that the system fulfils its objectives, as a flexible working decision system.

3. Installing the system on-board a research vessel, Picket Boat 9, equipped with ARPA, setting up a number of encounter situations involving a sister vessel (the 'hazard'), and following the directions of the expert system in each case to assess its efficiency. This exercise proved the efficacy of the expert system in its intended environment - at sea, within the command centre of a marine vessel. In this respect the sea trials achieved their intended objectives.

Since installing the model the only real visible difference is the reduction in speed that takes place, this in turn causes the selected manoeuvre to be 'safer' as the closest distance between own and hazard vessel will increase. This allows the system to return the vessel to its desired course/track earlier, and if the ACAS was installed as a closed loop system, with the autopilot, could result in an economic saving.

The energy saving capability of autopilots has long been known. Katebi and Byrne (1988) referred to adaptive autopilots based on the optimisation of a cost function which represents the energy used in maintaining a set heading.

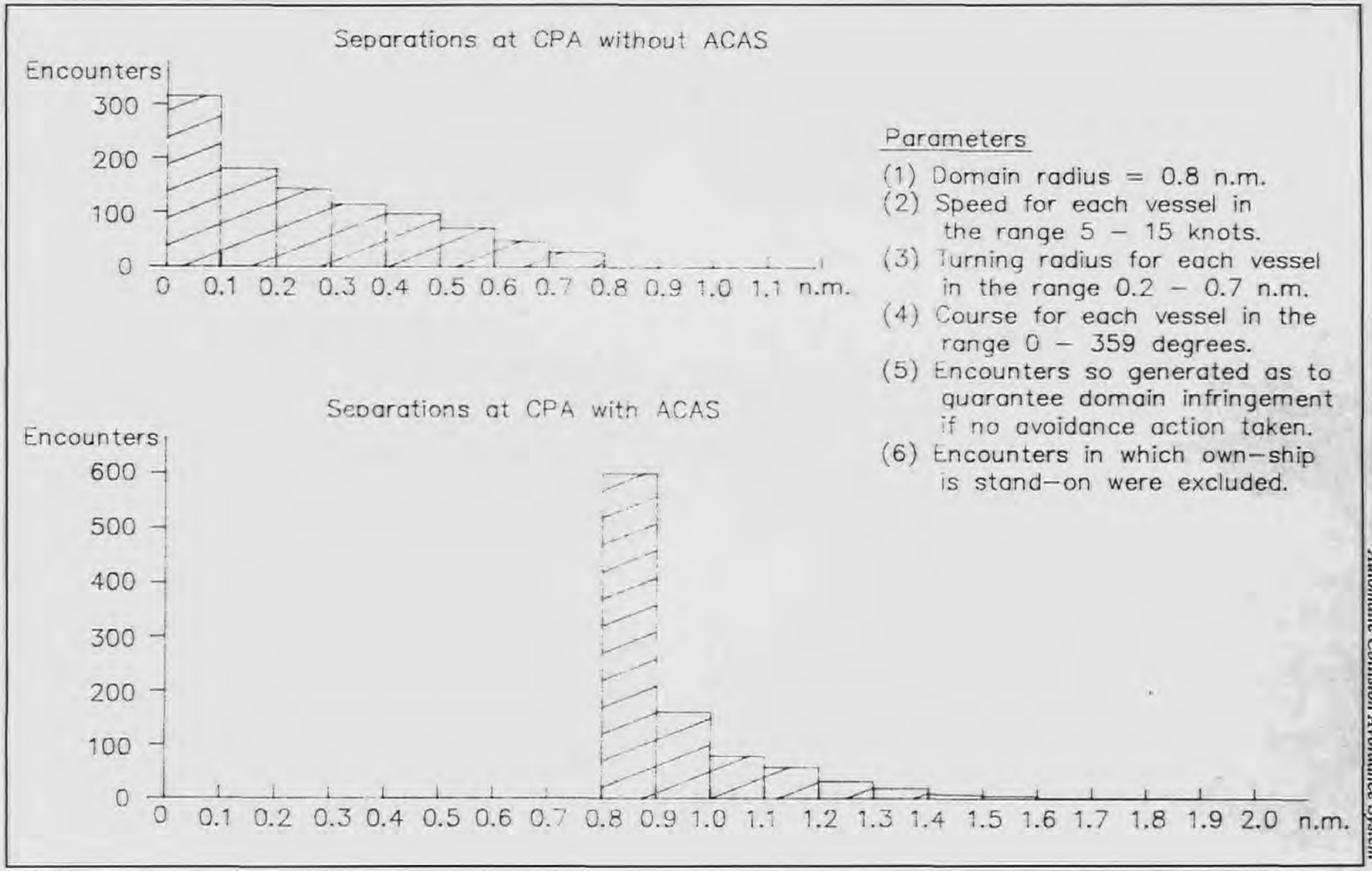


Figure 7.3. Effects of ACAS on a sample of 1000 randomly generated encounter situations. After Blackwell (1992).

The cost function should ideally represent the added resistance due to steering and the elongation of distance sailed effects, due to sway and yaw motions. The economic benefits in reducing the distance sailed was underlined by Meek (1980) when it was estimated, in a computer cost/revenue sensitivity study on a Panamax vessel that a 2% reduction in distance steamed was equivalent to reducing the crew cost by 10%. Hence, should the ACAS be fitted in a close loop scenario it would be important to model the 'own' vessel as accurately as possible. Figures 7.4 and 7.5 show the comparison between the ACAS using a simple arc model and the adaptable mathematical model developed previously, for two different encounter situations. It clearly shows that the system fitted with the adaptable mathematical model can regain course sooner, and hence, reduce the cost function.

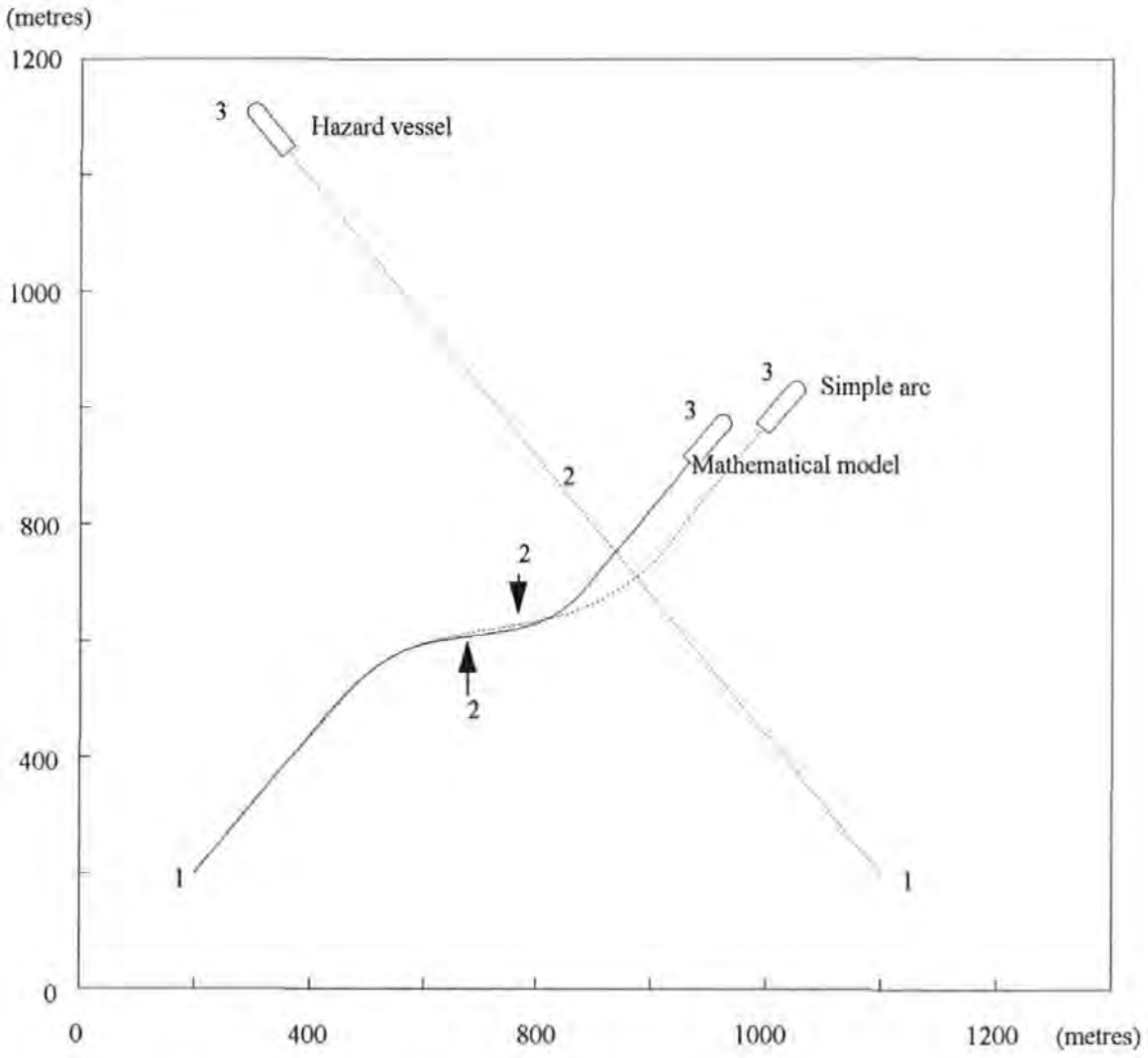


Figure 7.4. Comparison of 'arc' and 'adaptable' models in a crossing situation.

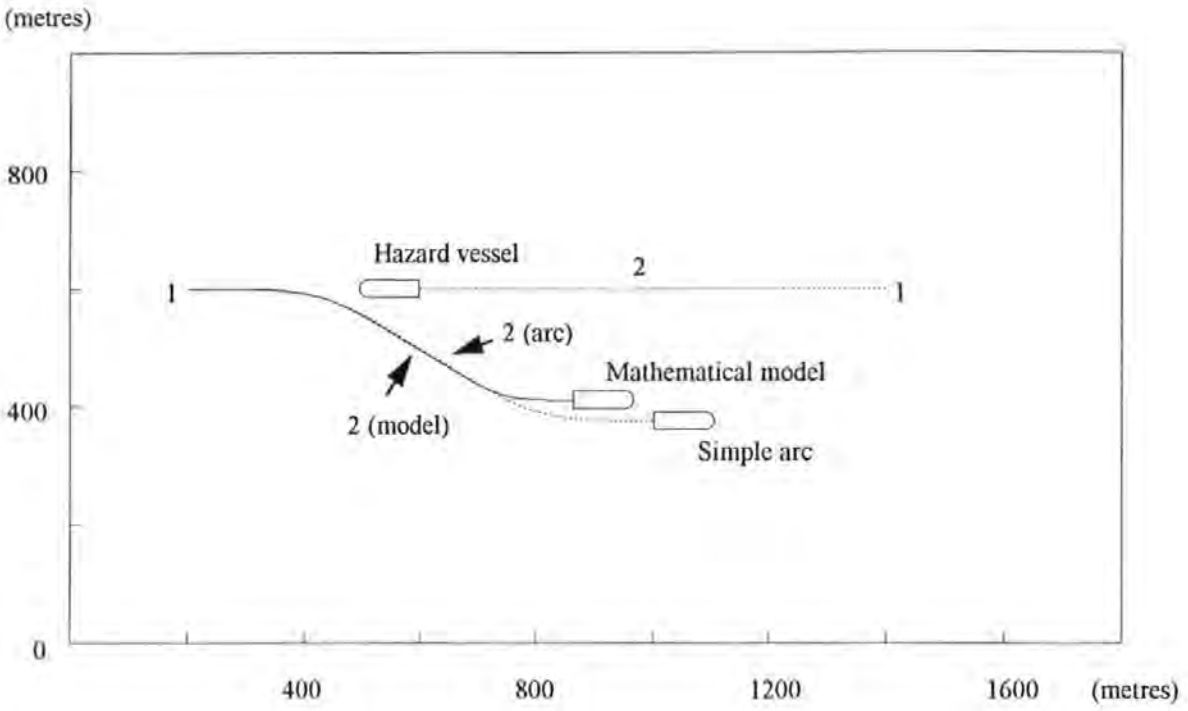


Figure 7.5. Comparison of 'arc' and 'adaptable' models in a head on situation.

7.6 Discussion

The adaptable mathematical model, presented in chapter 5, has been included into the ACAS with success. The overall benefits achieved by using the model can be analysed from figures 7.4 and 7.5, these two figures show simulations for the ACAS with the Esso Osaka model installed as own vessel. In both the head on and crossing situations the final position difference between the simple arc and mathematical model is approximately 100 m. The numbers on the diagrams show the vessels position at the same time intervals. This, together with the economic considerations outlined in section 7.5, show there is some benefit in fitting the model to the ACAS. With the model now fitted the software is being extended to include shipping lanes and coastline/shallow water features, Atkinson et al (1993).

In conclusion, the simple arc model would be acceptable if the system were to be only used for training purposes. However, as the ACAS is being developed as an onboard system and an integral part of the INS, where the model is already being used, it makes sense to utilise the mathematical model.

CHAPTER 8

CONCLUSIONS AND FURTHER WORK

The outcome of any serious research can only be to make two questions grow where only one grew before.

Thorstein Bunde Veblen (1857-1929).
The Place of Science in Modern Civilisation.

8.1 Introduction

The prime aim of this research has been to produce an adaptable mathematical model that can be used in various elements of the integrated navigation system. The objectives to achieve this aim have entailed:

- a survey of automatic navigation and existing 'state of the art' integrated navigation systems;
- an investigation of all existing mathematical model types and a comparison, through various simulations, of their accuracy and adaptability;
- the development of a new mathematical model and its validation against a range of vessels differing in size;
- implementation of this mathematical model into a new collision avoidance system.

In addition to the primary objectives two secondary objectives were identified at the outset:

- to develop a personal computer (PC) based simulator that could be used for manoeuvring predictions at the preliminary design stage;
- for the model to be used in other research work, undertaken by members of the Marine Dynamics Research Group, in different applications.

All of the above objectives have been undertaken and achieved.

8.2 Conclusions

8.2.1 The Adaptable Mathematical Model

During the past ten years members of the MDRG have developed a range of models for different tasks. Much debate has been undertaken as to the complexity and non-linearity of the model. The linear equations of motion only include first order terms and do not make allowance for alteration of course and speed, for this reason they are of limited use when considering large heading and speed changes. Dove (1984) attempted to overcome this problem by developing a quasi-linear model. If sample times were kept small it was reasoned that the linear equations could then be extended to incorporate the surge equation and thus make allowance for variation in forward speed. The quasi-linear model was unsuccessful. In turning circle tests the model turned much tighter; this also resulted in the lateral velocity, and hence the drift angle, being greater than that of the real ship. From this work it was concluded that the model should contain many high order non-linear terms to accurately predict the vessels manoeuvring characteristics.

Miller (1990), on continuation of Dove's work, produced a non-linear holistic model that proved to be very accurate but also very complex. It was not possible to evaluate all of the necessary hydrodynamic coefficients without vessel trials. After assessment of this work, and the simulations undertaken in chapter 4, it was clear that a model with no non-linear terms would result in the adaptability required, but not the accuracy.

The modular model that was produced from this research, as shown in chapter 5, is a solution to this problem. It has been seen that the modular model has the following structure.

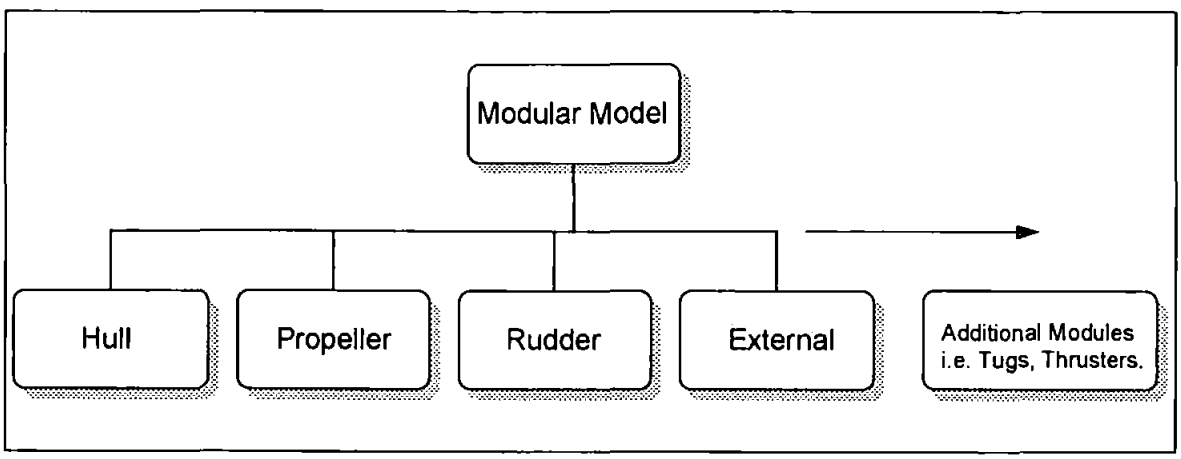


Figure 8.1. Structure of the modular model.

The hull module, except for the surge forces, contain no non-linear terms. Thus the hydrodynamic coefficients can be obtained by numerical methods. The second and third order non-linear surge terms can easily be assessed from resistance information, as shown in section 5.2.2. The developed adaptable modular model differs from the aforementioned quasi-linear holistic model, in that the propeller and rudder modules are modelled independently and to a very high accuracy. A novel application, using the circulation theory to model the propeller forces and moments, allows the model to be more flexible compared to using traditional B-series four-quadrant propeller design charts.

Ship models have been developed and validated, and incorporated into a collision avoidance system. An adaptable mathematical model has been presented that will allow the system to be 'portable' between vessels, without requiring expensive trials. The requirements of the specification is to be able to input the principal dimensions of the vessel and calculate the hydrodynamic coefficients for the model without sea trials, hence keeping initial cost down. The model presented allows for this in a wide range of vessel size.

The adaptability of the model is highlighted by the fact that fellow members of the MDRG have utilised the model in other research projects. Witt (1993) has been undertaking research into the use of a neural network autopilot for ship guidance, and is at present including an adaptive strategy using the modular mathematical model.

8.2.2 The PC Simulator

Two of the long term objectives of the MOSES program, as introduced in section 1.3, are to:

- produce versatile simulation programs, which access experimentally derived hydrodynamic forces and moments, or predict the necessary terms directly from a knowledge of the hull form particulars;
- develop *manoeuvring for design* software, capable of modifying a ship hull form design, which gives rise to manoeuvring behaviour that satisfies prevailing manoeuvrability standards.

The modular model presented in this thesis allows all the necessary terms to be directly derived from a knowledge of hull, propeller and rudder particulars. The *designer* can then alter any of the vessel principal particulars and undertake manoeuvring simulations to appraise the vessels characteristics. The propeller details can be assessed in detail once the vessels powering requirements have been calculated, allowing paddle wheel effect and its effect on the turning performance to be investigated.

Although this research work has been directed towards producing a model for an integrated navigation system and ACAS, it has also been shown that the resulting adaptable model can be used to aid the designer/naval architect at the preliminary design stage of work.

8.2.3 External Effects

A number of modules can be used to describe various external effects which, in keeping with the modular structure, are treated simply as additional forces and moments imposed on the basic hull hydrodynamics. The required complexity and operating conditions of the model determines the external force modules needed. These can include, for example, such effects as wind, current, thrusters, tugs etc. Figure 8.2 shows the Esso Osaka model with the additional effects of wind and tide. The wind was modelled using research published by Isherwood (1983), and the tide modelled using simple vector analysis, Tapp (1989).

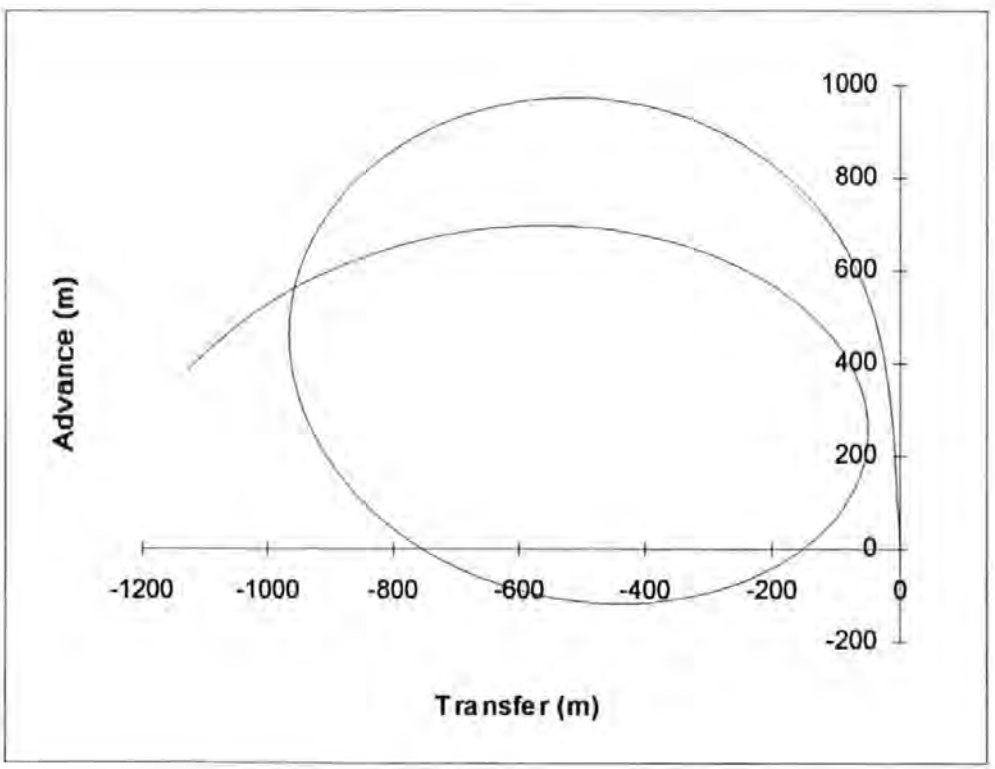


Figure 8.2a. 35° Port turning circle for the Esso Osaka.
Tide: 0.85 kts set towards 210°.
Wind: 8.0 kts from 180°

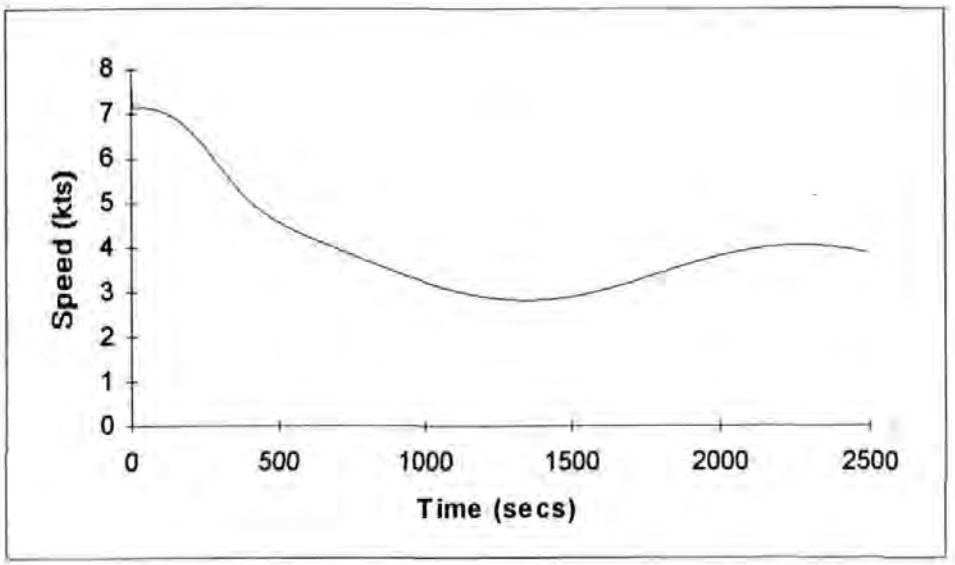


Figure 8.2b. Speed reduction.

8.3 Concluding Summary and Future Work

The shipping industry and the level of technology available to it is changing. Automation of many traditional watchkeeping processes is now either complete or in the midst of this transformation. Although it is now generally accepted that nautical charting will eventually follow this route too, the operational benefits and numerous potential applications of electronic chart display and information systems are still to be realised.

It is unlikely that economic concern will ever permit a reversal of the downward trend in manning levels. It is therefore essential that alternative methods of sustaining, or better still improving safety at sea are pursued. The extent to which automation and central control of vessels at sea is taken will determine the nature of the demands on the mariner. There are widely felt doubts within the industry about the wisdom of one-man bridge operation. However this practice need not be unsafe; with the aid of an ACAS, incorporating an electronic chart display system (ECDIS), and a deadman's handle safety alarm much of the drudgery and risk can be alleviated. For example, unlike the human lookout, a computer system monitoring radar and ECDIS data cannot be distracted from its specific task, nor is it susceptible to fatigue or boredom which may result in sleep in the case of the human operator. However, it must be realised that the computer may sustain hardware or software failure; this problem may be averted by developing, running and monitoring software routines in triplicate and acting on the majority recommendation. If ACAS is to offer tangible solutions to the pressures currently faced by the watchkeepers it must preserve mariner's physical and mental health and self respect.

At present, the master of a ship is accountable, in the eyes of the law, for all decisions made by members of his crew. If automatic collision avoidance systems are to become accepted tools of the trade then the legal anomalies surrounding responsibility and liability for them must be resolved. If an ACAS equipped vessel is involved in an accident then where does the buck-passing stop, with the master, the software engineer, the hardware installation and maintenance engineer...? Until these legal questions have been answered it is essential that man remains part of the collision avoidance strategy forming process.

Future work at the University of Plymouth will build on the existing system, that now incorporates the adaptable mathematical model, with the aim of devising a computer based system incorporating a rule base which is able to suggest anti-grounding and collision avoidance manoeuvres for both single and multiple ship encounters in all surroundings. Work is already underway to achieve this, Atkinson (1993).

Although current legislation restricts the function of automatic collision avoidance systems to an advisory role only, technological capabilities do not. In the long term there is no technical reason why ACAS should not be able to accept full command and responsibility for collision avoidance tactics. Under such circumstances the mariner would be offered a preferred course of action which he may choose to execute or override. However, if a predetermined time period elapses and the mariner has failed to respond in either way, the system would automatically administer the recommended manoeuvre via a computer link to the vessels steering gear. Nonetheless, a question mark still hangs over the notoriously conservative maritime industry's willingness to concede this change in responsibility.

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APPENDIX A

VESSEL PRINCIPAL DIMENSIONS

Table A.1 Data for vessels used in simulations.

DETAILS	SOMERSET	SAND SKUA	CATFISH	ESSO OSAKA	MARINER
			surveying		
PHYSICAL DIMENSIONS:					
No. of hulls	1	1	2	1	1
Length (m)	24.61	62.79	11.17	325	160.9
Beam (m)	5.4	12.49	4.3	53	
Draught (m)	2.09	4.5		21.76	
Cb	.48	.767		.831	.604
DWT (kg)	116000	1838000	8500	278000000	
Vol. of displacment (m^3)	133	2707		310400	18541
Hull c/line separation (m)	-	-	3.7	-	-
Distance LCG to Xg (m)					3.7 aft
Metacentric height, GM (m)	.33	.365			
PROPELLER DETAILS:					
QPC				.8	
No. of props.		1	2	1	1
No. of blades		4		5	
Diameter (m)		2		9.1	6.7
Pitch (m)		1.422		6.507	
Pitch ratio				.715	
Disc area ratio		.685			
Expanded area ratio				.682	
Projected area ratio				.572	
Turning direction		CLOCKWISE		CLOCKWISE	
RUDDER MODELLING:					
No. of rudders		1	2	1	1
Rudder area (m)		5.48	.359 each	119.82	30
Mean height (m)		3.125			7.51
Mean span (m)		1.756		13.85	
Mean chord				9	3.995
Aspect ratio		1.78		1.539	1.88
Details required for programs:					
Iz	4408559.8	501993672.5		1.166e14	21750000000
Ix	314897.1286	35856690.89			
PCG	1	1			
YRG	28	35			
Recommended speed (m/s)	5	5			

DETAILS	M/S ZENOBIA	CONTAINER	CONTAINER	CAR FERRY	CAR FERRY
		Full Scale	Model	Full Scale	Model
PHYSICAL DIMENSIONS:					
No. of hulls	1	1	1	1	1
Length (m)	150	151.8	1.265	150	3.419
Beam (m)	23			24.8	.565
Draught (m)	6.325			5.9	.134
Cb				.64	.64
DWT (kg)	14100000	14800000	8.571	14400000	166.4
Vol. of displacment (m^3)	13760			14046	.166
Hull c/line separation (m)					
Distance LCG to Xg (m)	-4.65				
Metacentric height, GM (m)	.85	.66	.0055		
PROPELLER DETAILS:					
QPC					
No. of props.				2	3
No. of blades				-	
Diameter (m)					
Pitch (m)					
Pitch ratio					
Disc area ratio					
Expanded area ratio					
Projected area ratio					
Turning direction				-	CLOCKWISE
RUDDER MODELLING:					
No. of rudders					
Rudder area (m)					
Mean height (m)					
Mean span (m)					
Mean chord					
Aspect ratio					
Details required for programs:					
Iz		21300000000		24363950000	1.498937e11
Ix		639000000			
PCG	2.5	1.2		2.5	
YRG	150	75		150	
Recommended speed (m/s)	5	9.265		5	

APPENDIX B

VESSEL HYDRODYNAMIC COEFFICIENTS

Table B.1 Hydrodynamic Coefficients for ITV Somerset.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
X_a			Y_a			N_a		
X_δ	0	0	Y_δ	.0022	.01276542	N_δ	-.0011	-.0063827
X_n	0	0	Y_ϕ			N_ϕ		
X_u	0	0	Y_p			N_p		
$X_{\dot{u}}$	-.0007963	-.0446200	$Y_{\dot{p}}$			$N_{\dot{p}}$		
X_r	0	0	Y_r	.003	.5409463	N_r	-.0067	-.1208113
$X_{\dot{r}}$	-.001569	-.0091041	$Y_{\dot{r}}$	-.0002082	-.0116663	$N_{\dot{r}}$	-.001058	-.0592842
$X_{\delta\delta}$	9.308		Y_u	0	0	N_u	0	0
X_{nn}			$Y_{\dot{u}}$	0	0	$N_{\dot{u}}$	0	0
X_{rp}			Y_v	-.009	-.1622839	N_v	-.005	-.0901577
X_{rr}	0	0	$Y_{\dot{v}}$	-.01418	-.7945650	$N_{\dot{v}}$	-.005176	-.2900330
X_{ua}			$Y_{\delta\delta}$			$N_{\delta\delta}$		
X_{uu}	-528.8	-29630.89	Y_{nn}	0	0	N_{nn}	0	0
X_{un}	0	0	Y_{un}			$N_{r\|r\|}$		
X_{up}			$Y_{r\|r\|}$			N_{ua}		
X_{va}			Y_{up}			N_{up}		
X_{vr}			Y_{ur}			N_{ur}		
X_{vu}	0	0	Y_{uu}	0	0	N_{uv}		
X_{vv}	-.00758	-.4247393	Y_{uv}			N_{vb}		
$X_{\delta\delta\delta}$			Y_{vb}			$N_{v\|r\|}$		
X_{uuu}	0	0	$Y_{v\|r\|}$			N_{vu}	0	0
X_{uuuu}			Y_{vu}	0	0	$N_{v\|v\|}$		
$X_{uvv\|v\|}$			$Y_{v\|v\|}$			$N_{\delta\delta\delta}$	.015	.08703699
			$Y_{\delta\delta\delta}$	.03	.17407398	$N_{\delta vv}$	0	0
			$Y_{\delta rv}$	0	0	N_{rvv}	-.5	-8.706498
			$Y_{\delta vv}$			N_{uur}		
			Y_{rvv}	.15	26.119495	N_{uuv}		
			$Y_{ur\|\phi\|}$			N_{uva}		
			$Y_{uu\delta}$			$N_{uv\|\phi\|}$		
			$Y_{uu\phi}$			N_{uvu}	0	0
			Y_{uur}			N_{vvv}	.016	2.7860794
			Y_{uuv}					
			$Y_{uv\|\phi\|}$					
			Y_{vvv}	-.08	-13.93040			

Table B.2 Hydrodynamic Coefficients for Sand Skua.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
X_a			Y_a			N_a		
X_δ			Y_δ			N_δ		
X_n			Y_φ			N_φ		
X_u			Y_p			N_p		
$X_{\dot{u}}$			$Y_{\dot{p}}$			$N_{\dot{p}}$		
$X_{\dot{r}}$			Y_r	.00458621	.20970397	N_r	-.0039804	-.1820013
$\overline{X}_{\delta\delta}$			$Y_{\dot{r}}$	-.0017390	-.0795179	$N_{\dot{r}}$	-.0008688	-.0397258
$\overline{X}_{nn}$			Y_u			N_u		
$\overline{X}_{rp}$			$Y_{\dot{u}}$			$N_{\dot{u}}$		
$\overline{X}_{rr}$			Y_v	-.0298549	-.1.365115	N_v	-.0108356	-.4954575
X_{ua}			$Y_{\dot{v}}$	-.0183627	-.8396355	$N_{\dot{v}}$	-.0016932	-.0774231
$\overline{X}_{uu}$			$\overline{Y}_{\delta\delta}$			$\overline{N}_{\delta\delta}$		
X_{un}			Y_{nn}			N_{nn}		
$\overline{X}_{up}$			Y_{ua}			$\overline{N}_{r\|r\|}$		
X_{va}			$\overline{Y}_{r\|r\|}$			N_{ua}		
$\overline{X}_{vr}$			$\overline{Y}_{up}$			$\overline{N}_{up}$		
$\overline{X}_{vu}$			$\overline{Y}_{ur}$			$\overline{N}_{ur}$		
$\overline{X}_{vv}$			$\overline{Y}_{uu}$			$\overline{N}_{uv}$		
$\overline{X}_{\delta\delta\delta}$			$\overline{Y}_{uv}$			N_{vb}		
$\overline{X}_{uuu}$			Y_{vb}			$\overline{N}_{v\|r\|}$		
$\overline{X}_{uuuu}$			$\overline{Y}_{v\|r\|}$			$\overline{N}_{vu}$		
$\overline{X}_{uvv\|v\|}$			$\overline{Y}_{vu}$			$\overline{N}_{v\|v\|}$		
			$\overline{Y}_{v\|v\|}$			$\overline{N}_{\delta\delta\delta}$		
			$\overline{Y}_{\delta\delta\delta}$			$\overline{N}_{\delta vv}$		
			$\overline{Y}_{\delta rv}$			$\overline{N}_{rvv}$		
			$\overline{Y}_{\delta vv}$			$\overline{N}_{uur}$		
			$\overline{Y}_{rvv}$			$\overline{N}_{uuv}$		
			$\overline{Y}_{ur\|\varphi\|}$			N_{uva}		
			$\overline{Y}_{uu\delta}$			$\overline{N}_{uv\|\varphi\|}$		
			$\overline{Y}_{uu\varphi}$			$\overline{N}_{uvu}$		
			$\overline{Y}_{uur}$			$\overline{N}_{vvv}$		
			$\overline{Y}_{uuv}$					
			$\overline{Y}_{uv\|\varphi\|}$					
			$\overline{Y}_{vvv}$					

Table B.3 Hydrodynamic Coefficients for Catfish.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
$X_{\dot{a}}$			$Y_{\dot{a}}$			$N_{\dot{a}}$		
X_{δ}	0		Y_{δ}	.299621		N_{δ}	-.014981	
X_{n}	0		Y_{ϕ}			N_{ϕ}		
X_{u}	0		Y_{p}			N_{p}		
$X_{\dot{u}}$	-.000624		$Y_{\dot{\beta}}$			$N_{\dot{\beta}}$		
$X_{\dot{r}}$	0		Y_{r}	.004		N_{r}	-.0089	
$\overline{X}_{\delta\delta}$	-.005173		$Y_{\dot{r}}$	-.000288		$N_{\dot{r}}$	-.001464	
$\overline{X}_{nn}$	.2772		Y_{u}	0		N_{u}	0	
$\overline{X}_{rp}$			$Y_{\dot{u}}$	0		$N_{\dot{u}}$	0	
$\overline{X}_{rr}$	0		Y_{v}	-.018		N_{v}	-.01	
X_{ua}	0		$Y_{\dot{v}}$	-.0111		$N_{\dot{v}}$	-.004054	
$\overline{X}_{uu}$	-269.84		$\overline{Y}_{\delta\delta}$	-.23234		$\overline{N}_{\delta\delta}$	-.0116172	
X_{un}	0		Y_{nn}	0		N_{nn}	0	
$\overline{X}_{up}$			Y_{ua}	0		$\overline{N}_{r\|r\|}$		
X_{va}	0		$\overline{Y}_{r\|r\|}$			N_{ua}	0	
$\overline{X}_{vr}$			$\overline{Y}_{up}$			$\overline{N}_{up}$		
$\overline{X}_{vu}$			$\overline{Y}_{ur}$			$\overline{N}_{ur}$		
$\overline{X}_{vv}$	-.00758		$\overline{Y}_{uu}$			$\overline{N}_{uv}$		
$\overline{X}_{\delta\delta\delta}$	0		$\overline{Y}_{uv}$			N_{vb}		
$\overline{X}_{uur}$			Y_{vb}	0		$\overline{N}_{v\|r\|}$	0	
$\overline{X}_{uuu}$			$\overline{Y}_{v\|r\|}$			$\overline{N}_{vu}$		
$\overline{X}_{uuuu}$			$\overline{Y}_{vu}$			$\overline{N}_{v\|v\|}$		
$\overline{X}_{uvv\|v\|}$			$\overline{Y}_{v\|v\|}$			$\overline{N}_{\delta\delta\delta}$		
			$\overline{Y}_{\delta\delta\delta}$	.1818182		$\overline{N}_{\delta vv}$	-.090909	
			$\overline{Y}_{\delta rv}$			$\overline{N}_{rvv}$	0	
			$\overline{Y}_{\delta vv}$	0		$\overline{N}_{uur}$	-.0833333	
			$\overline{Y}_{rvv}$	.15		$\overline{N}_{uuv}$		
			$\overline{Y}_{ur\|\phi\|}$			N_{uva}		
			$\overline{Y}_{uu\delta}$			$\overline{N}_{uv\|\phi\|}$		
			$\overline{Y}_{uu\phi}$			$\overline{N}_{uvu}$		
			$\overline{Y}_{uur}$			$\overline{N}_{vvv}$		
			$\overline{Y}_{uuv}$				.016	
			$\overline{Y}_{uv\|\phi\|}$					
			$\overline{Y}_{vvv}$	-.08				

Table B.4 Hydrodynamic Coefficients for Esso Osaka.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
$X_{\dot{u}}$			$Y_{\dot{v}}$			$N_{\dot{v}}$		
X_{δ}	.00000076	.000042	Y_{δ}	-.0000016	-.000089	N_{δ}	.00000085	.000047
$X_{\dot{r}}$			$Y_{\dot{\phi}}$			$N_{\dot{\phi}}$		
X_{u}	-.0000103	-.000568	Y_{p}			N_{p}		
$X_{\dot{u}}$	-.0009042	-.05	$Y_{\dot{p}}$			$N_{\dot{p}}$		
$X_{\dot{r}}$			Y_{r}	.00031002	.017143	N_{r}	-.0002340	-.01294
$\overline{X}_{\delta\delta}$			$Y_{\dot{r}}$	-.0015366	-.084968	$N_{\dot{r}}$	-.0009003	-.049782
$\overline{X}_{nn}$			$Y_{\dot{u}}$			N_{u}		
$\overline{X}_{rp}$			Y_{u}			$N_{\dot{u}}$		
$\overline{X}_{rr}$	.00090421	.05	Y_{v}	-.0016693	-.092304	N_{v}	-.0006094	-.0337
X_{ua}			$Y_{\dot{v}}$	-.0167340	-.925333	$N_{\dot{v}}$	-.0011199	-.061927
$\overline{X}_{uu}$	-.0005493	-.030373	$\overline{Y}_{\delta\delta}$			$\overline{N}_{\delta\delta}$		
X_{un}			Y_{nn}		.000003	N_{nn}		-.0000015
$\overline{X}_{up}$			Y_{ua}			$\overline{N}_{r\|r\|}$		
X_{va}			$\overline{Y}_{r\|r\|}$			N_{ua}		
$\overline{X}_{vr}$			$\overline{Y}_{up}$			$\overline{N}_{up}$		
$\overline{X}_{vu}$			$\overline{Y}_{ur}$			$\overline{N}_{ur}$		
$\overline{X}_{vv}$	-.0002261	-.0125	$\overline{Y}_{uu}$			$\overline{N}_{uv}$		
$\overline{X}_{\delta\delta\delta}$			$\overline{Y}_{uv}$			N_{vb}		
$\overline{X}_{uuu}$	-.0005204	-.0287788	Y_{vb}			$\overline{N}_{v\|r\|}$		
$\overline{X}_{uuuu}$			$\overline{Y}_{v\|r\|}$			$\overline{N}_{vu}$		
$\overline{X}_{uvv\|v\|}$			$\overline{Y}_{vu}$			$\overline{N}_{v\|v\|}$		
			$\overline{Y}_{v\|v\|}$			$\overline{N}_{\delta\delta\delta}$		
			$\overline{Y}_{\delta\delta\delta}$			$\overline{N}_{\delta vv}$		
			$\overline{Y}_{\delta rv}$			$\overline{N}_{rvv}$	-.0474713	-2.625
			$\overline{Y}_{\delta vv}$			$\overline{N}_{uur}$		
			$\overline{Y}_{rvv}$	.04219669	2.3333333	$\overline{N}_{uuv}$		
			$\overline{Y}_{ur\|\phi\|}$			N_{uva}		
			$\overline{Y}_{uu\delta}$			$\overline{N}_{uv\|\phi\|}$		
			$\overline{Y}_{uu\phi}$			$\overline{N}_{uvu}$		
			$\overline{Y}_{uur}$			$\overline{N}_{vvv}$	.13412520	7.4166667
			$\overline{Y}_{uuv}$					
			$\overline{Y}_{uv\|\phi\|}$					
			$\overline{Y}_{vvv}$	-.2109835	-11.66667			

Table B.5 Hydrodynamic Coefficients for Mariner.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
X_a	0	0	Y_a	0	0	N_a	0	0
X_δ	.00000032	.000036	Y_δ	-.0000025	-.000279	N_δ	-.0000013	.000133
X_n	0	0	Y_ϕ	0	0	N_ϕ	0	0
X_u	-.0000584	-.001274	Y_p	0	0	N_p	0	0
$X_{\dot{u}}$	-.00042	-.04718	$Y_{\dot{p}}$	0	0	$N_{\dot{p}}$	0	0
$X_{\dot{v}}$	0	0	Y_r	.0022	.055	N_r	-.00166	-.042
$X_{\delta\delta}$	0	0	$Y_{\dot{r}}$	-.000086	-.009961	$N_{\dot{r}}$	-.000437	-.0491
X_{nn}	0	0	Y_u	0	0	N_u	0	0
X_{np}	0	0	$Y_{\dot{u}}$	0	0	$N_{\dot{u}}$	0	0
X_{rr}	.00018	.02022	Y_v	-.0116	-.25323	N_v	-.002365	-.051629
X_{ua}	0	0	$Y_{\dot{v}}$	-.00748	-.84025	$N_{\dot{v}}$	-.000227	-.025499
X_{uu}	-.0001395	-.01569	$Y_{\delta\delta}$	0	0	$N_{\delta\delta}$	0	0
X_{un}	0	0	Y_{nn}	.00000001	.0000014	N_{nn}	169291.5	.0000007
X_{up}	0	0	Y_{ua}	0	0	$N_{r\|r\|}$	0	0
X_{va}	0	0	$Y_{r\|r\|}$	0	0	N_{ua}	0	0
X_{vr}	0	0	Y_{up}	0	0	N_{up}	0	0
X_{vu}	0	0	Y_{ur}	0	0	N_{ur}	0	0
X_{vv}	-.00899	-1.009645	Y_{uu}	0	0	N_{uv}	0	0
$X_{\delta\delta\delta}$	0	0	Y_{uv}	0	0	N_{vb}	0	0
X_{uuu}	-.0001577	-.091105	Y_{vb}	0	0	$N_{v\|r\|}$	0	0
X_{uuuu}	0	0	$Y_{v\|r\|}$	0	0	N_{vu}	0	0
$X_{uvv\|v\|}$	0	0	Y_{vu}	0	0	$N_{v\|v\|}$	0	0
			$Y_{v\|v\|}$	0	0	$N_{\delta\delta\delta}$	.00041	0
			$Y_{\delta\delta\delta}$	-.00082	0	$N_{\delta vv}$	-.00489	0
			$Y_{\delta rv}$	0	0	N_{rvv}	-.05483	-.31.69318
			$Y_{\delta vv}$	0	0	N_{uur}	0	0
			Y_{rvv}	.15356	29.587235	N_{uuv}	0	0
			$Y_{ur\|\phi\|}$	0	0	N_{uva}	0	0
			$Y_{uu\delta}$	0	0	$N_{uv\|\phi\|}$	0	0
			$Y_{uu\phi}$	0	0	N_{uvu}	0	0
			Y_{uur}	0	0	N_{vvv}	.016361	9.4570867
			Y_{uuv}	0	0		0	0
			$Y_{uv\|\phi\|}$	0	0		0	0
			Y_{vvv}	-.080782	-46.69412		0	0

Table B.6 Hydrodynamic Coefficients for M/S Zenobia.

SURGE	* PRIME	BIS
X_a	0	0
X_δ	0	0
X_n	0	0
X_u	0	0
$X_{\dot{u}}$	-.0004892	-.06
X_i	0	0
$\overline{X}_{\delta\delta}$	0	0
$\overline{X}_{nn}$	0	0
$\overline{X}_{rp}$	0	0
$\overline{X}_{rr}$	-.0004077	-.05
X_{us}	0	0
$\overline{X}_{uu}$	-.0002931	-.03595
X_{un}	0	0
$\overline{X}_{up}$	0	0
X_{vs}	0	0
$\overline{X}_{vr}$	.00048924	.06
$\overline{X}_{vu}$	0	0
$\overline{X}_{vv}$	0	0
$\overline{X}_{\delta\delta\delta}$	0	0
$\overline{X}_{uuu}$	0	0

ROLL	PRIME	* BIS
K_δ	-.0000011	-.00014
K_ϕ	-.0000026	-.00032
K_p	0	0
$K_{\dot{p}}$	0	0
K_r	0	0
K_i	.00003832	.0047
K_v	-.0000016	-.000195
$K_{\dot{v}}$	0	0
$\overline{K}_{p\|p\|}$	-.0000029	-.00035
$\overline{K}_{r\|r\|}$	.00008969	.011
$\overline{K}_{uv}$	.000023239	.0285

SWAY	* PRIME	BIS
Y_a	0	0
Y_δ	0	0
Y_ϕ	0	0
Y_p	0	0
$Y_{\dot{p}}$	0	0
Y_r	0	0
Y_i	-.0009785	-.12
Y_u	0	0
$Y_{\dot{u}}$	0	0
Y_v	0	0
$Y_{\dot{v}}$	-.0064417	-.79
$\overline{Y}_{\delta\delta}$	0	0
Y_{nn}	0	0
Y_{us}	0	0
$\overline{Y}_{r\|r\|}$	-.0020385	-.25
$\overline{Y}_{up}$	0	0
$\overline{Y}_{ur}$	.00172051	.211
$\overline{Y}_{uu}$	0	0
$\overline{Y}_{uv}$	-.0042809	-.525
Y_{vb}	0	0
$\overline{Y}_{v\|r\|}$	-.0013862	-.17
$\overline{Y}_{vu}$	0	0
$\overline{Y}_{v\|v\|}$	-.0191621	-2.35
$\overline{Y}_{\delta\delta\delta}$	0	0
$\overline{Y}_{\delta rv}$	0	0
$\overline{Y}_{\delta vv}$	0	0
$\overline{Y}_{rvv}$	0	0
$\overline{Y}_{ur\|\phi\|}$	0	0
$\overline{Y}_{uu\delta}$	.00038052	.04666667
$\overline{Y}_{uu\phi}$	0	0
$\overline{Y}_{uur}$	.00068494	.084
$\overline{Y}_{uuv}$	0	0
$\overline{Y}_{uv\|\phi\|}$	0	0
$\overline{Y}_{vvv}$	0	0

YAW	* PRIME	BIS
N_a	0	0
N_δ	0	0
N_ϕ	0	0
N_p	0	0
$N_{\dot{p}}$	0	0
N_r	0	0
N_i	-.0003588	-.044
N_u	0	0
$N_{\dot{u}}$	0	0
N_v	0	0
$N_{\dot{v}}$	-.0003099	-.038
$\overline{N}_{\delta\delta}$	0	0
N_{nn}	0	0
$\overline{N}_{r\|r\|}$	-.0008969	-.11
N_{us}	0	0
$\overline{N}_{up}$	0	0
$\overline{N}_{ur}$	-.0008154	-.1
$\overline{N}_{uv}$	-.0007257	-.089
N_{vb}	-.0038324	-.47
$\overline{N}_{v\|r\|}$	.00203852	.25
$\overline{N}_{vu}$	0	0
$\overline{N}_{v\|v\|}$	-.0038732	-.475
$\overline{N}_{\delta\delta\delta}$	0	0
$\overline{N}_{\delta vv}$	0	0
$\overline{N}_{rvv}$	0	0
$\overline{N}_{uur}$	-.0006387	-.0783333
$\overline{N}_{uuv}$	-.0014365	-.1761667
$\overline{N}_{uvs}$	0	0
$\overline{N}_{uv\|\phi\|}$	-.0007339	-.09
$\overline{N}_{uvu}$	0	0
$\overline{N}_{vvv}$	0	0
	0	0
	0	0
	0	0
	0	0

Table B.7 Hydrodynamic Coefficients for a Container Ship (No Surge Coefficients).

SWAY	* PRIME	BIS	YAW	* PRIME	BIS	ROLL	* PRIME	BIS
Y_a	0	0	N_a	0	0	K_δ	-.0000098	0
Y_δ	.00153483	0	N_δ	-.0133100	0	K_ϕ	0	0
Y_ϕ	-.0003120	0	N_ϕ	.00230884	0	K_p	-.0000764	0
Y_p	0	0	N_p	0	0	$K_{\dot p}$	0	0
$Y_{\dot p}$	0	0	$N_{\dot p}$	0	0	K_r	.00018945	0
Y_r	.00259022	0	N_r	-.0017893	0	$K_{\dot r}$	0	0
$Y_{\dot r}$	-.00020526	0	$N_{\dot r}$	-.0004256	0	K_v	0	0
Y_u	0	0	N_u	0	0	$K_{\dot v}$	0	0
$Y_{\dot u}$	0	0	$N_{\dot u}$	0	0	$K_{p\|p\|}$	0	0
Y_v	-.0158862	0	N_v	-.0057610	0	$K_{r\|r\|}$	0	0
$Y_{\dot v}$	-.0072679	0	$N_{\dot v}$	-.0001166	0	K_{up}	0	0
$Y_{\delta\delta}$	0	0	$N_{\delta\delta}$	0	0	K_{uv}	0	0
Y_{nn}	0	0	N_{un}	0	0	$K_{v\|r\|}$	0	0
Y_{ua}	0	0	$Y_{r\|r\|}$	0	0	$K_{v\|v\|}$	0	0
$Y_{r\|r\|}$	0	0	N_{ua}	0	0			
Y_{up}	0	0	N_{up}	0	0			
Y_{ur}	0	0	N_{ur}	0	0			
Y_{uu}	0	0	N_{uv}	0	0			
Y_{uv}	0	0	N_{vb}	0	0			
Y_{vb}	0	0	$N_{v\|r\|}$	0	0			
$Y_{v\|r\|}$	0	0	N_{vu}	0	0			
Y_{vu}	0	0	$N_{v\|v\|}$	0	0			
$Y_{v\|v\|}$	0	0	$N_{\delta\delta\delta}$	0	0			
$Y_{\delta\delta\delta}$	0	0	$N_{\delta vv}$	0	0			
$Y_{\delta rv}$	0	0	N_{rvv}	0	0			
$Y_{\delta vv}$	0	0	N_{uur}	0	0			
Y_{rvv}	0	0	N_{uuv}	0	0			
$Y_{ur\|\phi\|}$	0	0	N_{uva}	0	0			
$Y_{uu\delta}$	0	0	$N_{uv\|\phi\|}$	0	0			
$Y_{uu\phi}$	0	0	N_{uvu}	0	0			
Y_{uur}	0	0	N_{vvv}	0	0			
Y_{uuv}	0	0		0	0			
$Y_{uv\|\phi\|}$	0	0		0	0			
Y_{vvv}	0	0		0	0			

Table B.8 Hydrodynamic Coefficients for a Container Ship (Model) (No Surge Coefficients).

SWAY	* PRIME	BIS	YAW	* PRIME	BIS	ROLL	* PRIME	BIS
Y_a	0	0	N_a	0	0	K_d	-.000098	0
Y_δ	.00154476	0	N_δ	-.0011129	0	K_ϕ	0	0
Y_ϕ	-.0003146	0	N_ϕ	.00019328	0	K_p	-.0000766	0
Y_p	0	0	N_p	0	0	$K_{\dot{p}}$	0	0
$Y_{\dot{p}}$	0	0	$N_{\dot{p}}$	0	0	K_r	.00018997	0
Y_r	.00264302	0	N_r	-.0017955	0	$K_{\dot{r}}$	0	0
$Y_{\dot{r}}$	-.0159335	0	$N_{\dot{r}}$	-.0004254	0	K_v	0	0
Y_u	-.0072684	0	N_u	0	0	$K_{\dot{v}}$	0	0
$Y_{\dot{u}}$	0	0	$N_{\dot{u}}$	0	0	$K_{p\|p\|}$	0	0
Y_v	0	0	N_v	-.0057816	0	$K_{r\|r\|}$	0	0
$Y_{\dot{v}}$	0	0	$N_{\dot{v}}$	-.0001169	0	K_{up}	0	0
$Y_{\delta\delta}$	0	0	$N_{\delta\delta}$	0	0	K_{uv}	0	0
Y_{nn}	0	0	N_{rrr}	0	0	$K_{v\|r\|}$	0	0
Y_{ua}	0	0	$Y_{r\|r\|}$	0	0	$K_{v\|v\|}$	0	0
$Y_{r\|r\|}$	0	0	N_{ua}	0	0			
Y_{up}	0	0	N_{up}	0	0			
Y_{ur}	0	0	N_{ur}	0	0			
Y_{uu}	0	0	N_{uv}	0	0			
Y_{uv}	0	0	N_{vb}	0	0			
Y_{vb}	0	0	$N_{v\|r\|}$	0	0			
$Y_{v\|r\|}$	0	0	N_{vu}	0	0			
Y_{vu}	0	0	$N_{v\|v\|}$	0	0			
$Y_{v\|v\|}$	0	0	$N_{\delta\delta\delta}$	0	0			
$Y_{\delta\delta\delta}$	0	0	$N_{\delta vv}$	0	0			
$Y_{\delta rv}$	0	0	N_{rvv}	0	0			
$Y_{\delta vv}$	0	0	N_{uur}	0	0			
Y_{rvv}	0	0	N_{uuv}	0	0			
$Y_{ur\|\phi\|}$	0	0	N_{uva}	0	0			
$Y_{uu\delta}$	0	0	$N_{uv\|\phi\|}$	0	0			
$Y_{uu\phi}$	0	0	N_{uvu}	0	0			
Y_{uur}	0	0	N_{vvv}	0	0			
Y_{uuv}	0	0		0	0			
$Y_{uv\|\phi\|}$	0	0		0	0			
Y_{vvv}	0	0		0	0			

Table B.9 Hydrodynamic Coefficients for a Car Ferry.

SURGE	* PRIME	BIS	SWAY	* PRIME	BIS	YAW	* PRIME	BIS
X_a	-.015	-1.803917	Y_a	-.087	-10.46272	N_a	-.0026	-.3126790
X_δ	0	0	Y_δ	.0034178	.41102859	N_δ	-.0016011	-.1925501
X_n	0	0	Y_ϕ	0	0	N_ϕ	0	0
X_u	76.1783	0	Y_p	0	0	N_p	0	0
$X_{\dot{u}}$	-.000426	-.0512313	$Y_{\dot{p}}$	0	0	$N_{\dot{p}}$	0	0
X_i	0	0	Y_r	.0004926	.05924065	N_r	-.002143	-.2577197
$X_{\delta\delta}$	-.00221	-.2657772	$Y_{\dot{r}}$	-.0001368	-.0164517	$N_{\dot{r}}$	-.0006952	-.0836056
X_{nn}	73339.8	0	Y_u	0	0	N_u	0	0
X_{np}	0	0	$Y_{\dot{u}}$	0	0	$N_{\dot{u}}$	0	0
X_{rr}	0	0	Y_v	-.0098675	-1.186677	N_v	-.0043535	-.5235570
X_{ua}	0	0	$Y_{\dot{v}}$	-.007583	-.9119404	$N_{\dot{v}}$	-.00023	-.0276601
X_{uu}	-14446.16	0	$Y_{\delta\delta}$	0	0	$N_{\delta\delta}$	0	0
X_{un}	-39468.78	0	Y_{nn}	0	0	N_{nn}	0	0
X_{up}	0	0	Y_{ua}	0	0	$N_{r\|r\|}$	0	0
X_{va}	0	0	$Y_{r\|r\|}$	0	0	N_{ua}	0	0
X_{vr}	0	0	Y_{up}	0	0	N_{up}	0	0
X_{vu}	0	0	Y_{ur}	0	0	N_{ur}	0	0
X_{vv}	-.00617	-.7420114	Y_{uu}	0	0	N_{uv}	0	0
$X_{\delta\delta\delta}$	0	0	Y_{uv}	0	0	N_{vb}	0	0
X_{uuu}	-450.1888	0	$Y_{vb}Y_{r\|r\|}$	0	0	$N_{v\|r\|}$	0	0
X_{uuuu}	0	0	Y_{vu}	0	0	N_{vu}	0	0
$X_{uvv\|v\|}$	0	0	$Y_{v\|v\|}$	0	0	$N_{v\|v\|}$	0	0
			$Y_{\delta\delta\delta}$	0	0	$N_{\delta\delta\delta}$	.0007421	.08924581
			$Y_{\delta ru}$	-.0009569	-.1150779	$N_{\delta vv}$	0	0
			$Y_{\delta vv}$	0	0	N_{rvv}	-.047235	-5.680536
			Y_{rvv}	0	0	N_{uur}	0	0
			$Y_{ur\|\phi\|}$	.022934	2.7580694	N_{uuv}	0	0
			$Y_{uu\delta}$	0	0	N_{uva}	-.00072	-.0865880
			$Y_{uu\phi}$	0	0	$N_{uv\|\phi\|}$	0	0
			Y_{uur}	0	0	N_{uvu}	0	0
			Y_{uuv}	0	0	N_{vvv}	-.0326335	-3.924543
			$Y_{uv\|\phi\|}$	0	0		0	0
			Y_{vvv}	-.441178	-53.05658		0	0
							0	0

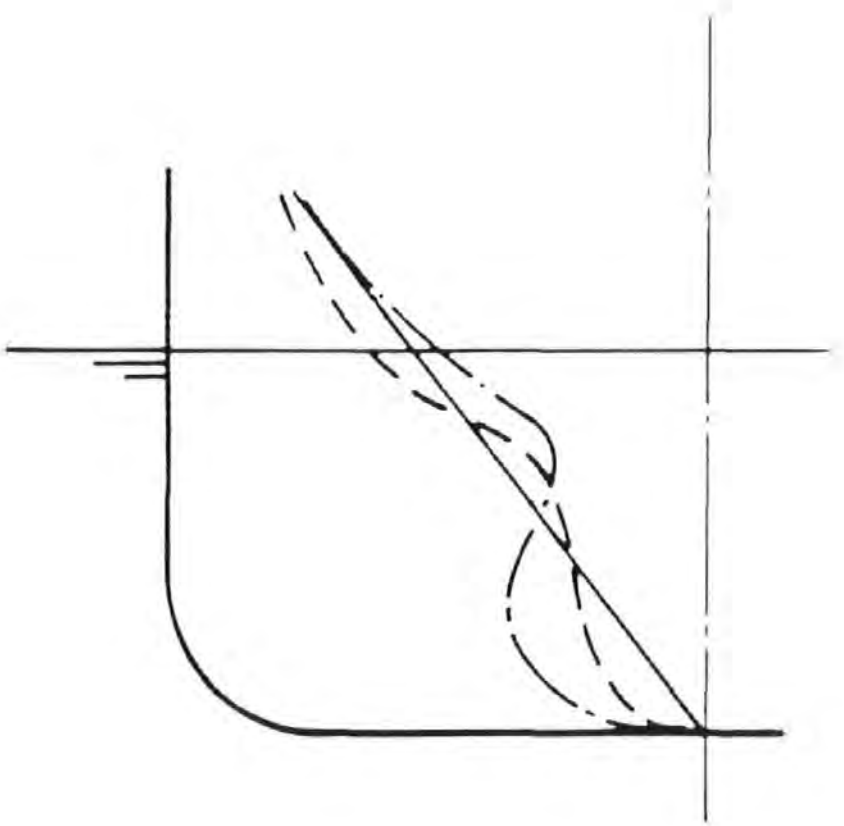
APPENDIX C

AFTERBODY FORMS

V-section

U-section

Hogner bulbous stern



APPENDIX D

ADAPTABLE MODEL VESSEL DIMENSIONS AND PROGRAM INPUT DATA

	ESSO OSAKA	*SAND SKUA*	*PICKET BOAT 9*
L	343	67.145	12.547
Lpp	325	62.789	11.683
B	53	12.192	3.542
T_F	21.76	4.4	0.99
T_A	21.76	4.4	0.99
∇	310400	2613	21.48
C_M	0.95	0.95	0.743
C_{WP}	0.9	0.85	0.871
C_B	0.831	0.767	0.53
A_T	15	12	0.35
S_{app}	400	6	0.3
ABT	63	0	0
hB	4.5	0	0
C_{stern}	0	0	0
ΣApp	3	2	2
Rudder area	119.82	5.476	0.1547
Rudder mean chord	9	1.752	0.300
Rudder aspect ratio	1.539	1.78	1.338
Prop dia	9.1	2.032	0.521
Prop pitch	6.507	1.4224	0.432
Prop no of blades	5	4	3
Prop rotation	RH	RH	-
Prop DAR	0.682	0.685	0.5

Table D.1. Adaptable model vessel dimensions and program input data.

APPENDIX E

PROPELLER GEOMETRY

E.1 Details of Non B-Series Screw

Diameter	0.3048 m
Pitch	Varying
No. of blades	5
Rotation	Right hand screw
Mean line	NACA a=1.0
Section	Elliptic-parabolic thickened according to $x^{1.2}$ at the leading edge.

Table E.1. Principle particulars of non B-series screw.

x	P/D	C/D	t/D	f/c
0.2	1.201	0.231	0.0382	0.0123
0.3	1.302	0.275	0.0338	0.0213
0.4	1.381	0.358	0.0294	0.0252
0.5	1.422	0.462	0.0249	0.0236
0.6	1.423	0.527	0.0205	0.0211
0.7	1.369	0.517	0.0161	0.0200
0.8	1.253	0.432	0.0119	0.0203
0.9	1.080	0.281	0.0082	0.0223

Table E.2. Detailed particulars of non B-series screw.

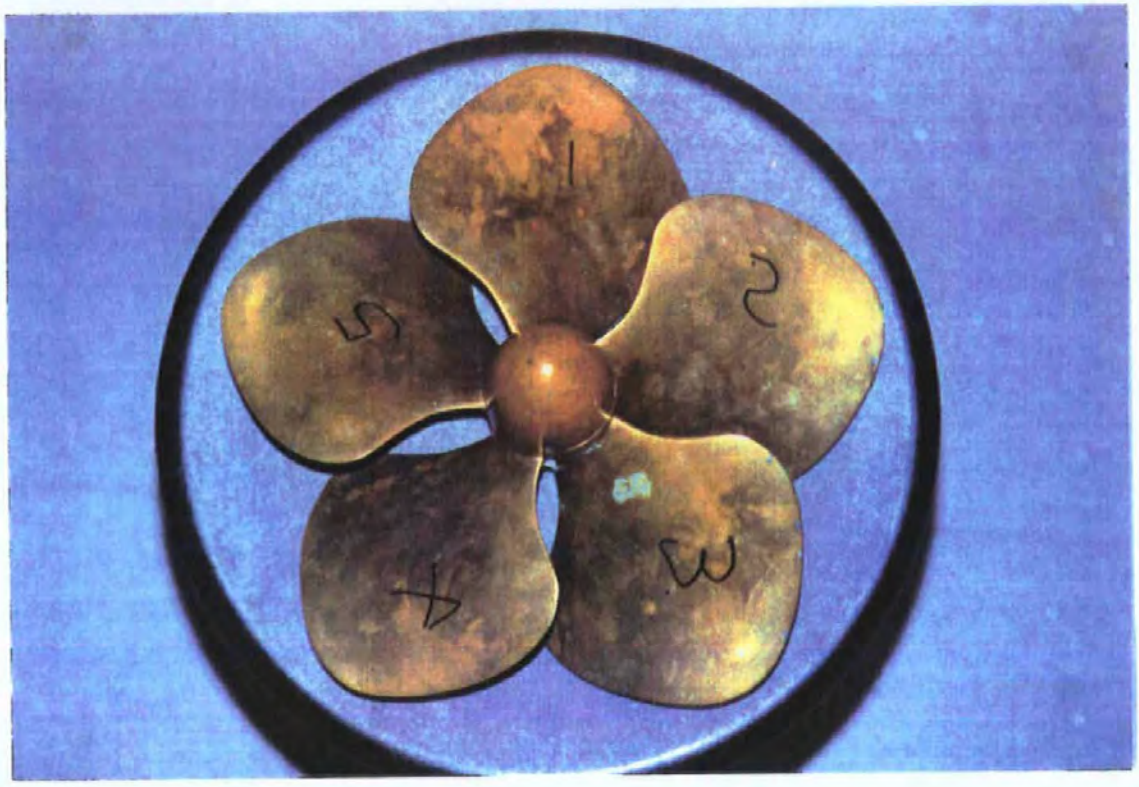


Plate E.1. Non B-Series Screw.

E.2 Details of B-Series Screw

Diameter	21"
Pitch	19"
No. of blades	4
Rotation	Right hand screw
Mean line	NACA a=1.0
Section	Standard B-series

Table E.3. Principle particulars of B-series screw.

x	*P/D*	*C/D*	*t/D*	*f/c*
0.2	0.9048	0.291	0.0270	0.0163
0.3	0.9048	0.326	0.0241	0.0173
0.4	0.9048	0.354	0.0212	0.0214
0.5	0.9048	0.371	0.0185	0.0254
0.6	0.9048	0.375	0.0156	0.0208
0.7	0.9048	0.367	0.0128	0.0239
0.8	0.9048	0.339	0.0100	0.0202
0.9	0.9048	0.271	0.0072	0.0179

Table E.4. Detailed particulars of B-series screw.

APPENDIX F

TANK TESTS

As the after-body of a ship may be varied in many ways, model testing is carried out in a homogenous field of flow, i.e. the open water condition. The tank at the Royal Naval Engineering College is 32m in length, 4m wide and 2m deep. It is generally used for resistance and lift experiments but has been easily adapted for open water propeller tests. The carriage has its own control/operating terminal and can run at speeds up to and including three metres per second.

For each advance coefficient, three runs were executed so to minimise random errors in the tests. The procedure is summarised below:

1. load set-up file on SPECTRA data acquisition software;
2. create data file;
3. ensure the propeller speed is set to that required;
4. check carriage has returned to its datum;
5. set carriage speed;
6. enable carriage and start propeller;
7. start data-logging as carriage movement starts;
8. stop logging when carriage stops, and return carriage;
9. repeat from 1. when the water surface has calmed down to a reasonable state, i.e. as calm as possible.

Twenty-one data-logged runs were accomplished in one day.

Calibration coefficients were applied to the corresponding logged outputs, after the steady-state data had been chosen and averaged.

APPENDIX G

STANDARD SHIP MANOEUVRES

G.1 Turning Circle

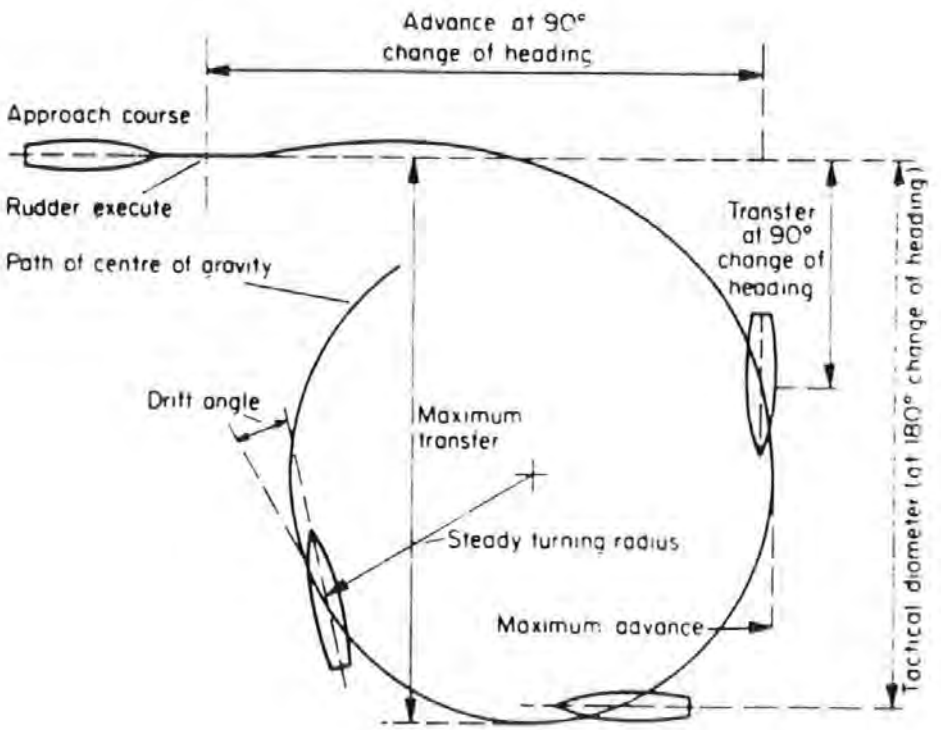


Figure G.1. Turning circle.

This manoeuvre shows the ship's response to a step input. It can also be used to determine the following parameters:

1. Drift Angle This is the angle between the centre line of the ship and the tangent to the path of the point of reference on the ship, usually the centre of gravity.

2. Advance This is the distance travelled by the point of reference in a direction parallel to the original course after the instant that the rudder is activated, It is usually quoted for a 90° change of heading.

3. Transfer This is the distance travelled by the point of reference perpendicular to the original course and is usually given for 90° change of the heading.

4. Tactical Diameter This is the value of transfer when the ships heading has changed by 180°.

5. Diameter of Steady Turning Circle Following the initial application of rudder there is a period of transient motion, but finally the speed, drift angle and turning diameter reach steady values. This usually occurs after about 90 ° change of heading.

6. Pivoting Point This is defined as the fixed perpendicular from the centre of turn onto the middle line of the ship; extended as necessary. This is not fixed by varies with rudder angle and speed.

G.2 Zig Zag Manoeuvre

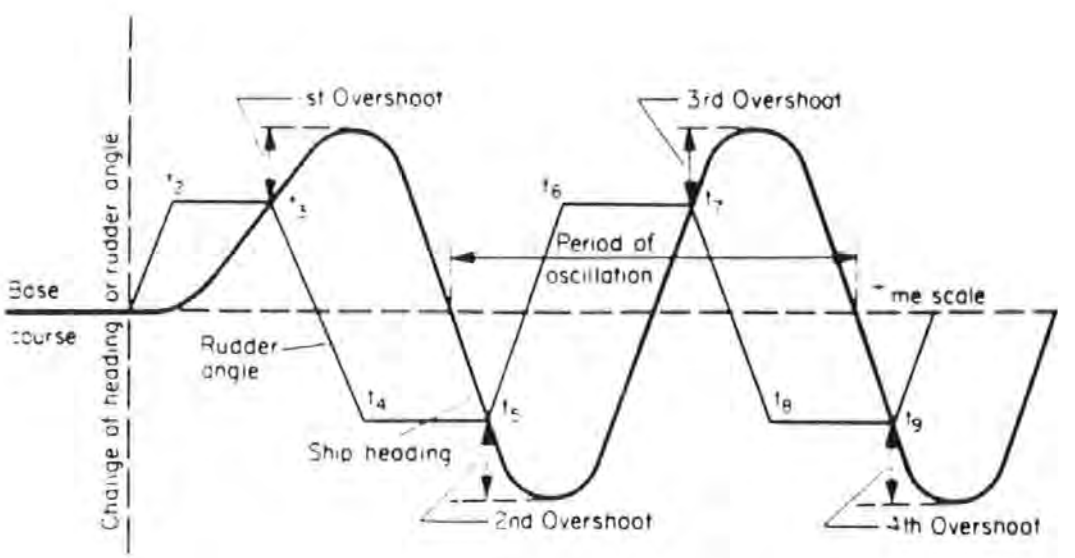


Figure G.2. Zig zag manoeuvre.

From a steady base course and speed the rudder is set to a specified angle. As the ship heading changes by the specified amount the rudder is reversed by the specified amount until once again the change of heading matches the rudder angle. The rudder is reversed again to the specified angle. The procedure is carried out a minimum of five times.

G.3 Direct Spiral

The rudder is put over to 15° to port and the ship allowed to turn until a steady rate of change of heading is achieved. This rate is recorded and the rudder angle is reduced by 5° until a new steady rate of change of heading is recorded. This is repeated for successive values of rudder angle of 5°P, 0°P, 5°S, 10°S, 15°S, 10°S, 5°S, 0°, 5°P, 10°P, 15°P. The steady state rate of change of heading is recorded for each rudder position and the results are displayed as a plot of rate change of heading vs. rudder angle.

If a ship is directionally unstable a hysteresis loop is evident in the plot as the rate of turn for small rudder angles is dependent on whether the rudder angle is decreasing or increasing.

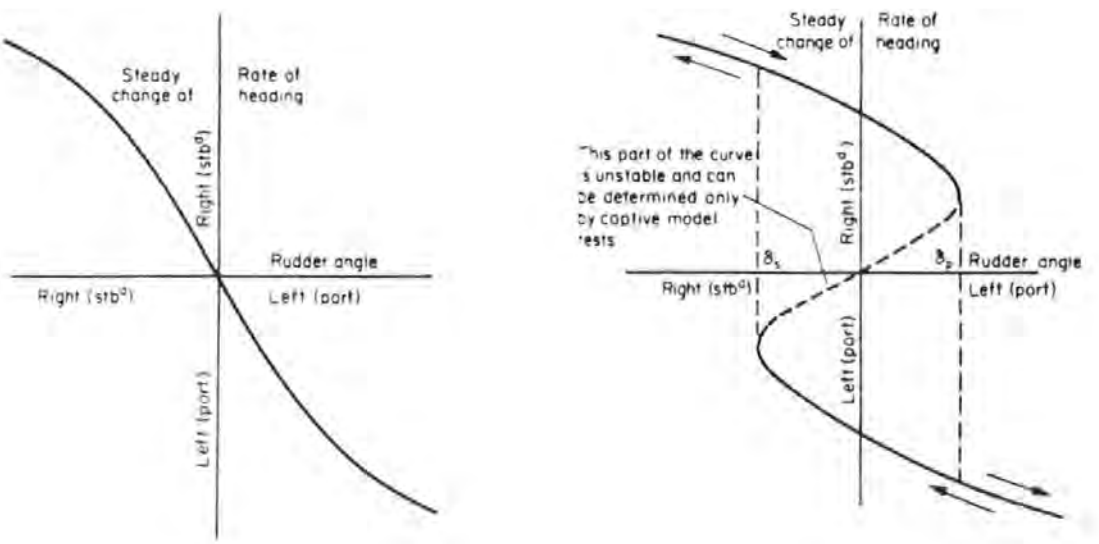


Figure G.3. Expected Results From a Spiral Test For a Stable Ship and Unstable Ship.

G.4 Pull Out Manoeuvre

This is a simple test to give a quick indication of the ship's directional stability. A rudder angle is applied and a steady rate of turn established, at this point the rudder is returned to midships. For a stable ship the rate of turn will decay to zero for turns to both port and starboard.

APPENDIX H

VESSEL TRIALS DATA

H.1 Sand Skua 10° Port Turning Circle

Time (secs)	Speed (kts)	Eastings	Northings
30	9.5	132219.5	454950.7
60	9	132075.1	454959.1
90	9	131954.3	454921.4
120	8.5	131837.6	454838.9
150	7.5	131798.3	454729.6
180	7.5	131837.9	454615.7
210	7	131899.1	454534.1
240	7	131996.9	454517.3
270	6.75	132085.5	454567.9
300	6.25	132136.6	454654.3
330	6.5	132124.5	454788.8
360	6.25	132049.6	454860.1
390	6.25	131953.7	454910.3
420	6	131855.2	454915.9
450	5.75	131773.2	454864.9
480	5.75	131747.1	454754.8
510	5.75	131770.3	454586.1
540	5.75	131849.7	454592.7
570	5.75	131948.2	454587
600	5.75	132023	454627.3
630	5.75	132074.1	454713.6
660	5.75	132060.8	454826
690	5.75	132000.3	454918.7
720	5.75	131880.1	454970.3

H.2 Sand Skua 10° Starboard Turning Circle

Time (secs)	Speed (kts)	Eastings	Northings
60	9.5	129490.8	454472.7
90	9.25	129328.6	454515.7
120	9	129221.5	454600
150	8.75	129196.4	454735.4
180	8.25	129235.7	454844.7
210	7.75	129338.1	454905.6
240	7.5	129436.6	454899.9
270	7.25	129546.2	454860.1
300	7	129587	454768.4
330	7	129547.7	454659.1
360	7	129451.3	454586.6
390	7	129331.8	454571.3
420	7	129236.5	454632.6
450	7	129163.6	454737.3
480	7.25	129170	454848.5
510	7.25	129234.3	454934
540	7.25	129336	454983.9
570	7.25	129454.2	454977
600	7.25	129529.8	454916.8
630	7.25	129564	454825.5
660	7.25	129525.3	454727.4
690	7.25	129447.9	454642.6

H.3 Sand Skua 20° Port Turning Circle

Time (secs)	Speed (kts)	Eastings	Northings
30	9.5	130647.4	454762.6
60	8.5	130481.9	454749.9
90	7.5	130391.4	454665.9
120	6.5	130371.8	454555.5
150	5.25	130433	454473.8
180	3.75	130526.2	454490.7
210	3.25	130582	454543.3
240	3	130600.2	454631.5
270	3.25	130545.7	454712.7
300	3.25	130460.9	454728.8
330	3.5	130373.7	454700.4
360	3.5	130356	454623.3
390	3.5	130385.6	454565.8
420	3.5	130450.6	454550.9
450	3.5	130524.8	454580.1
480	3.5	130555.6	454656.4
510	3.5	130526.6	454725
540	3.5	130451	454785.2

H.4 Sand Skua 20° Starboard Turning Circle

Time (secs)	Speed (kts)	Eastings	Northings
30	9.5	128417.1	454702.7
60	9.5	128285.7	454710.4
120	6	128167.4	454940.5
150	5.5	128225.1	455026.4
180	4.75	128319.7	455065.5
210	4.5	128403.7	455038.3
240	4.25	128418.9	454959.3
270	4.25	128382.1	454894.5
300	4.25	128307.3	454854.2
330	4.5	128231.1	454903.3
360	4.5	128182.5	454973.1
390	4.5	128194.9	455072.8
420	4.5	128244.1	455125.7
450	4.5	128330.1	455131.8
480	4.5	128392.5	455072.4
510	4.5	128387.3	454983.4
540	4.25	128344.7	454930.1
570	4.25	128251.5	454913.3

APPENDIX I

PUBLICATIONS

I.1 List of Publications

An Adaptable Mathematical Model for use in a Marine Collision Avoidance System.
Proceedings of the Summer Computer Simulation Conference, Boston, USA, July 1993, pp520-525.

What Lies Ahead?...Automatic Collision Avoidance at Sea.
Proceedings of the Summer Computer Simulation Conference, Boston, USA, July 1993, pp514-519.

A Review of Mathematical Models Used in Ship Manoeuvres.
Proceedings of CADMO 91, Miami, USA, Jan 1991, pp243-257.

The use of a Mathematical Model in a Collision Avoidance System.
Proceedings of the Second International Conference of Maritime Communications and Control, IMarE, London, Nov 1990, pp53-59.

The Role of a Mathematical Model for Improvement of Marine Navigation.
Proceedings of the Ninth Ship Control Systems Symposium, Washington DC, USA, Sept 1990, pp3.167-3.182.

A Survey of Automatic Navigation.
Proceedings of the Ninth Biennial Seminar on 'A Decade of Development in Marine Engineering', IMarE(Singapore) & SNAMES, Singapore, Nov 1989.

Marine Autopilot Development.
Proceedings of the Ninth Biennial Seminar on 'A Decade of Development in Marine Engineering', IMarE(Singapore) & SNAMES, Singapore, Nov 1989.

A Review of Ship Simulator Models - Past, Present and Future.
Proceedings of the Third European Simulation Congress, Edinburgh, Sept 1989, pp449-456.

I.2 Copies of Published Papers

Shown on following pages.

The Proceedings of the

1993 Summer Computer Simulation Conference

Edited by
Joel Schoen

Boston, Massachusetts
July 19-21, 1993

SCS THE SOCIETY FOR COMPUTER SIMULATION

ISBN: 1-56555-057-9

What Lies Ahead?... Automatic Collision Avoidance at Sea

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ABSTRACT

This paper commences with an insight into to the dilemmas and pressures experienced by the modern day watchkeeper whose job specification and working environment now appear to be dictated by economic forces rather than sound maritime practices. Reduced manning levels, flag of convenience ships and under trained crews together with other cost-cutting exercises within the shipping industry, are putting at risk both the lives of those who trade on the world's high seas and the environment in which we all live. If this downwards trend is to be reversed it is imperative that the frequency of human error in shipping accidents is identified as a matter of urgent attention.

The incidence of and opportunity for human error in visual watchkeeping at sea is addressed in some detail in the earlier sections of the paper. The significance of factors such as isolation, boredom and fatigue in the operation of one-man bridge watches are also discussed.

The middle portion of the paper is concerned with nautical charting. Attention is drawn to the fact that charting is currently trailing well behind the technological advancements sweeping through other aspects of the shipping industry. Consideration is given to the necessary adaptation of traditional cartographic conventions for use in the twenty first century. It is suggested that a technological revolution in this area could have a profound effect on navigation safety.

The latter part of the paper is explores marine collision avoidance and the possibilities for automation of this process. Three distinct marine arenas are identified and the principal risks to vessels operating in each are summarised. Research work in this area, currently being undertaken at the University of Plymouth, is cited in the closing paragraphs of this paper.

INTRODUCTION

In recent years there have been simultaneous significant reductions in the level of bridge manning and increases in the use of sophisticated electronic and satellite-based navigation aids on board ship. The two factors have culminated in the 24 Hour One-man Bridge Operations concept; the Det norske Veritas (DnV) classification society have now classified a number of vessels as safe for operation by a single person on the bridge by day or by night. Ships categorised in this way must satisfy rigorous instrumentation and surveillance criteria.

Thoughtful bridge design and the inclusion of integrated navigation and guidance systems all having controls within arms' length can substantially increase the amount of time the mariner is able to spend on his other essential watchkeeping duties. Consequently the bridges of most ships now contain an escalating number of instruments and associated display screens; during the hours of darkness the officer of the watch (OOW) on a typical bridge is presented with an illuminated assortment of coloured lamps, digital readouts and cathode ray tube screens.

Now as always, the mariner must combine his navigational and seamanship skills together with his knowledge of the Collision Regulations *(IMO, 1972)* to ensure the safe passage of his ship from port to port. He is expected to absorb an enormous volume of data from a variety of sensors and then apply it judiciously in decision making processes. Decisions of this nature, are almost by definition, limited by the ability and response speed of the OOW and the lack of inherent error checking mechanisms.

In recent decades the rapid growth in traffic densities in waters such as the Dover Straits and the Straits of Singapore coupled with other factors such as the increasing size and speed of fast container ships and VLCCs (very large cargo carriers) and the resultant decrease in manoeuvrability have produced a greater than acceptable number of maritime incidents. For example, in August 1991 the Brixham based trawler *OCEAN HOUND* sank in the Dover Straits, with the loss of five lives, after being struck by a ship or ships that have never been identified *(MAIB, 1992)*.

Approximately ninety percent of all marine accidents occur in confined waters such as channels, fairways and inshore traffic zones; the vast majority taking the form of collisions or groundings *(Cockcroft, 1984)*. Although the implementation of Traffic Separation Schemes has significantly reduced the number of such incidents this is far from a complete solution to the problem. Human error, in the form of ignorance or negligence, is estimated to be responsible at least in part, for up to eighty five percent of these accidents *(Panel on Human Error in Merchant Marine Safety, 1976)*.

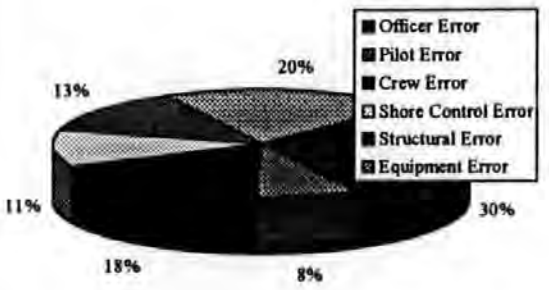

Figure 1: Main Causes of Major Shipping Accidents (1987-1991) (Hamer, 1993).

The above observations testify to the need for further improvement of marine navigation and guidance. Fundamental to safe navigation and collision avoidance are the provision of an efficient lookout at all times, an awareness of the potential threat posed by static hazards such as the seabed or navigation marks combined with knowledge of their proximity to the vessel's current position, and an accomplished understanding of the Collision Regulations including where, when and how to take avoiding action for both static and dynamic hazards. Hence, three areas in which to seek to advance navigational safety can be identified as: watchkeeping, nautical charting and adherence to the Collision Regulations.

VISUAL WATCHKEEPING

Currently there is considerable interest in the visual lookout aspect of navigational watchkeeping. The law is unequivocal on the subject of bridge manning; there must be a qualified officer on watch at all times. The reality is very different, however *(Seaways, 1988)*. It is now, not uncommon for ships to operate at sea without a lookout; some masters are forced to administer this practice against their better judgement, their hands being tied by economic forces such as increasing workloads and reduced manning levels.

There has to be a balance between operational effectiveness and safety in any commercial undertaking. With respect to bridge manning, the former can be equated in terms of the cost per crew member lookout. However, it is impossible to put a price on the safety benefit which encompasses the crew's duty to safeguard the ship, crew and cargo, avoid potentially disastrous situations with other ships and hazards and also to protect the marine environment.

Certain classes of ship, principally coastal, gas and chemical tankers, make particularly heavy demands upon their crews, which in can in turn result in fatigue and give rise to impaired judgement and responses.

Problems can arise in assessing the effectiveness of one-man bridge operations if for no other reason than the presence of researchers on board interacts with the watch system and negates the results of the study. In addition to this the researchers are not experiencing the same pressures and responsibilities as those doing the watchkeeping.

One of the most thorough studies into the cause of collisions and groundings was performed by the Norwegian Maritime Research Institute *(1981)*. The study focused on 3600 casualties to Norwegian vessels occurring between 1970 and 1978. Although now dated, this investigation identified some important relationships. The findings of this study presented the following causal factors:

External conditions	27.6%
Navigational error	24.5%
Inadequate coverage of the watch	13.7%
Other ship	11.4%
Inadequate navigational factors	8.3%
Special human factors	7.0%
Technical failure	6.7%

A study conducted by the British Department of Transport *(Lusted, 1977)* into the stranding of 38 vessels, at about the same time, concluded that:

* 84% occurred in darkness;
* 76% failed to lay off a safe route on the chart;
* 55% failed to establish their position at regular intervals;
* 42% failed to check their primary method of position finding;
* 40% failed to check by dead reckoning;
* 1% used a third method of position fixing.

There are various reasons why during watchkeeping, which can be a prolonged and monotonous activity, human error is such an important factor to consider *(Beetham, 1989)*. Although a range of human factors are at work, all ultimately result in a lack of vigilance or in error. They can be summarised as:

* **Training**: Too much is often expected of junior watchkeepers who may not have been taught how to keep an efficient lookout.
* **Boredom**: A general malaise may result from lack of sensory stimulation and social interaction on minimally manned bridges.
* **Fatigue**: This can have many dimensions, but is essentially the product of prolonged periods of overwork, sleep deprivation and disrupted body rhythms.
* **Motivation and self-esteem**: These are significant factors in the well-being and morale of seafarers. Lack of authority and social contact can influence attitudes towards responsibility.

* **Community spirit**: Multi-national crewing and the associated tensions and language barriers can have adverse effects on commitment and motivation.

* **Bridge ergonomics**: This general heading encompasses aspects of the working environment such as the bridge layout, its instrumentation, working practices and noise levels.

When operating a one-man bridge it is essential that the workload placed on the single OOW in maintaining safe and efficient navigation, surveillance and performing other vital bridge tasks does not exceed the normal capability of one person. In addition the vessel must not be placed in a situation where the incapacity of the watchkeeper could pose a threat to either that vessel or another.

Radar and electronic navigation aids are now a standard requirement for most ships. The efficiency of this equipment will determine the actual effectiveness of any electronic lookout, provided of course, that the mariner is able to monitor this equipment intelligently. As far as the lone watchkeeper himself is concerned, the only possible defence against falling asleep *at the wheel* or sudden disability is a *deadman's handle*. This is an alarm sounded at regular intervals which requires a response from the OOW; if a response is not received the alarm is then sounded in the master's cabin. Alarms such as these cannot ensure the immediate arrival of a replacement officer on the bridge but they do offer a solution to the psychological problems of one-man bridge in open-ocean; responding to the alarm breaks the monotony of long periods of isolation and mental inactivity.

THE ELECTRONIC CHART

Traditionally, models of the marine environment have taken the form of paper charts and in spite of all of the technological advancements in marine navigation, the hydrographic office (HO) publications (charts, tide tables, lists of lights and radio signals, etc.) have retained their printed format. One of the most tedious tasks faced by mariners is that of manual chart correction.

Electronic chart is a term which has been applied to a variety of devices ranging from a digitally generated paper chart equivalent to a more complex expert system of interfaced components capable of world-wide navigation without the need for human intervention. It is anticipated that the electronic chart display and information system (ECDIS) will offer solutions to many of the problems faced by mariners and hydrographic offices alike by presenting the mariner with:

'... nautical and hydrographic information of standardised quality and format compiled from existing charts and other authorised material, supplied with necessary features and properties for intelligent use on computer assisted navigation systems aboard crafts.' (Norwegian Hydrographic Service, 1991)

The principles and requirements of the ECDIS concept are defined in Section 1.3 of the provisional specifications *(IHB, 1990)*. Essentially the two issues addressed in this document are those of *paper chart equivalency* and the provision, integration and updating of all information necessary to ensure safe navigation. It has been suggested that two issues are being addressed in the design of an ECDIS *(Morris, 1985)*; the first is the development of a geographical information system (GIS) or database and the second is the creation of a *box of tricks* which the mariner employs to aid the navigation of his craft.

The cartographic content of the electronic chart database (ECDB) will consist of *features and attributes*. A light for example, is a feature; its position, structure, colour and characteristics are attributes. It is essential that there is a convention for the digitisation of features and attributes. A wreck can be digitised as a feature, its depth as an attribute or, on the other hand, a depth figure or sounding could be digitised as the feature and the wreck giving rise to it as the attribute.

Colour is a vital constituent of any ECDIS. The current paper chart colour scheme is a good foundation on which to build a colour scheme for ECDIS, if only because mariners are already familiar with it. It will however, be necessary to modify the existing scheme owing to the differing qualities of coloured paper and colour video display. For example white is too bright for video displays and in particular, the glare it produces can hamper night vision. In addition some colour combinations simply do not work on cathode ray tube displays. Unique colours will also have to be identified for transparent radar overlays and for features needed for navigation but not printed on paper charts, such as vessel tracks, routing waypoints and fix times. For any system of visual communication employing colour coding the number of colours actual displayed should be kept to a minimum *(Lawson, 1983)*. A system designed for users with normal colour vision operating in their normal working environment should not use more than six colours, or for ease of discrimination, four colours plus black and white (for example, British Admiralty charts use cyan, magenta, yellow and green).

The evolution of integrated navigation systems should herald improvements in standards of navigation safety, man-hour consumption and vessel operational efficiency. It has been stated *(Hvide, 1991)* that ECDIS is probably the best method of avoiding oil pollution by reducing the risk of grounding which has previously been the cause of many of the major environmental disasters such as that of the EXXON VALDEZ in Prince William Sound, Alaska on 24th March 1989 and the AMOCO CADIZ on the northern shores of Brittany in March 1977. It is therefore a potential source of large savings in both cargo and hull insurance, particularly for high premium hazardous cargoes.

Once international agreement has been reached on the standards for ECDIS, electronic charts will undoubtedly be included in

tegrated navigation systems. The existing systems integrating vigation aids with ARPA (automatic radar plotting aid) are t capable of setting or adjusting courses. Although many ship wners believe that ARPA and ECDIS perform the same nction, Øyvind Stene of the Norwegian Hydrographic Service reported *(Wilding-White, 1989)* to have made the distinction at ARPA is a collision avoidance tool whilst ECDIS is an anti-ounding device.

lectronic charting is undergoing a period of rapid development ith ideas changing in the light of experience. Although andards are being developed by legislative authorities cluding the IMO (International Maritime Organisation) and IO (International Hydrographic Office), it must be realised at their present publications are only guidelines and not andards. It is currently forecast that the final specifications for CDIS will be ratified in 1995. Difficulties can arise in the velopment of standards for a piece of equipment that has been ed in a trial situation. If standards are set too firmly, then novative future developments may be inhibited. However anufacturers do need to be given some early indications of the neral direction that the legislative bodies are taking. In the velopment of standards for ECDIS, HOs are making a parture from their traditional arena into fields such as ectronic engineering, computing and even perception ychology.

OLLISION AVOIDANCE

ne technology of this decade and the last, coupled with the er increasing economic constraints, has lead the shipping dustry to attempt to reverse its decline through drastic and rhaps dangerous, reductions in manning levels. Casualty udies have consistently demonstrated the superior reliability of achinery over man. However, missing from this surge towards tomation of ship operations and minimal manning are gnificant attempts to monitor consequences of this trend on the ychological and operational health of the ship's crew. If tomation is to be beneficial to the shipping industry and prove navigation safety it must reduce rather than increase e number of monotonous tasks to be performed by the lone atchkeeper, such tasks where boredom and lack of mental mulation can be problematic are frequent sources of human ror. For these reasons most of the world's maritime nations are w addressing the problem of collision avoidance and its tomation.

arly work in this field employed mathematical techniques to velop simulation models which were subsequently run on nputers *(Curtis, 1979) (Davis et al, 1982)*. This approach was nited by the ability of traditional mathematics to mirror man thought processes. In recent years a number of projects ve investigated the use of artificial intelligence in the velopment of expert collision avoidance systems *(Imazu et al, 89) (Coenen et al, 1989)*.

Ships operate in all meteorological conditions by day and by night. Throughout its voyage a ship will always be operating in one of three modes:

* **Open-ocean**: on passage in deep water clear of obstructions risk of collision is solely dependent on vessel traffic and fishing activity in the area.

* **Coastal**: where risk of grounding exists together with higher densities of shipping traffic and fishing vessels and increased small craft activity.

* **Port approaches and estuarine waters**: where a more immediate risk of grounding exists and close quarters situations dominate, many vessels being constrained by confined channels.

Research undertaken by the Marine Dynamics Research Group at the University of Plymouth, under its former title of Ship Control Group of Polytechnic South West (Plymouth), has examined the issues surrounding automatic collision avoidance in open-ocean *(Rangachari, 1991) (Blackwell, 1992)*. This work resulted in the development of a prototype expert system capable of simulating multiple ship encounters in open-ocean conditions by use of optimal manoeuvring strategies. The system was designed to run on an Acorn Archimedes computer and is supported by the windows-icon-mouse-pointer (WIMP) environment. However, this is not a complete solution to the problem of automatic collision avoidance; it neglects coastal waters or port approaches where as previously stated the vast majority of incidents occur.

From making a landfall, the navigator has to monitor the ship's track with increasing accuracy while be ready to take avoiding action for multiple hazards in confined waters. Research work now in progress at the University of Plymouth is investigating the application of a similar automatic collision avoidance system (ACAS) in coastal and confined waters and traffic separation zones. In waters such as these, so-called *static hazard* avoidance techniques, including anti-grounding procedures, must also be considered. In order to assess the potential treat posed by static features, including the depth of water under the keel, such a system must have at its heart a sophisticated electronic navigation chart capable of intelligent interrogation and interface links with radar and electronic position fixing (EPF) systems. The latter system is being developed on an IBM-compatible PC.

Preliminary PC-based investigations into own ship representation and routines for coastline avoidance have been performed. The work commenced with the question of iconic portrayal of the own ship (refer to Figure 2). In the system devised, the co-ordinates of the centre of the circle correspond with the vessel position and the bearing of the vector is concurrent with the ship's heading. The vector length is directly proportional to the vessel's velocity. In future developments the vessel states, namely position, heading and velocity, will be read directly into the computer's serial port from the ship's

navigation instruments; however, in these early stages they have been simulated in response to user keystrokes.

In order to consider hazard avoidance it is necessary to define a safety domain around the own ship and hence the icon. If an object, either static or dynamic infringes this zone it is deemed to be a potential hazard. When describing a safety domain it is essential that the extent of the domain is proportional to vessel speed in order to maintain a constant *look-ahead time domain*; a vessel closing a coastline at 10 knots has less time in which to implement avoiding action than an identical vessel closing on the same coastline at 5 knots. For this reason a domain radius equal to twice the length of the icon velocity vector has been adopted for these preliminary studies. Although the icon is currently positioned at the centre of this domain, decisions regarding its offset to the rear port (left) quadrant in respect of the collision regulations will be made in the future. Domain infringement checks are made at each pixel along the domain radius at a bearing coincident with the vessel heading, and then along subsequent radii at 20° increments of this heading. This scanning procedure can be equated to the technique used by a radar antenna observing the area surrounding a ship.

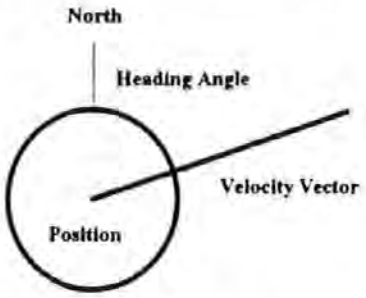

Figure 2: Iconic Representation of the Own Ship

Using a data set of approximately one thousand digitised points along the coastline of Plymouth Sound (SW England), an extremely rudimentary *chart* of the area was produced. The chart is confined to two dimensions only, that is, it does not convey any depth data or contour profiles. It has however, proved to be a perfectly adequate starting point for investigation into coastline avoidance algorithms. The approach currently being practised involves *pixel colour determination*. In this process a hazard is defined as a pixel whose colour differs from those reserved for *safe* water or the icon itself. As the icon is manoeuvred around the chart the colour of each pixel within the icon's safety domain is determined using the domain infringement software; if a *hazard colour* is identified the *distance-off* is evaluated. If this distance drops below a predetermined tolerance level a danger warning is displayed on the screen until suitable avoidance manoeuvre is completed.

Work is currently focused on the adaptation of the earlier open-ocean algorithms in order that they may be run on an IBM-compatible PC. The varied and often parallel tasks of a watchkeeper who must juggle his skills as a lookout, navigator and tactician cannot be adequately mirrored by a single tasking computer system. Unlike the disk operating system (DOS) the Acorn reduced instruction set computer (RISC) operating system is capable of multi-tasking. For these reasons this adaptation work is being carried out in the *Windows™* operating system using the *Windows™ Graphical Development Environment*.

CONCLUSIONS

The shipping industry and the level of technology available to it is changing. Automation of many of the traditional watchkeeping processes is now either complete or in the midst of this transformation. Although it is now generally accepted that nautical charting will eventually follow this route too, the operational benefits and numerous potential applications of electronic chart display and information systems are still to be realised.

It is unlikely that economic concern will ever permit a reversal of the downward trend in manning levels. It is therefore essential that alternative methods of sustaining, or better still improving safety at sea are pursued. The extent to which automation and central control of vessels at sea is taken will determine the nature of the demands on the mariner. There are widely felt doubts within the industry about the wisdom of one-man bridge operation. However this practice need not be unsafe; with the aid of an automatic collision avoidance system, incorporating an ECDIS, and a deadman's handle safety alarm much of the drudgery and risk can be alleviated. For example unlike the human lookout, a computer system monitoring radar and ECDIS data cannot be *distracted* from its specified task, nor is it susceptible to fatigue or boredom which may result in sleep in the case of the human operator. However, it must be realised that the computer may sustain hardware or software failure; this problem may be averted by developing, running and monitoring software routines in triplicate and acting on the majority recommendation. If ACAS is to offer tangible solutions to the pressures currently faced by the watchkeepers it must preserve mariner's physical and mental health and self-respect.

At present, the master of a ship is accountable, in the eyes of the law, for all the decisions made by members of his crew. If automatic collision avoidance systems are to become accepted tools of the trade then the legal anomalies surrounding responsibility and liability for them must be resolved. If an ACAS equipped vessel is involved in an accident then where does the buck-passing stop, with the master, the software engineer, the hardware installation and maintenance engineer...? Until these legal questions have been answered it is essential that man remains part of the collision avoidance strategy forming process.

Future work at the University of Plymouth will build on the existing algorithms with aim of devising a computer-based system incorporating a rule base which is able to suggest anti-grounding and collision avoidance manoeuvres for both single and multiple ship encounters in all surroundings.

Although current legislation restricts the function of automatic collision avoidance systems to an advisory role only, technological capabilities do not. In the long term there is no technical reason why ACAS should not be able to accept full command and responsibility for collision avoidance tactics. Under such circumstances the mariner would be offered a *preferred* course of action which he may choose to execute or override. However, if a predetermined time period elapses and the mariner has failed to respond in either way, the system would automatically administer the recommended manoeuvre via a computer link to the vessel's steering gear. Nonetheless, at the end of the day a question mark still hangs over the notoriously conservative maritime industry's willingness to concede this change in responsibility.

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BIOGRAPHY

Helen Atkinson graduated from the Institute of Marine Studies, Polytechnic South West, Plymouth with a first class honours degree in *Hydrography with Marine Control Systems* in July 1990. Since October of that year she has been a post-graduate research student in the Institute, the title of her PhD studies being *An Expert System for Marine Navigation*. Helen is a member of the Royal Institute of Navigation, the Hydrographic Society and the Sea Safety Group (UK).

Helen has a keen interest in offshore sailing and possesses a number of sailing/navigation qualifications. She regularly sails as a watch leader with the UK-based sail training organisation *Ocean Youth Club* with which she learned to sail. In addition to competing in a number of Tall Ships Races Helen completed a two-man Trans-Atlantic crossing in 1989.

AN ADAPTABLE MATHEMATICAL MODEL FOR USE IN A MARINE COLLISION AVOIDANCE SYSTEM

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ABSTRACT

Research has been undertaken by the Marine Dynamics Research Group, (MDRG), into mathematical modelling of marine vehicles for several years. In addition to the development of mathematical models for use in marine simulators, members of the MDRG have produced a prototype integrated navigation system, (INS). Included in the INS is an automatic collision avoidance system, (ACAS), the evolution of which has been presented at a previous SCS conference. A mathematical model has now been included in the software, that allows the whole system to be adapted to suit various vessel types without requiring expensive trials.

This paper will present details of the model, including a novel approach to modelling the propeller forces and moments that allow the model to be adaptable when compared to using traditional B-series four-quadrant propeller design charts. The inclusion of the model into the ACAS will then be shown for both 'own' and 'hazard' vessels. Until recently the track of 'own' vessel has been simulated by a simple arc, with no speed reduction in the turning manoeuvre. The simulations undertaken did not show any significant difference in general avoidance manoeuvres between using a simple arc and the mathematical model.

INTRODUCTION

Recent accidents at sea, together with a series of oil crises that have increased the price of fuel oil, have made ship owners and operators more safety and economy conscious; this in turn has made the requirements on ship steering more demanding, particularly in confined waters where extensive manoeuvring is needed. It is therefore important to be able to predict the path of the ship precisely. It has been suggested that 85% of all marine collisions and grounding are due to human error and of these 90% occur in coastal waters, (Cockcroft 1984). On this evidence alone there is a case for research and development into automating the control and guidance systems which are installed on ships.

During the past ten years members of the MDRG have developed a comprehensive range of mathematical models for various vessel types, including high speed planing craft. The main drawback with these models is that they are time consuming to formulate and expensive to produce, requiring tank tests or full scale trials to obtain the necessary hydrodynamic coefficients. In addition to the development of mathematical models for use in PC based simulators, MDRG have produced a prototype INS. The INS is now installed in a research vessel and undergoing trials. Included in the INS is the ACAS, the evolution of which has been presented at a previous SCS conference. (Blackwell et al 1991). Until recently, research has been concentrated on producing the rule base and ensuring the ACAS obeys the rules of the road, even in multi-ship encounters. A mathematical model has now been included into the software that allows the whole system to be adapted to suit various vessel types without requiring expensive trials.

MATHEMATICAL MODELLING

Between different research establishments there is little commonality of ship manoeuvring mathematical models and hydrodynamists have over the years developed models of various forms and fidelity. The many different types of mathematical model can generally be placed under one of four headings, namely:

i) input-output relationship model;
ii) holistic model;
iii) force mathematical model;
iv) modular manoeuvring model.

A study has been undertaken as to the type and complexity of the required model for the proposed INS, (Chudley et al

1991). The model found to be most suitable being of the modular form. A modular manoeuvring model is one in which the individual elements, such as the hull, propeller, rudder, engines and external influences, of a manoeuvring ship are each represented as separate interactive modules. Each module, whether it relates to hydrodynamic or control forces or external effects, is self contained. The modules are constructed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and describing their interaction by other physical expressions.

The equations of motion for a modular manoeuvring model are expressed generally by:

$$\begin{aligned} m\dot{u} - mrv &= X_H + X_P + X_R + X_E \\ m\dot{v} - mru &= Y_H + Y_P + Y_R + Y_E \\ I_Z\dot{r} &= N_H + N_P + N_R + N_E \end{aligned} \qquad \text{.....(1)}$$

where the suffixes H, P, R and E denote components of hull, propeller, rudder and external forces.

For the majority of ship types the three degree model is adequate, however, vessels are now being seen with greater freeboards than ever before, some of these ships such as container ships and RO-RO ferries can generate considerable roll in a manoeuvre. The manoeuvring motion of ships that can generate large roll angles should be calculated taking the coupling effect due to roll into consideration. The equation for roll can be expressed by:

$$I_X\dot{p} = K_H + K_P + K_R + K_E \qquad \text{.....(2)}$$

Hull Forces and Moments

The hull forces and moments module contains all the hydrodynamic data which is specific to the hull alone. They can be expressed as shown in equation set (3), (Tapp 1989). The equations are a further development of previous research work on the holistic type model, with the important non-linear terms being similar to enable comparisons of the models to be made. The multiplier v/|u| included in some of the terms is to correct the sign of the derivative during astern motion of the ship.

The term R_H in the surge equation represents the resistance of the ship on a straight course, the derivatives within this term are calculated using a program adapted from the work by Holtrop (1984).

$$\begin{aligned} X_H &= X_{\dot{u}}\dot{u} + X_{vr}vr + X_{vv}v^2 + \frac{u}{|u|}X_{rr}r^2 + R_H \\ Y_H &= Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{uv}v + \frac{u}{|u|}Y_{ur}r + Y_{vvv}v^3 + Y_{rrv}rv^2 \\ N_H &= N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{ur}r + \frac{u}{|u|}N_{uv}v + N_{vvv}v^3 + N_{rrv}rv^2 \end{aligned} \qquad \text{.....(3)}$$

Propeller Forces and Moments

In order to model the motion of the ship for both ahead and astern motion it is important to determine correctly the propeller forces and moments. Tapp (1989), to cover all manoeuvring regimes, adopted the method of modelling the propeller forces and moments published by Oltmann and Sharma (1984). This method is based on the use of published open-water test results with standard B-series propeller forms in the four quadrants of operation, (Van Lammeren et al 1969). The types of propeller that can be modelled by using these design charts are restricted as published data on the complete B-series range is limited.

A novel approach, in terms of manoeuvring mathematical models, is to adopt the use of circulation theory techniques to predict the propeller thrust. By adopting this method the use of propeller design charts, or data based on open water model tests, is not required. Hence, propeller modelling is not limited only to propellers of the B-series form.

The mathematical model becomes more adaptable.

Basic Circulation Theory

The modern theoretical methods of circulation theory used to design propellers are based upon the concept that the lift developed by the propeller blade is caused by a circulation flow that takes place around the blade.

There are two practical ways in which the circulation theory can be applied in propeller calculations:

i) it can be used in selecting the geometrical characteristics of a propeller corresponding to the specified design condition, i.e. in designing screws;

ii) it can be adapted to calculate the performance of a screw with given geometrical constraints over a range of operating conditions, i.e. to make detailed screw performance calculations.

From the above, it is point ii) that is of interest for use in propeller modelling.

Wake Distribution

Standard propeller model tests are undertaken in the open water condition and not in the 'behind hull' condition. When a propeller is placed behind the hull of a vessel conditions alter; the water in which the propeller is working has been disturbed by the hull and generally the water in the area of the stern has some forward motion. This forward moving water is called the wake and results in the propeller advancing at speed v_a when the ship is advancing at a speed v_s. The relationships between thrust, torque and revolutions in open water will now alter causing a change in the propeller efficiency as the inflow velocity is not now uniform. From this it can be seen that as a propeller rotates, a section at any given radius passes through regions with varying wake contributions. Wake diagrams can be obtained for various ship types and after body forms, the general form of which can be seen in figure 1. Using these the average circumferential wake can be calculated for any particular radius.

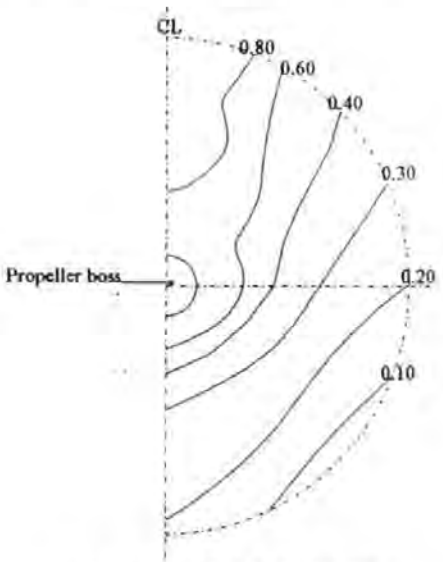

Figure 1. Wake distribution.

For a mathematical model using the circulation theory the wake fraction is required to be calculated at varying radii. An equation involving the speed of the vessel, radius of the propeller and longitudinal velocity is required. One such equation is that developed by Hadler et al (1964) as shown:

$$(1-\omega_x)R = \frac{2}{1-x_h}\int_{x_h}^{1}\frac{v_x(x)}{v_s}dx \qquad .....(4)$$

To calculate the wake fraction at any radius, equation (4) is integrated and the limits applied. The wake fractions calculated are introduced to the propeller module prior to calculating the thrust coefficient, and are integrated over the whole propeller blade for any change in ship speed. Table 1 shows the calculated values of wake fraction for the propeller fitted on the Esso Osaka, a 278000 dwt tanker, at a speed of 3.96 ms^{-1}. The values calculated compare favourably with the 'average' wake calculated using the prediction method of Holtrop (1984).

Non dimensional radius x	Wake fraction ω_x
0.4	0.727
0.5	0.689
0.6	0.590
0.7	0.522
0.8	0.455
0.9	0.390
1.0	0.320

Table 1. Esso Osaka wake fractions.

Calculation of Propeller Forces

Once the wake fractions for varying radii have been obtained, circulation theory can be developed to calculate the thrust coefficient C_T, and hence the propeller thrust for the whole range of the advance angles for the propeller.

$$C_T = \frac{2T}{\rho A_o(up^2+cp^2)} \qquad .....(5)$$

It is not the intention of this paper to present the complete details of the circulation theory and calculation of the terms therein, however this information is published in Davison (1993). Validation of the method was undertaken

y carrying out tank tests. The results of these tests gave enough confidence for the theoretical method to be adopted, thus the reliance on propeller charts is no longer a problem.

The propeller terms can then be calculated using:

$$X_P = (1-t)T$$
$$Y_P = Y_{nn}n^2 \qquad \text{.....(6)}$$
$$N_P = N_{nn}n^2$$

If the screw is located at a distance *L/2* from the *LCG*, then:

$$N_P = Y_{nn}\frac{L}{2}n^2 \qquad \text{.....(7)}$$

The term Y_{nn} is a function of the propeller pitch and its subsequent "paddle wheel" effect i.e. a propeller turning clockwise will cause the vessel to turn to the left when there is 0° rudder. In simulation it is possible to adjust this value to model the vessel correctly. However, the model for the ACAS system has to be adaptable to model any vessel without trials being necessary. Research is at present being undertaken to produce a regression formulae based on a number of already successfully simulated vessels. This will allow Y_{nn} to be calculated for any vessel within reasonable limits.

Rudder Forces and Moments

In common with the propeller modelling it is important to calculate accurately the rudder control forces and moments in order to model correctly the turning and coursekeeping performance of the ship. From Hirano et al (1987), using Tapp's adopted sign convention, the forces and moments induced on the ship due to rudder action are given by:

$$X_R = (1-t_R)F_N \sin(\delta)$$
$$Y_R = -(1+a_H)F_N \cos(\delta) \qquad \text{.....(8)}$$
$$N_R = (1+a_H)F_N X_R \cos(\delta)$$

where;

F_N is the normal force produced by the rudder.

a_H and t_R are the correction factors to adapt the open-water characteristics of the rudder to the behind hull condition.

AUTOMATIC COLLISION AVOIDANCE SYSTEM (ACAS)

The nature and complexity of ship models incorporated in collision avoidance systems depends primarily on whether one is concerned with shore based Vessel Traffic Control, (VTC), or bridge based advisory systems. Research has been advancing on both fronts.

A shore based advisory/control system requires a working knowledge of the performance characteristics of all vessels under surveillance at any time, since the ability to give helpful directives presupposes a capability to accurately predict the likely outcome of one or more vessels. In general, those vessels will each fall into one of three categories:

i) known vessel, for which hydrodynamic coefficients are either documented or can be calculated using the method shown previously in this paper;

ii) known or unknown vessel, for which hydrodynamic coefficients cannot be calculated, but which may be fitted into one of a number of 'classes' of ship, and thus matched approximately to a less tightly defined model;

iii) unknown vessel for which no performance data can be obtained (apart from immediate observation), and which therefore must be judged on a very broad basis.

Shore based VTC, with its requirement for detailed modelling of a number of ships simultaneously, demands substantial computing power to operate effectively in real-time; hence parallel processing will be required. In most other respects the problems of shore based collision avoidance, and the function of ship models therein, mirror those of bridge based systems.

The requirement for ship models in the shipboard ACAS is twofold. Firstly, the expert system logic must be able to model ship behaviour in order to predict likely outcomes of manoeuvres. Secondly, the development environment for such a system for much of the time will consist of a simulated environment in which own-ship and various

hazard vessels are represented by appropriate computer models.

Modelling of Own-ship in the ACAS

The mathematical model outlined has been incorporated into various elements of the proposed INS and has proved to be very successful. Shown in figure 2 is a simulation of a turning circle using the developed adaptable mathematical model.

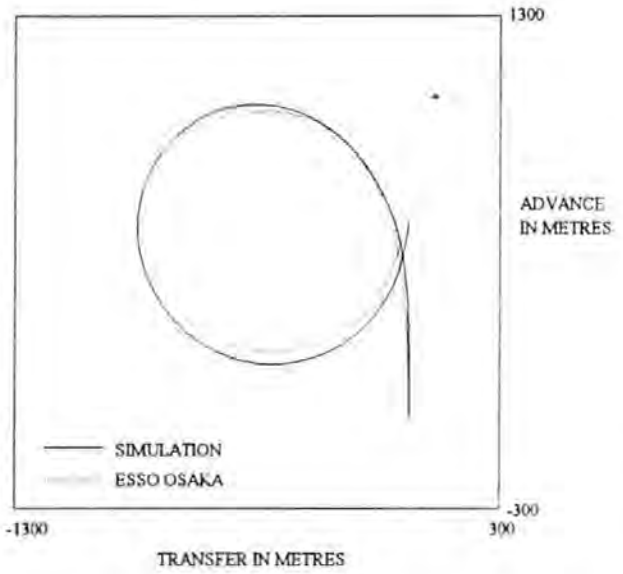

Figure 2. Simulation of a 35° Port Turning Circle. Approach Speed 7.7 knots.

The results of a simulation involving the Esso Osaka have been shown. A number of vessels have been simulated including a 33' Royal Navy training boat, (Chudley 1993), with a great deal of success, and thus showing the range of vessels that the model can simulate.

The model has now been included in the ACAS and validation is at present being undertaken. It is not intended to describe the ACAS, only to present the findings of the inclusion of the model to date. Prior to using the described mathematical model the turning manoeuvre was modelled by a simple arc, this may seem crude but worked exceptionally well. Since installing the model the only real visible difference is the reduction in speed that takes place, this in turn causes the selected manoeuvre to be 'safer' as the closest distance between own and hazard vessel will increase. Speed reduction in a turning manoeuvre for the Esso Osaka can be seen in figure 3. Work is at present ongoing and further findings, including sea trials, will be published at a later date.

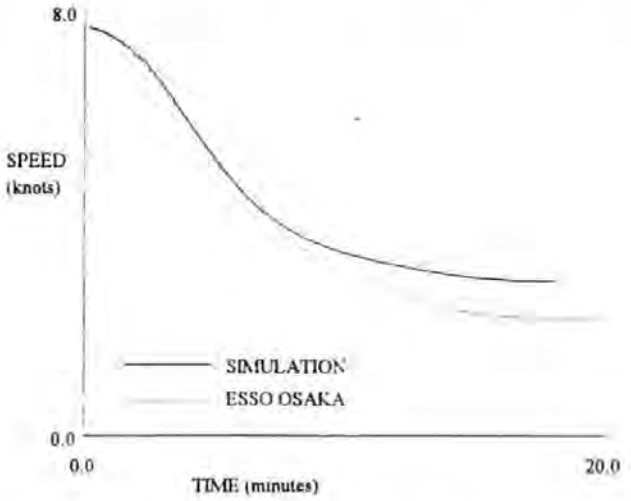

Figure 3. Reduction in Speed During a 35° Port Turn. Approach Speed 7.7 knots.

Modelling of the Hazard Vessel in the ACAS

For the ACAS to work it may be reasonably assumed that the hazard vessel will conform with the 'rules of the road'. Any attempt to model the hazard vessel's likely avoidance manoeuvres would be purely speculative, and should not form the basis for the action on the part of the own-ship. However, it is necessary to attempt to predict the hazard vessels manoeuvring characteristics. When, and indeed if, it becomes possible to recognise a vessel by using an Automatic Radar Plotting Aid (ARPA) then, and only then, will it become possible to model the hazard vessel accurately.

One solution is to have a range of simple linear ship models and for the mariner to select, from experience, the vessel type. This method has not been adopted as a long computation time will be involved in multi-hazard simulations, as the system works on a look-ahead basis simulating a number of manoeuvres until the least cost manoeuvre is found. The method adopted is to use a recognised regression type formulae, as published by the US. Coastguard, (Barr et al 1981), to predict the hazard vessels manoeuvring performance. The only formulae used is to predict the tactical diameter, being;

$$D_T = \frac{D' \times 35 \times L}{\delta} \quad \text{.....(9)}$$

This method produces results that are accurate enough to be included in the look-ahead module of the ACAS. The following example shows the tactical diameter calculated for the Esso Osaka for a 35° turn;

Esso Osaka	L	325 m
	Δ	278000 dwt
	Δ@ trials	319400 dwt
Results	D_T calculated	894 m
	Modular model	900.2 m
	Actual	915 m

CONCLUSIONS

Ship models have been developed and validated, and incorporated into a collision avoidance system. An adaptable mathematical model has been presented that will allow the system to be 'portable' between vessels, without requiring expensive trials. The requirements of the specification is to be able to input the principal dimensions of the vessel and calculate the hydrodynamic coefficients for the model without sea trials, hence keeping initial cost down. The model presented allows for this in a wide range of vessel size. The adaptable model can be highlighted by the fact that it has been used in other parts of the INS, and has also been used for the purpose of training a neural network ship control system, Witt (1993).

NOMENCLATURE

A_o	Propeller disc area
cp	Tangential propeller velocity
D'	Non-dimensional tactical diameter
D_T	Tactical diameter
I_x	Moment of inertia about x axis
I_z	Moment of inertia about y axis
K	Hydrodynamic roll moment
L	Ship length between perpendiculars
m	Mass of ship
n	Propeller revolution rate
N	Hydrodynamic yaw moment
N_v, N_r etc.	Yaw hydrodynamic derivatives
p	Roll rate
R	Propeller radius
r	Yaw rate
T	Propeller thrust
t	Thrust deduction fraction
u	Forward velocity
up	Axial propeller velocity
v	Lateral velocity
v_a	Velocity of advance
v_s	Ship speed
v_x	Mean longitudinal velocity at x
ω_x	Wake fraction
X	Hydrodynamic surge force
x_h	Hub radius coefficient
Y	Hydrodynamic sway force
δ	Rudder angle

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Computer Methods in Marine and Offshore Engineering

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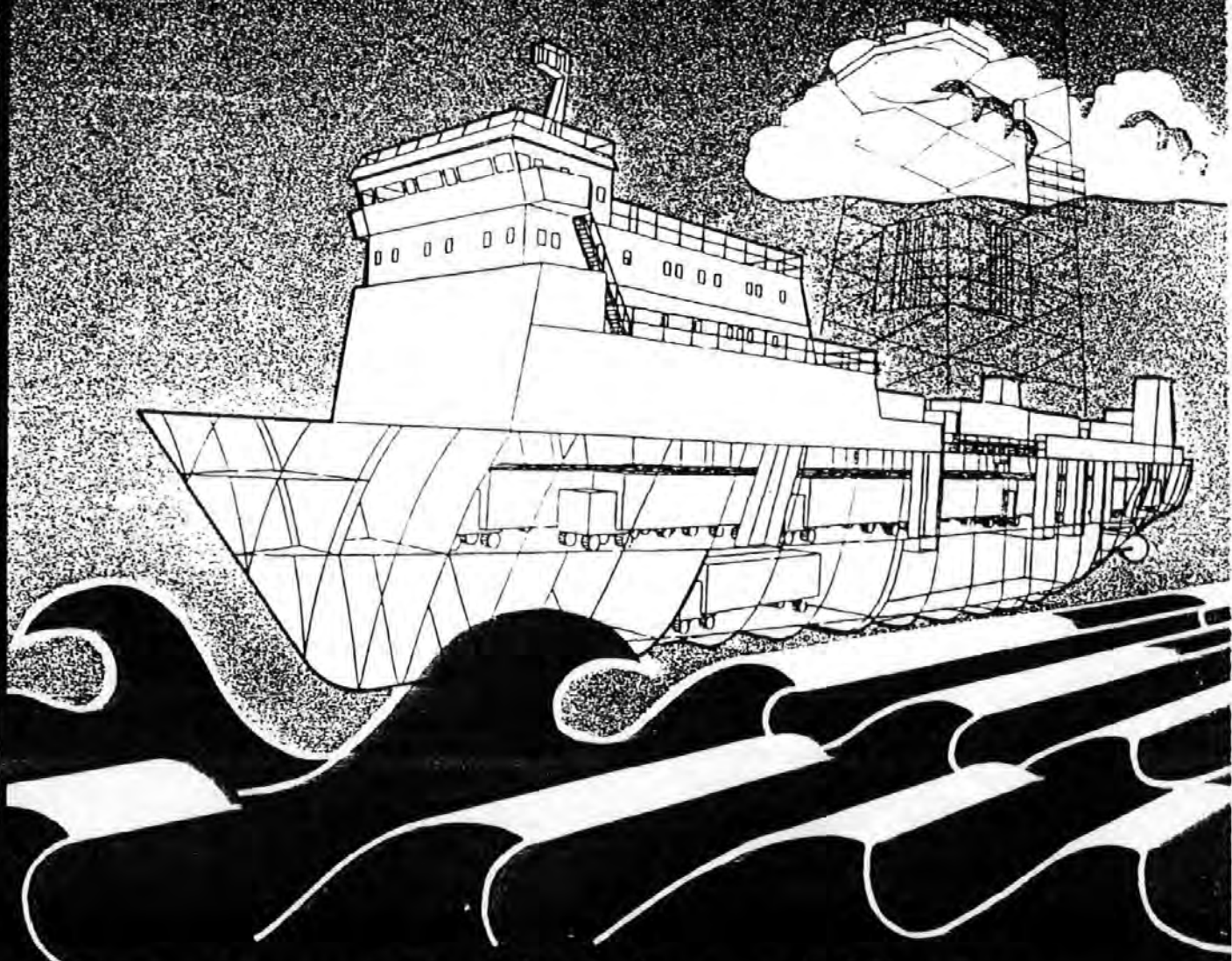

Computational Mechanics Publications

A Review of Mathematical Models used in Ship Manoeuvres

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ABSTRACT

The Ship Control Group at Polytechnic South West is developing, in conjunction with a UK marine electronics company and consultants, an Integrated Navigation System that will automatically steer the vessel along a predetermined track, avoiding any obstructions and taking the necessary precautions to avoid collision with another vessel. Central to the research programme is the development of simple, yet accurate, mathematical models of own ship and target ships. The paper describes the research into different types of model and concludes that a non-linear modular type could be used for 'own ship' and a simple linear model for the 'target ship'.

INTRODUCTION

Recent accidents at sea, together with a series of oil crises that have increased the price of fuel oil, have made ship owners and operators more safety and economy conscious; this in turn has made the requirements on ship steering more demanding, particularly in confined waters, where extensive manoeuvring is needed. It is therefore important to be able to predict the path of the ship precisely. It has been suggested [1] that 85% of all marine collisions and groundings are due to human error and of these 90% occur in coastal waters [2]. On this evidence alone there is a case for research and development into automating the control and guidance systems which are installed in ships. Mariners on a sea passage are likely to experience periods of relatively uneventful sailing, interspersed with periods requiring careful attention and substantial decision-making - such as traversing a busy seaway or

entering port. The potential hazards of such a regime are twofold: on the quiet stretches, a false sense of security can lead to impending danger being overlooked until it is too late; conversely, information input at busy times may overload the decision-making process (i.e. the Officer of the Watch), leading to ill-judged actions or dangerous delays in manoeuvring. Both of these problems could be obviated by an electronic monitoring system, which would analyse sensory inputs such as ARPA and navigational information, and give reasoned and pertinent advice to the mariner on the bridge. If such a system was available to advise the Officer of the Watch, perhaps disasters such as those involving the Exxon Valdiz and the Marchioness could be avoided.

Development of a production system for fully automated ship control probably lies well into the future. The technology exists, but there are other considerations governing the instrumentation installed on a vessel, such as cost and legislation which may pose constraints in the immediate future but may subsequently be relaxed. In connection with development towards automatic navigation, research at Polytechnic South West (formerly Plymouth Polytechnic) is underway, to maintain the vessel not only on course but also on track. To undertake this, more than just positional information is required by the autopilot. That is, in particular, velocity feedback in the two dimensions of surge and sway and rate of turn are necessary in order to stabilize the system. While such measurement devices are available they are rarely found in commercial shipping due to financial constraints. To overcome the problem of providing the appropriate measurements, the use of Kalman filtering techniques may be adopted. Research in this area has been underway for a number of years and Dove [3] has shown the concept of Kalman filtering as applied to marine navigation; combining state estimates from measurements with those from a mathematical model. This has further been investigated by Miller [4].

The overall aim of the work is to investigate, design and develop an integrated navigation and collision avoidance system to provide advice to the master of the vessel. This is a wide spectrum to cover and involves two full time research staff. A schematic diagram of the system is shown in figure 1.

The system will;

i) interface to the ship's navigational aids,
ii) perform the mathematical model computations,
iii) perform the filter computations,
iv) display an electronic chart showing ship status, desired track

and information on target vessels,

v) interface to the radar,

vi) run heuristics for collision avoidance (ACAS) [5],

vii) make modifications to the mathematical model if necessary,

viii) present track information.

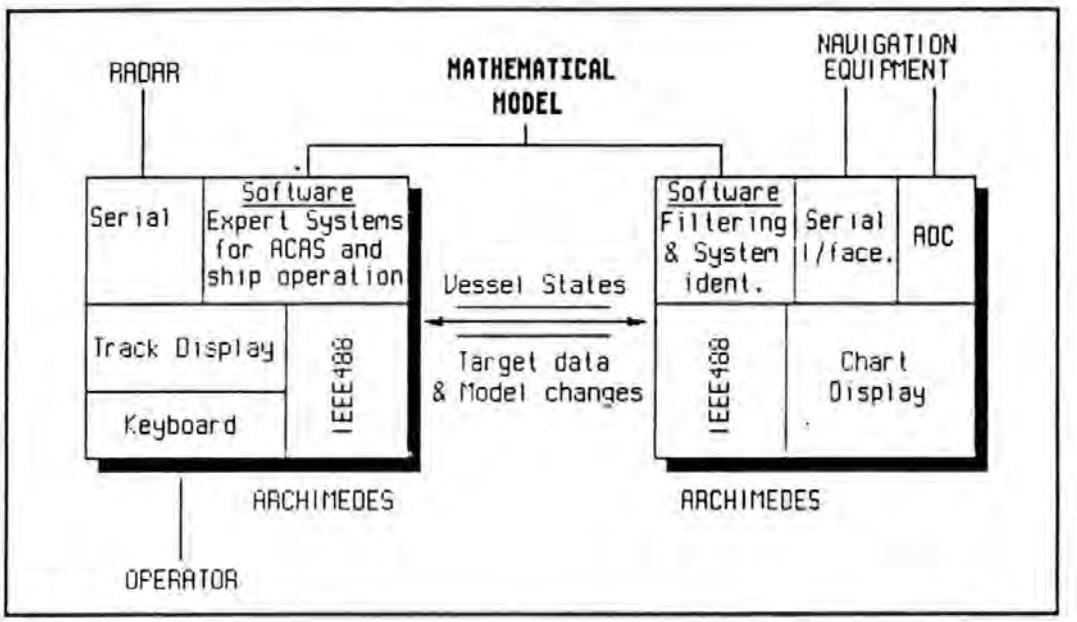

Figure 1. Prototype System Schematic showing that the central element is the mathematical model.

The project comprises of a team approach through the formation of the 'Ship Control Group' involving a wide range of disciplines including control and guidance, navigation, naval architecture, computing, artificial intelligence, mathematical modelling and signal processing. The prototype system will be fitted on board one of the Polytechnic's research vessels with the aim of having it operational within a period of two years.

MATHEMATICAL MODELLING AT POLYTECHNIC SOUTH WEST

Central to the overall system being developed is the mathematical model. Mathematical modelling has been undertaken by the Ship Control Group for a number of years, culminating in the modular manouevring model developed for use in a marine simulator by N.J. Tapp [6].

Between different research establishments there is little commonality of ship manouevring mathematical models and hydrodynamicists have over the years developed models of various forms and fidelity. The major reason for this is the complexity of the flow phenomena around the hull, propeller and rudder particularly on the subject of generation and losses of vorticity and surface waves [7]. The mathematical model designed for the system

must be capable of representing a wide range of ship types and configurations, machinery and propulsion/steering devices. The many different types of mathematical model can generally be placed under one of four headings, namely;

i) Input-Output relationship model,
ii) An holistic model,
iii) A force mathematical model,
iv) A modular manouevring model.

Recently a study has been undertaken as to the type and complexity of the required model for the proposed integrated navigation system. The two types looked at in detail are the holistic model and modular manouevring model.

The holistic model

This type of model is highly formal and systematic. It treats the hull-water interface as a black box and models the system as a complete entity. It is based on the premise that a manoeuvre is a small perturbation from an equilibrium state of steady forward motion at a nominal service speed. It has been used successfully for the simulation of ship manoeuvres by the application of rudder control by Strom-Tejsen [8] and in a modified form has been applied to engine manoeuvres by Crane [9] and Eda [10], despite the fact that such manoeuvres can hardly be described as small perturbations. Dand [11] describes this type of model as;

" A model which performs satisfactorily when taken as a whole, but does not allow individual elements to be changed readily as the design is changed."

The modular manoeuvring model

Current research on ship manoeuvring modelling tends to favour this type of model. The Mathematical Model Group (MMG) of the Society of Naval Architects of Japan, first published a paper describing a model of this type in 1978 [12]. This was subsequently followed by various papers on the subject [13-14], and a further refined model in 1984 to simulate various ship manoeuvring motions in harbour [15]. Research in Germany, by Oltmann and Sharma [16], is based on the modular concept, as is the modular manoeuvring model developed at British Marine Technology Ltd (BMT) between 1983 and 1984.

A modular manoeuvring model is one in which the individual elements, such as the hull, propeller, rudder, engines, and external influences, of a

manoeuvring ship are each represented as separate interactive modules. Each module, whether it relates to hydrodynamic or control forces or external effects is self-contained. The modules are constructed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and expressing their interaction by other physical expressions.

The equations of motion for a modular manoeuvring model are generally expressed by;

$$\begin{aligned} m\dot{u} - mrv &= X_H + X_P + X_R + X_E \\ m\dot{v} - mru &= Y_H + Y_P + Y_R + Y_E \\ I_z\dot{r} &= N_H + N_P + N_R + N_E \end{aligned} \qquad (1)$$

where the suffixes H, P, R and E denote components of hull, propeller, rudder and external forces.

The model arranged in this way lends itself to a number of applications. For example it allows research on one particular module and the effect that module has on the system model as a whole. This is invaluable when trying to determine the effect of various rudder areas on the manoeuvring performance of a vessel. Previously, a series of captive model tests had to be undertaken to select optimal rudder area. Advances in any particular field of related research can be incorporated into a module and into the system as a whole without having to alter other system modules. Other advantages of this approach are the expansion facilities it allows. In addition to the modules shown in equation set (1) extra modules can be employed, to simulate bow thrusters and stern thrusters for example. Hence the model can be tailored to suit a number of applications and such effects as ship to shore and ship to ship interaction can be investigated. Gradually a very sophisticated model incorporating all of the more specialised attributes can be developed.

MODEL FORMULATION AND SIMULATION

The study involved the simulation of a number of different vessels, however, to show the adaptability of the models the paper will show the simulation results for two completely different vessels;

i) 278000 dwt tonnage tanker,
ii) 2000 tonne converted dredger engaged in the European coastal trade.

The different models used in the study were;

i)	Linear holistic	-	3 degrees of freedom,
		-	4 degrees of freedom,
ii)	Non-linear holistic	-	3 degrees of freedom,
iii)	Modular	-	3 degrees of freedom.

A description of each model follows along with example plots. A comprehensive range of results can be found in ref [17].

Linear holistic - 3 degrees of freedom

A floating body can move in all six degrees of freedom of motion - translation along three orthogonal axes and rotation about each of the three axes - surge, sway, heave, roll, pitch and yaw. Although work has been carried out on six degree of freedom models [18], it is not usual for a vessel to be represented by all six equations. The equations describing ship motions in the horizontal plane, which typically covers the most practical needs of ship simulators, are a particular case of the general equations of the six degrees of freedom, and are therefore reduced to surge, sway and yaw. The equations are further simplified if the origin of the ship co-ordinate system is selected to coincide with the mass centre of the vessel. The 3 degree of freedom linear holistic model is of the simplest possible form derived from Abkowitz [19]. This type of model performed reasonably well when rudder movements were relatively small but when performing a complete turning circle the results were inaccurate. For exampla, the linear model generally has turning circle of approximately half that of the ship being modelled.

Linear holistic - 4 degrees of freedom

It was decided to expand the equations to include a fourth degree of freedom, namely roll [20]. Results are shown for the 2000 tonne converted dredger in figs 2-3.

The results obtained were not an improvement over the 3 degree of freedom model and it was decided at this stage not to use the 4 degrees in the modular model. The roll equation would be required if the navigation system was ever to be installed in a long thin warship or perhaps, on smaller craft where roll influences a turning manoeuvre.

Non-Linear Holistic Model

The Ship Control Group at Polytechnic South West has used this model in past research. The selection of the important non-linear terms were made by reviewing the work of Strom-Tejsen, Lewison [21], Gill [22-23] and Eda and Crane [24]. The non-linear functions of the control parameters

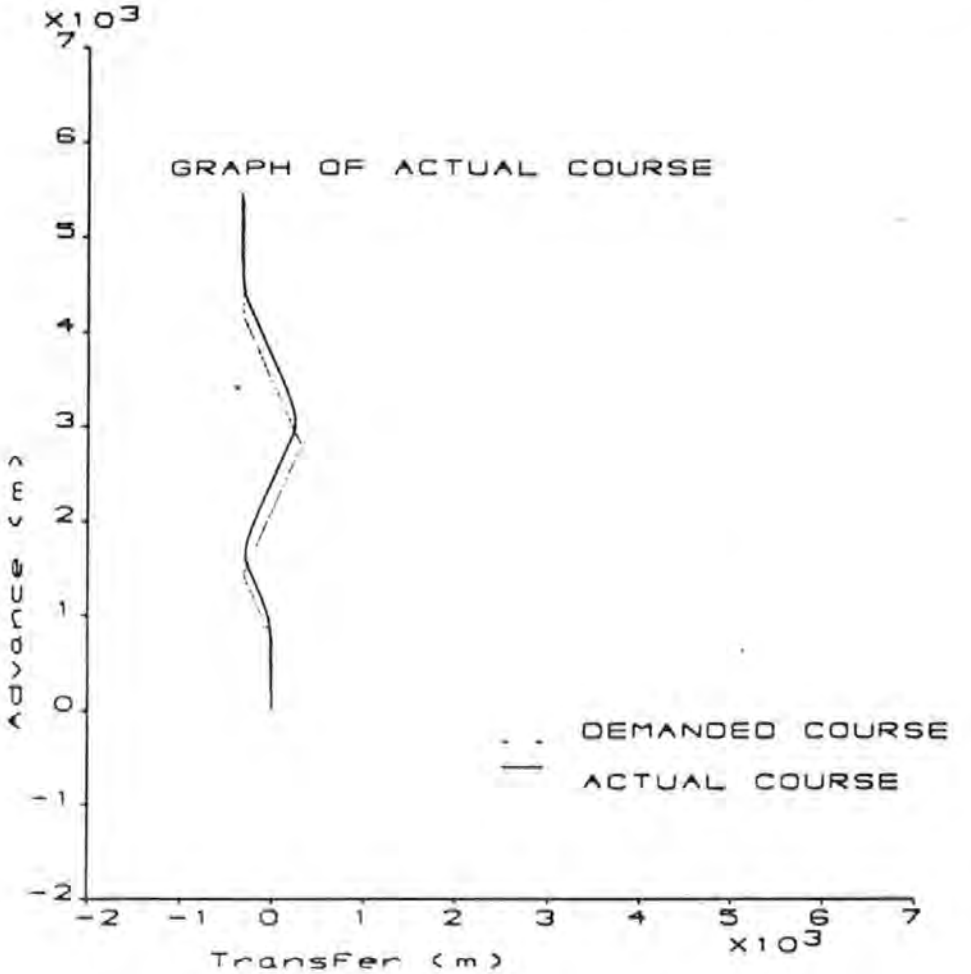

Fig 2. Linear 4 degree holistic model. Approach speed 5 m/s. Course 0 degrees. Deviation 20 degrees.

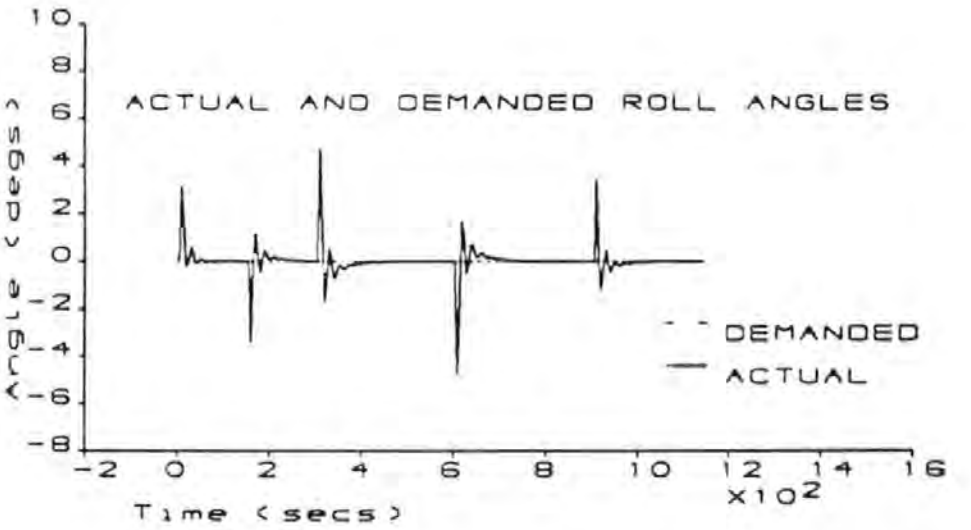

Fig 3. Roll Angle.

(rudder and propeller) were also required in the final non-linear equations of motion.

The complete set of the holistic model non-linear equations of motion as used by the Ship Control Group has been described in various papers [25-26] and has been shown to give accurate representation of the three degrees of ship motion in all manoeuvring situations. A comparative evaluation of the mathematical model was made with full scale measurements taken by Morse and Price for the USS Compass Island [27]. The USS Compass Island was constructed with a Mariner type hull form, and a complete set of hydrodynamic coefficients for this class of vessel, have been measured by Chislet and Strom-Tejsen [28] using the Planar Motion Mechanism Test.

Although this model gives accurate simulations of ship manoeuvring it does not allow rudder, propeller or hull geometry to be changed with ease; a major requirement of the system model is that it should be adaptable.

Modular Model

This model has the general form of equation set (1). Taking this equation set each of the modules can be looked at in turn.

Hull Forces and Moments The hull forces and moments module contains all the hydrodynamic data which is specific to the hull alone. They can be expressed by the following equations;

$$
\begin{aligned}
X_H &= X_{\dot{u}}\dot{u} + X_{vr}vr + X_{vv}v^2 + \frac{u}{|u|}X_{rr}r^2 + R_H \\
Y_H &= Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{uv}v + \frac{u}{|u|}Y_{ur}r + Y_{vvv}v^3 + Y_{rvv}rv^2 \qquad (2) \\
N_H &= N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_{ur}r + \frac{u}{|u|}N_{uv}v + N_{vvv}v^3 + N_{rvv}rv^2
\end{aligned}
$$

The equations are a further development of previous research work on the holistic type model with the important non-linear terms being similar to enable comparisons of the models to be made. The multiplier $\frac{u}{|u|}$ included in some of the terms is to correct the sign of the derivative during astern motion of the ship.

The term R_H in the surge equation of equation set (2) represents the ships resistance on a straight course and is modelled by the following expression;

$$R_H = X_u u + \frac{u}{|u|} X_{uu} u^2 + X_{uuu} u^3 \qquad (3)$$

Propeller Forces and Moments In order to model the motion of a ship for both ahead and astern motion it is important to determine correctly the propeller forces and moments. To cover all manoeuvring regimes, Tapp adopted the method of modelling the propeller forces and moments published by Oltmann and Mikelis [29]. This method is based on the knowledge of the thrust coefficient;

$$C_T^* = \frac{2\ T_p}{\rho\ A_0\ (up^2 + cp^2)} \qquad (4)$$

for the whole range of the advance angles ε for the propeller.

Propeller Forces and Moments for a Single Screw Ship

$$X_p = (1 - t_p)\ T_p$$

$$Y_p = Y_{nn} n^2 \qquad (5)$$

$$N_p = N_{nn} n^2 \qquad \text{where } N_{nn} = Y_{nn} L/2$$

assuming that the screw is located at a distance $L/2$ from the LCG.

Propeller Forces and Moments for a Twin Screw Ship Obviously the modelling of a twin screw ship is a more complex problem than a single screw. It is not the intention of this paper to present these equations as the results that will be shown are based on single screw vessels. Basically, the surge term is a summation of the effect of both propellers as is the yaw term. The sway term is dependent on a number of factors including rotation of propellers and their operating condition i.e. port propeller ahead and starboard propeller astern.

Rudder Forces and Moments In common with the propeller modelling it is important to calculate accurately the rudder control forces and moments in order to model correctly the turning and course keeping performance of the ship. From Hirano et al [30], using Tapp's adopted sign convention, the forces and moments induced on the ship due to rudder action are given by;

$$X_R = (1 - t_R)\ F_N \sin(\delta)$$

$$Y_R = -(1 + a_H)\ F_N \cos(\delta) \qquad (6)$$

$$N_R = (1 + a_H)\ F_N\ X_R \cos(\delta)$$

where;

F_N is the normal force produced by the rudder. a_H and t_R are correction factors to adapt the open-water characteristics of the rudder to behind-hull conditions. a_H can be determined from knowledge of the form factor of the hull, C_B. The value of t_R can be estimated from the reduction in forward speed of the ship when turning.

External Disturbance Forces and Moments A number of modules can be used to describe various external effects which, in keeping with the modular structure, are treated simply as additional forces and moments imposed on the basic hull hydrodynamics. The required complexity and operating conditions of the model determines the external force modules needed. These can include, for example, such effects as wind, tide, thrusters, bank effects, tugs, anchorage, ship to ship interaction, and squat. Tapp's model, for use in a marine simulator, had external forces and moments modules for wind and tide, the wind module being based on research by Isherwood [31].

Results of the Modular Model

Exxon International published a report in 1979 detailing the performance of a modern supertanker [32], describing full-scale trials of the 278000 dwt Esso Osaka. The modular model outlined was verified by using it to simulate the full scale results given in the report.

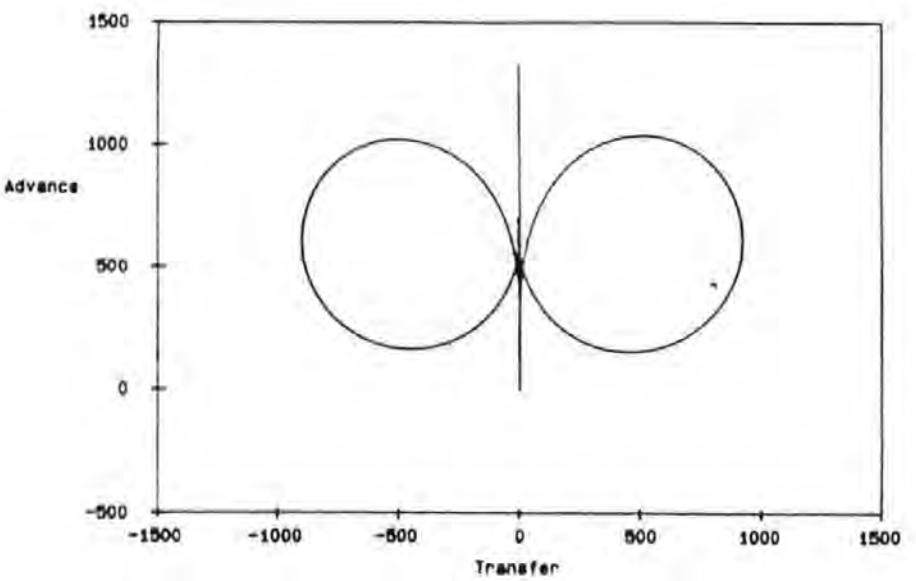

Fig 4. 35 degree turning circles and 0 degree course setting in deep water

The simulated results obtained were comparable with the full scale trials results. Simulations were carried out at varying depths and with wind and tide influences. It was noted that on some simulated turning circles and Kempf manoeuvres, the model tended to respond slowly to rudder alterations, particularly to rudder angle alterations. This aspect of the model performance is being investigated in the next phase of the research programme.

CONCLUSION

The ultimate aim of the research into modelling at Polytechnic South West is to develop an adaptable model that can be implemented into the navigation system onboard any vessel. The requirements of the specification is to be able to input the principal dimensions of the vessel and calculate the hydrodynamic coefficients for the model without sea trials, hence keeping initial cost down. Without doubt the model that is most practical and accurate is the modular type model. Its adaptability is shown by the allowance of a new propeller being fitted with a new pitch; by inputing the new dimensions manually through a keyboard, the propeller module would be re-calculated, altering the model without sea trials.

The majority of the hydrodynamic coefficients can be derived adequately by various analytical means. The surge terms can be found using a program adapted from the work by Holtrop et al [33]. The linear acceleration and velocity components for sway and yaw can be calculated using such formulae as that developed by Clarke [34]. The propeller and rudder modules can be found as outlined earlier. The problem coefficients are the third order hull terms, and investigations are in progress, to discover the relationship between their value and the principal dimensions of the vessel. These terms are at present evaluated from physical model tests or sea trials.

The investigation into the different levels of complexity of the model showed inaccuracies in the simple linear model. The navigation system will, however, require two levels of model for two distinctly separate tasks:

i) The more complex non-linear modular form is required to model the vessel in the navigation system.

ii) A simple linear form represents the target vessel in the ACAS element of the system. It is intended to include a number of models representing different vessel categories; on detecting a target vessel on the ARPA, the system will plan its own manoeuvre taking due account of the estimated manoeuvring capabilities of the target vessel.

A simplified protoype system is fitted onboard the Polytechnics' research vessel and encouraging results are being obtained. The model in use at present will need to be expanded to simulate;

i) slow speed operations of a vessel in the pilotage phase of a voyage,
ii) stopping in narrow channels,
iii) ship handling procedures in an emergency,
iv) anchoring procedures,
v) manoeuvring in shallow water,
vi) berthing,
vii) use of bow and stern thrusters.

This section of work is central to the overall research at the Polytechnic. It is intended to improve the model in use on the research vessel, so that the software can be tested under operational conditions. The complete integrated navigation system will ultimately be fitted in the vessel, displaying the required data on VDU's, thus creating a central navigation console.

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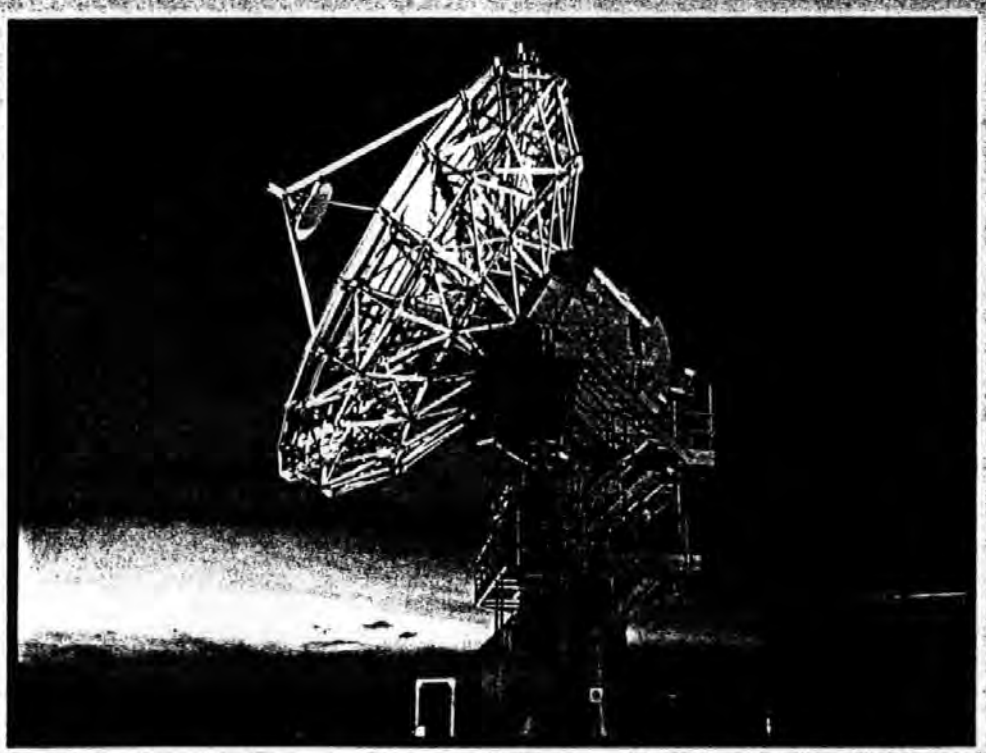

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Paper 7

The use of a mathematical model in a collision avoidance system

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SYNOPSIS

The work of the Ship Control Group at Polytechnic South West encompasses a number of research areas. The overall objective is an integrated navigation system, which will automatically steer a vessel along a predetermined track, dealing with hazards competently and in accordance with the regulations.[1] This has, to date, included substantial research on both ship models and automatic control and guidance systems.

The authors are concerned with the development of an on board intelligent knowledge-based system (IKBS) for marine collision avoidance, as part of an overall voyage management system. A purpose-built expert system shell and rule structure has been implemented in the context of a windows-icons-mouse-pointer system (WIMPS) environment on a multitasking microcomputer suitable for installation on board ship.

Sensory inputs from radar and associated instrumentation may be supplemented by data via the keyboard. Output is in the form of advisory messages and alarms where appropriate. An auto-control option facilitates computer controlled manoeuvring through encounter situations. Simulation runs in conjunction with a computerised track-keeping system, already in operation aboard the polytechnic research vessel, confirming the ability of the combined system to divert around potential hazards and then return the vessel onto track. Field trials are anticipated early in the new year, following the installation of the necessary instrumentation.

INTRODUCTION

Recent accidents at sea, together with a series of crises that have increased the price of fuel oil, have made shipowners and operators more safety and economy conscious; this in turn has made the requirements on ship control more demanding, particularly in confined waters, where extensive manoeuvring is needed. The ability to predict the path of the ship with a high degree of precision is clearly of major importance.

It has been suggested that 85% of all marine collisions and groundings are due to human error, and of these 90% occur in coastal waters.[2] On this evidence alone there is a case for research into, and development of, automated control and guidance systems. Mariners on a sea passage are likely to experience periods of relatively uneventful sailing, interspersed with periods requiring careful attention and substantial decision-making, such as traversing a busy seaway or entering port. The potential hazards of such a regime are twofold: on the quiet stretches a false sense of security can lead to impending danger being overlooked until it is too late; conversely, information input at busy times may overload the decision-making process (ie the officer of the watch), leading to ill-judged actions or dangerous delays in manoeuvring. Both of these problems could be obviated by an electronic monitoring system, which would analyse sensory inputs such as radar and navigational information, giving reasoned and pertinent advice to the mariner on the bridge. If such a system were available to advise the officer of the watch, perhaps disasters such as those involving the *Exxon Valdez* and the *Marchioness* could be avoided.

Grahame Blackwell gained a BTech degree in maths, statistics and computing, and a PGCE from Brunel University. He has since been engaged in a variety of computer applications, notably in the scientific and real-time fields. He later moved into education, and played an active part in the development of educational computing, and is now a senior lecturer in computing at Polytechnic South West. He is currently registered for a part-time PhD, the subject of which is 'an expert systems approach to collision avoidance'.

Whilst serving an apprenticeship with a marine engineering company, John Chudley gained an HNC in mechanical and production engineering. This was followed by a first class honours degree in nautical studies from Plymouth Polytechnic (now Polytechnic South West). He has since undertaken one year of full time research into mathematical modelling of ships and is now a lecturer at the Polytechnic.

Before becoming a lecturer, Dr M J Dove served 20 years as a navigator in the Merchant and Royal Navy. During this period he obtained an MSc in control technology. He recently gained a PhD for work in 'automatic control guidance'. This work led to the development of the Ship Control Group at Polytechnic South West. This group specialises in R&D in marine navigation and automatic guidance. Dr Dove is a member of RINA and was elected to a Fellowship of the Institute of Navigation for services to education development in navigation. He currently manages 400 undergraduates taking degrees in marine studies at the Polytechnic.

Much has been written about the fully automated unmanned ship, which may only feasibly be put into operation in the distant future. However, the Ship Control Group at Polytechnic South West have developed, and are improving, a system to assist the mariner. Dove,[3] investigated the use of Kalman filters for improvements to position fixing in the approaches to a port. In joint research with Dove, Burns,[4] has studied the guidance problem; the results from these twin projects form an optimal filter together with an optimal controller, thus breaking the optimal guidance problem down into two distinct phases. The system is now installed and operational aboard the Polytechnic survey vessel.[5] An expert system for collision avoidance, currently under development will be interfaced to the system at a later date.[6]

DEFINITION AND GENERAL FORM OF THE MATHEMATICAL MODEL

Mathematical models of ship dynamics may be broadly split into three categories, covering applications in:

1. ship manoeuvrability analysis:
   a. ship design;
   b. waterway improvement and port facilities;
   c. safety regulations and casualty studies.
2. training and research simulators;
3. shipboard manoeuvring predictors.

The research group in Plymouth is developing a shipboard manoeuvring predictor to provide assistance to the navigator in track control and path-keeping, and otherwise planning the trajectory of the vessel so as to minimise the likelihood of mishap.

Development of the model starts with a set of generalised equations to express the dynamics of a rigid body in a fluid medium, derived from Newton's second law of motion. These equations are then extended to model the complex hydrodynamic forces and moments experienced by a hull manoeuvring in response to the control inputs of rudder and propeller. By integrating through small time steps, the motions of the vessel can be solved. Further forces and moments are then introduced in response to the disturbance inputs of wind and tide.

A ship at sea has six degrees of freedom of motion: translation along three orthogonal axes and rotation about each of those axes. Three of these – heave, roll and pitch – may be ignored, since they make no contribution to motion in the horizontal plane (the area of concern for all practical purposes in ship manoeuvring predictors). By taking the ship's centre of mass as the origin for the co-ordinate system, the remaining three forms of motion may be represented by:

$$\begin{aligned} &\text{Surge:} && m(\dot{u} - vr) = X && \text{(forces generating surge)} \\ &\text{Sway:} && m(\dot{v} - ur) = Y && \text{(forces generating sway)} \\ &\text{Yaw:} && I_z\dot{r} = N && \text{(moments generating yaw)} \end{aligned} \quad (1)$$

The forces and moments on the left side of these equations represent the hydrodynamic and aerodynamic reactions on the hull of the ship in response to the applied control forces, in addition to any other disturbance inputs. The mathematical model for ship manoeuvring should cater for the following characteristics of ship dynamics:

1. realistic turning for all rudder angles including helm delay and loss of speed in the turn; the response to rudder action should be asymmetric for a single screw ship;
2. realistic acceleration and deceleration including inertial effects and engine delays;
3. ahead and astern motion;
4. reduction in ahead motion, effective helm and squat effect in shallow water;
5. drift caused by a variable tidal stream;
6. drift and yaw caused by a wind, variable in both magnitude and direction, acting on the hull and superstructure of the ship;
7. single or twin screw operation, including independent control of each screw in both directions, and turning rate;
8. variable pitch operation of the screw;
9. ship motion due to waves.

The ship model should also be amenable to alteration in order to simulate a wide range of hull forms and vessel sizes, ranging from a fishing boat to a supertanker.

Current research on ship manoeuvring modelling tends to favour the modular model, in which the individual elements such as the hull, propeller, rudder, engines and external influences on a manoeuvring ship, are each represented as separate interactive modules. Each self-contained module (relating to hydrodynamic or control forces, or to external effects) is constructed by reference to a detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements.

The equations of motion for a modular manoeuvring model are generally expressed in the form:

$$\begin{aligned} m\dot{u} - mrv &= X_H + X_P + X_R + X_E \\ m\dot{v} + mru &= Y_H + Y_P + Y_R + Y_E \\ I_z\dot{r} &= N_H + N_P + N_R + N_E \end{aligned} \quad (2)$$

where suffixes H, P, R and E denote components of hull, propeller, rudder and external forces respectively.

One advantage of this approach is its potential for expansion. Extra modules may be added to those above to simulate bow and stern thrusters, for example, represented in the equations by additional terms of the form X_B, X_S, Y_B, Y_S, N_B, N_S. Hence effects such as those referred to above may be investigated by 'customising' the model.

MATHEMATICAL MODELLING AT POLYTECHNIC SOUTH WEST

The hydrodynamic forces of a rigid body, with forward speed in free surface waves, present a difficult problem; accuracy of prediction of the motion depending significantly on the ability to determine these forces. The hydrodynamic coefficients required in the equations of motion of a body moving through a fluid, are usually classified into three general categories:

1. *Static*. Due to the components of linear velocities of the body relative to the fluid;
2. *Rotary*. Due to components of angular velocity;
3. *Acceleration*. Due to either linear or angular acceleration components (also termed 'added mass').

The number and type of hydrodynamic coefficients required will vary according to the complexity of the problem being investigated; the type of mathematical model; and the extent to which various effects are included in the representation. Research over a number of years at Polytechnic South West has culminated in a modular manoeuvring model developed by Tapp for use in a marine simulator;[7] the text includes an overview of the various methods for deriving the required coefficients for such a model, taking the form of equation (2).

SHIP MODELLING IN COLLISION AVOIDANCE

The nature and complexity of ship models incorporated in ollision avoidance systems depends primarily on whether one concerned with shore-based Vessel Traffic Control (VTC) or idge-based advisory systems. Research by the authors is dvancing on both fronts: the prototype ship-based IKBS escribed two years ago, has progressed substantially in vari- us respects and is the subject of most of the latter part of this aper[8]; and collaborative work with the University of Rome II yielding interesting developments in the field of parallel rocessing and shore-based marine traffic control.[9]

A shore-based advisory/control system requires a working nowledge of the performance characteristics of all vessels nder surveillance at any time, since the ability to give helpful rectives presupposes a capability to accurately predict the kely outcome of manoeuvres by one or more vessels. In eneral, those vessels will each fall into one of three categories:

1. known vessel, for which hydrodynamic coefficients are documented in detail, and for which an accurate model may be defined;
2. known or unknown vessel, for which hydrodynamic coefficients are not available, but which may be fitted into one of a number of 'classes' of ship, and thus matched approximately to a less tightly defined model;
3. unknown vessel for which little or no performance data is available (apart from immediate observation), and which must therefore be judged on a very broad basis, with a wide margin for error allowed around any assumptions which have to be made.

Such considerations lead naturally to the need for:

- a file of 'modelling' data for all vessels for which such data is available, and which frequent the waters under surveillance;
- a library of 'standard' vessel types, to which the majority of ships may be fitted with reasonable accuracy;
- a rule base which, in so far as is possible, avoids the need for suppositions about any ship not susceptible to handling by (1) or (2) – this may well mean preferential treatment for such vessels, on the basis of 'when in doubt, keep clear'.

Shore-based VTC, with its requirement for detailed model- g of a number of ships simultaneously, demands substantial mputing power to operate effectively in real-time; hence the 'erence to parallel processing. In most other respects the oblems of shore-based collision avoidance, and the function ship models therein, mirror those of bridge-based systems as nsidered further in the paper. Further references to this topic e to be found in Colajanni,[9] Degré,[10] and Bootsma and ldermann.[11]

The requirement for ship models in the shipboard Collision oidance System (CAS) is twofold: firstly, the expert system gic must be able to model ship behaviour in order to predict ely outcomes of manoeuvres; secondly, the development vironment for such a system for much of the time will consist a simulated environment in which own-ship and the various zard vessels are represented by appropriate computer mod-

In the latter case, all of the vessels may be represented as curately as current modelling techniques permit. There is no oblem of 'unknown identity', since vessels for the simulation ercise may be chosen from those for which full sets of drodynamic coefficients are available. The only hindrance is collection of a suitably representative cross-section of sample ship data. The gathering of hydrodynamic coefficients for a single ship is not a trivial task,[12] and few such sets are as yet readily available.[13] However, in the absence of specific data, parameters for a 'typical' ship of a specific type are adequate for such a task – as proposed above for 'standard vessel types'. The question of adequate computing power for such a task need not present a problem, since separate vessels may if necessary be simulated on separate processors – such a technique has been shown to have various benefits at certain stages of development.[14] Alternatively, a multitasking environment with substantial processing power (using one or more processors) yields comparable benefits; such a setup is described later in this paper. A less satisfactory solution is to run the simulation slower than real-time to circumvent processor limitations; such a technique could aid in early development, but may mask operational limitations of the system if relied upon too heavily.

Modelling of vessel behaviour, as an integral element of the expert system decision logic, falls into two very distinct categories: modelling of own-ship's response to applied controls and prevailing environment; and prediction of expected behaviour of a hazard vessel. There is no problem with the former, since installation of shipboard CAS presupposes prior evaluation of the hydrodynamic coefficients for the vessel in question. The latter, however, poses a very real pragmatic question: given that one cannot read (still less guide) the thoughts of the master of another vessel, what benefit may be derived from assessing the consequences if a specific control were applied at a specific time on that vessel? The situation is very different from shore-based VTC, where advice (or directives) may be communicated to any vessel, in the manner of air traffic control. At best, one may take into account the perceived manoeuvrability of the other vessel, and thus its ability to resolve a tricky situation; at worst, one has to admit the possibility of an adverse manoeuvre on his part. Until proven otherwise (by unreasonable procrastination or other 'rogue' action), it may be reasonably assumed that the other vessel will conform with the 'rules of the road'; but any attempt to model the other vessel's likely avoidance manoeuvres would be purely speculative, and should not form the basis for action on the part of own-ship.

Given the above caveats, the modelling of a hazard vessel has little part to play in the expert system logic, other than consideration of continuation on current course and speed. Turning action may be observed, and intent to avoid possibly inferred, but the extent of the manoeuvre may not be prejudged in detail. Manoeuvrability of the other vessel may be a factor for consideration in the decision logic for emergency situations – this has yet to be considered. Otherwise, any attempt to model the behaviour of another vessel, beyond constant velocity projection, is based on untested assumptions and therefore of dubious value. This is, of course, a separate issue from that of vessel manoeuvring restrictions and priorities as laid down in the anti-collision regulations, which should form an integral part of the decision structure.

THE COLLISION AVOIDANCE SYSTEM

An expert system comprises four major elements:

1. *The user interface*. Through which the user requests or provides information, and the expert system communicates its findings;
2. *The knowledge base*. Comprising all information to be considered in making decisions and formulating strategies;

3. *The rule structure*. That set of logical connectives by which the facts are assessed, and those decisions and strategies inferred;
4. *The inference engine*. The underlying abstract principles by which the rules are applied to the knowledge base, irrespective of the specific application (in this case, marine collision avoidance).

The functional demands of a marine CAS differ from those of more conventional expert systems in all of these respects. Considerations of the operating environment; the sensory nature of much of the input data; real-time processing of rules comparing vector relationships; a need to rationalise current decisions in terms of earlier events and anticipated future consequences, all call for specialist techniques not feasible in off-the-shelf packages. Basic requirements in these four areas, and continuing development in the Plymouth system, are outlined below.

The user interface

In computing circles much is made of the 'man-machine interface', and nowhere is it more important than in such a situation, where clear and rapid communication of meaningful information may avert potential disaster. Simple selection of available options should be matched by non-(computer-) technical presentation, without any need for the user to learn new skills. Input of relevant data may be facilitated by menu selection and 'dialogue boxes'.

A graphical representation of the current scenario is clearly a prerequisite; a well-planned display, invoking good use of colour and scale, allows the immediate situation to be taken in by a cursory glance, without excessive detail. Additional data considered relevant for optional selection comes in the form of:

1. a status report; giving present speed and bearing, details of any current manoeuvre, plus any pertinent data on nearby ships or other hazards (notably, projected time to collision or near-miss, if applicable);
2. an appraisal of the current situation, indicating advised course of action, with supporting rationale for such advice available on demand; in a real-time expert system, that rationale necessarily includes reference to prior and likely future events – a dimension absent from most IKBS.

These options are provided at the press of a button in a menu-drive WIMPS environment, with no requirement for keyboard dexterity or other new skills. Information is to hand exactly as and when needed, without confusion or complication – an important consideration for a facility likely to be most needed at times of greatest stress.

The screen display is in the form of three windows, as shown in Fig 1. The contents of these windows are in a broad sense as previously defined, and as described more fully in the 1988 paper.[8] Whilst there has been no reason to change the nature of the information displayed, substantial advances have been made in presentation and user control of that display: colour is used to good effect, notably to identify the tracks of different ships; scrolling and sizing of windows gives greater control over the information displayed; mouse-activated menus and dialogue boxes give instant access to a variety of features – an example of such a 'pop-up' menu is shown.

Figure 1 also shows a 'hazard control' window superimposed upon the expert system display. The development environment includes simulated hazard vessel(s) with optional manual control.

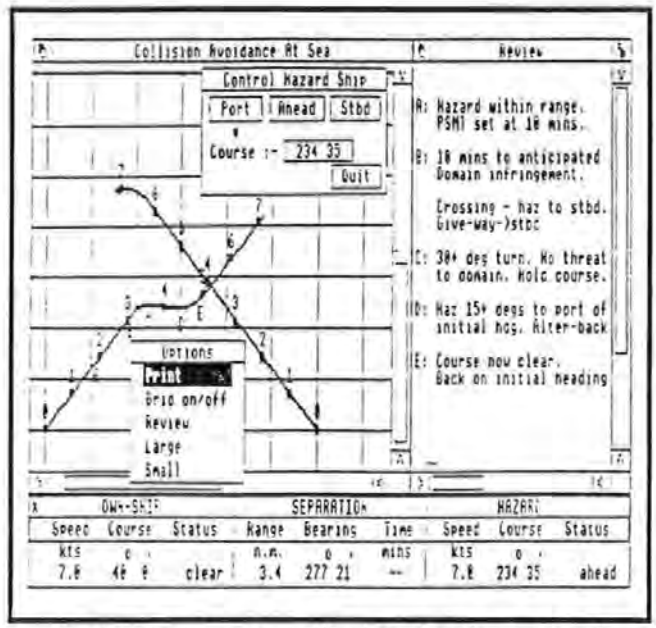


Fig 1: Example screen display, showing text and graphics windows, a pop-up option menu, and a dialogue box used to control a simulated hazard vessel

The knowledge base

Information relevant to the system comprises a combination of: static information, which relates to the vessel and any other relevant factors invariant over a voyage; and dynamic information which changes with time, such as heading, position, speed and data on potential hazards.

The former may be fixed parameters for the vessel (eg beam), or data for a particular voyage (eg gross tonnage); it could include relevant electronic chart data. The latter must be sampled at regular intervals, by sensors attached to engines, rudder etc, and interfaces to instrumentation such as Automatic Radar Plotting Aid (ARPA) and Decca. Secondary data on vector relationships must be calculated for reference by the rule base.

The expert system has been designed in a modular form to facilitate input from a variety of sources, as follows:

1. pop-up dialogue boxes are provided for keyboard input;
2. data from instrumentation is input via a parallel interface to a dedicated communications processor, linked to all sensor/control functions. Decca and ARPA are also accessed via this unit;
3. communication modules enable input from:
   a. other processors handling associated tasks, such as automatic track-keeping;
   b. other tasks running under the multitasking operating system on the same processor (notably for simulated test environment, described later in this paper);
   c. associated tasks running in multitasking mode on a shared-memory multiprocessor unit (a planned objective); data acquisition from electronic charts could also be handled by this technique, or by the front-end processor referred to in (b).

Parameters for the ship model constitute static data, whilst behaviour of the model at any time is determined with reference to current and predicted values of dynamic data. In particular circumstances such as shallow-water manoeuvring, alternative ship parameters will apply; a model which adapts dynamically to such conditions is a future aim.

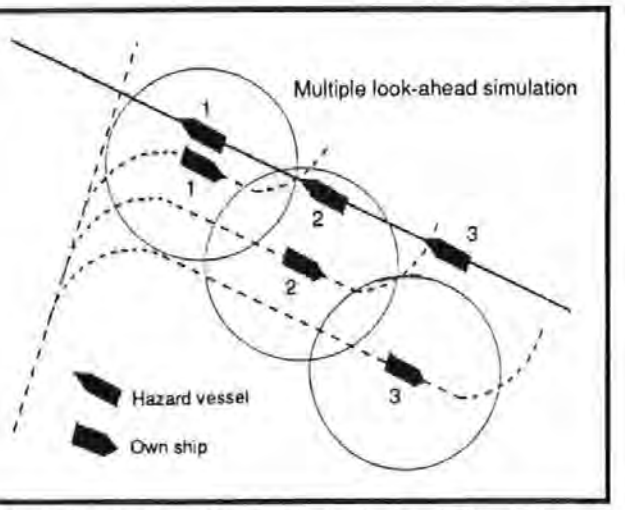
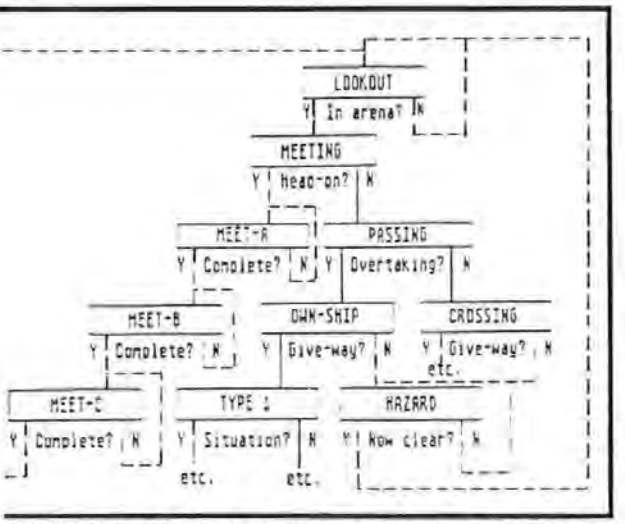


Fig 2: Illustration of multiple look-ahead simulation, showing consequences of starting manoeuvre 10, 12 and 14 min before anticipated domain infringement: in cases 1 and 2 (10 and 12 min respectively), the hazard vessel will still infringe the domain; in case 3, the hazard vessel will safely clear the domain – a PSMT of 14 min



g 3: Schematic of rule structure, showing immediate (solid) and deferred (dotted) links between rules

he knowledge base might also include information on other) types and behaviours, not so much for ship modelling as recognition purposes in implementing the regulations, eg ing vessels, vessels constrained by draught, etc. This is ly to need supplementing by manual input, as fully auto- ic vessel recognition is unlikely to be feasible in the near re. Manual identification, by selection from an option ıu, is envisaged initially for the present system once the rule : is extended to include such 'special cases'.

e rule structure

ıe ultimate objective of any collision avoidance procedure avoid collisions; a secondary objective is to inform other lners, through positive action, that the possibility of such an lent has been recognised and is being dealt with. Both these are served by manoeuvres which seek to maintain a zone lear water (generally termed the domain) around one's vessel. This observed practice of experienced mariners,[15] has been taken as the prime objective of the expert system. A broader area of concern, the arena, corresponds to the zone of proximity within which another vessel or object should be evaluated as a potential hazard, and appropriate avoidance action initiated if necessary.[16] Colley,[17] refined such considerations to a time-based criterion, the Range-to-Domain/Range-Rate (RDRR): this represents the expected time to domain infringement, calculated from current velocities. A ship's master applying a 12 min RDRR, for example (based on his experience of his vessel) would evaluate a potential encounter 12 min before domain infringement, and implement appropriate action at that time.

Results from an early version of the system, using the RDRR concept, indicate that such a fixed 'decision scheduler' is not appropriate to every encounter situation. A flexible time factor, matching decision time to interval needed for a safe manoeuvre, ensures adequate, but not excessive, manoeuvring time. This Predetermined Safe Manoeuvring Time (PSMT) is found by simulating any projected encounter well in advance for increasing RDRR values (starting from some fixed minimum, eg 10 min), until safe clearance is achieved. The simulation exercise is an integral element of the decision logic, corresponding to a human appraisal of whether or not a situation needs particularly early remedial action. Figure 2 shows the principle of the look-ahead simulation used within the expert system to select an appropriate RDRR, ie the PSMT, for any encounter. A fixed minimum RDRR is used rather than a free-floating Just In Time (JIT) strategy, since action must be taken in good time so as not to panic masters of other ships into emergency action. This look-ahead technique is currently being extended to evaluate various options in terms of an overall cost function of speed loss, time delay, fuel usage – subject to an overriding safety constraint.

The rule structure is designed to:

1. Note the presence of a potential hazard, assess the threat in terms of expected time to domain violation (if applicable) and derive the PSMT for avoidance action;
2. At PSMT: identify the type of encounter; fix the status of own-ship and perceived status of hazard ship (give-way or stand-on) at this time in the encounter; once decided, status is maintained throughout the encounter, unless circumstances change – the regulations rule out changes in status due solely to changes in relative positions through avoidance manoeuvres;
3. Negotiate the stages of the encounter, with appropriate safety margins; reactions to adverse action by hazard ship, including emergency manoeuvring, are currently being added to the rule base – hence the 'hazard control' test facility shown in Fig 1.

The structure is based on a binary tree, but with considerably more flexibility in nodal links to left and right sub-trees. Extension of the rule base is achieved by creating the relevant new nodes and resetting the necessary links to insert them at appropriate points in the structure. It is envisaged that a utility program will ultimately be provided to simplify this task.

Figure 3 shows a schematic of this structure, illustrating part of the initial rule base; dotted lines indicate deferred steps.

The inference engine

The inference engine operates on a discrete time-interval of 20s. At each step the inference engine will:

1. take dynamic information via communication channels from radar and own-ship sensors (or simulators). From

these parameters (speed, course, position) it will generate secondary data: relative bearing, relative velocity components, etc, for use in rule evaluation;
2. apply the appropriate rule to these data, to ascertain the new situation. Each rule involves a test on these system variables, and may entail evaluation of further functions of these variables; such functions form part of that rule.
3. trigger display and control/simulator outputs in response to any change in status; invoke any new rules indicated by such a change, until a 'defer' flag is reached, inhibiting any further action on the rule base until the next time-step.

A customised expert system shell, developed initially on an Atari ST microcomputer, has recently been transferred to an Acorn Archimedes Reduced Instruction Set Computer (RISC) system. Software development has been completely in the language C, for a number of reasons:

1. constraints of real-time processing dictate the need for optimum efficiency, in terms of speed, compatible with the complexities of program structure required for such a rule-based system;
2. many of the rules are expressed in terms of trigonometrical considerations, giving a substantial bias towards mathematical calculation, thus favouring a language which deals efficiently with such needs;
3. C is the native language of most WIMPS environments, providing access to facilities at all levels;
4. entities of various types; rules, ships, encounters (not to mention windows, icons etc within the WIMP system), may all be handled very effectively as 'structures' in C. Earlier intentions of using an object-oriented front-end to this system have been set aside, since this versatile C data type meets all perceived needs (particularly under the new ANSI standard) without the overheads of other, object-oriented or declarative languages.

Both computers were chosen on the basis of processing power at relatively low cost, good WIMPS and graphics facilities, and capability for a variety of input/output options, both digital and analog. A decision to transfer to the Acorn RISC machine was based on the need for compatibility with other ship management functions currently under development by the Ship Control Group at Plymouth, as well as its superiority on a number of fronts. The RISC_OS multitasking environment, coupled to versatile Input/Output handling, is well suited to a planned integrated system.

DEVELOPMENT ENVIRONMENT

The system is designed to operate in any of three modes, two being simulator trials, the third real data:

1. a semi-intelligent hazard vessel (guided by a simplified expert system, with manual option) and a dumb own-ship controlled by the current system, are both simulated as additional tasks under the multitasking RISC_OS, on the same computer as the expert system. Software communication channels between the tasks simulate radar data to and from hazard vessel, and sensor/control information between own-ship and expert system;
2. hazard and own-ship are simulated as above, but in separate computers from the expert system. Communications are via serial and parallel links respectively;
3. inputs via serial and parallel ports, as in (2), are from genuine ARPA and sensors aboard own-ship, ie a research vessel with the computer system on board. Control outputs are available for use with the automatic guidance system already in operation.

CONCLUSIONS

Thorough investigation and development of ship models has been incorporated into current development of a collision avoidance system. The ergonomics of the system have also benefitted from application of the latest Man-Machine Interface (MMI) techniques. The introduction into the decision logic of a look-ahead simulation module has resolved the question of a safe manoeuvring time, and paved the way for identification of optimal manoeuvres. Not least, the evolution of a totally modular structure provides for simple modification or extension of any aspect of the system: ship model(s); rules; communications and control; and user options.

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Discussion on papers 6 and 7

E Chapman (Marine Information Ltd) As the move towards the single-man bridge is now inevitable (and is already being practised in a growing number of vessels), would Capt Hunt explain what criteria needs to be set to ensure safe operation worldwide, with a single watchkeeper 24h per day.

It must be noted that shipboard overall safe manning levels are already set by criteria such as vessel size, trading area, level of automation, engine size/type, vessel design, layout etc.

Capt N W Hunt (The Nautical Institute) It is impossible to define criteria that will cover all situations 24h per day worldwide.

However, after considering the following items carefully, the master of a suitable ship may decide that the circumstances are safe for one man bridge operation:

1. traffic situation in the area ahead;
2. navigation situation ahead;
3. the weather forecast, in particular the visibility;
4. the status of the bridge equipment;
5. the status of the main engines and auxiliaries;
6. the status of the internal communications;
7. the availability of a lookout if required;
8. any other relevant fact or information.

The master must completely re-assess the situation at intervals, not exceeding, say, eight hours, recording his findings in the deck log book on each occasion.

G Lang (The Nautical Institute) Does Mr Blackwell envisage the auto-collision system acting and controlling one's own ship automatically?

G K Blackwell (Polytechnic South West) Technically, this is totally feasible. Our research vessel has been fitted with automatic controls and successfully piloted along a fixed course by a computer controlled autopilot. It would not be difficult to interface the collision avoidance system with this autopilot – indeed, this is planned for sea trials in the future.

However, two factors should be borne in mind regarding the commercial exploitation of such a facility. One is the possible consumer resistance of mariners to handing over control to such a system. The other is the need for exhaustive field testing of such a system in an advisory capacity before it is itself given control capability – and then only with fail safe manual override facilities.

I am not keen to make extravagant claims for this system, and there is much yet to be done even on the advisory version; but increased automation is inevitable, and this system could well have a part to play in that.

Capt J L Fear (INMARSAT) With fully manned ships there are opportunities to train inexperienced seamen, engineers and officers. With one man on the bridge and on minimally manned ships there are no opportunities for training; all watchkeepers must be experienced. How does Capt Hunt envisage experience being obtained if most ships are minimally manned?

Capt N W Hunt (The Nautical Institute) Deck and engineer officers can gain valuable experience from simulators. Some large oil companies are sending their deck officers and masters on ship simulator courses at intervals of about five years. Masters and chief officers can also gain valuable experience from manned model ship handling courses.

Most ratings are now 'general purpose'. They require adequate shore based training in their traditional skills as well as more specialised mechanical skills. I agree that there is much less opportunity to train at sea, but the skills required have also changed.

G S Penrose [MOD (PE)] Capt Hunt has presented an interesting paper, providing a succinct and balanced view of the main considerations on bridge manning.

I note, however, that the final paragraph of the paper states '...the Royal Navy has been using single man bridges for some time...'. This statement is incorrect. In RN ships there are always at least two men on the bridge at any time; this includes submarines when surfaced and underway. Minehunter/sweepers and small vessels will have an officer of the watch as well as a quartermaster and/or bosun's mate. Frigates will probably have an officer of the watch, second officer of the watch, signalman, quartermaster and bosun's mate.

PROCEEDINGS

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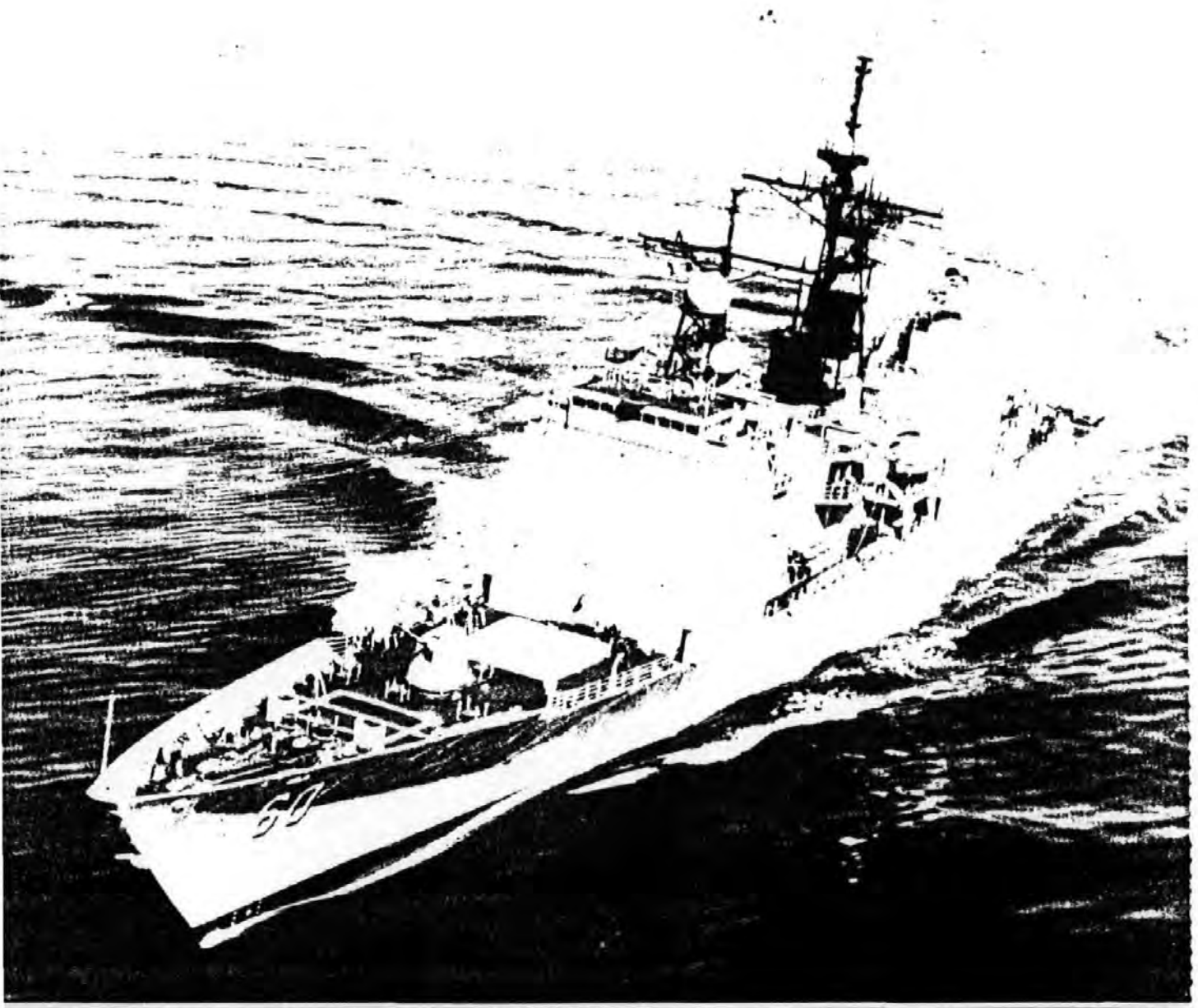

THE USE OF A MATHEMATICAL MODEL IN A TRACK GUIDANCE SYSTEM.

by Keith M Miller, Michael J Dove
and John Chudley.
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1. ABSTRACT

This paper describes part of an ongoing research program in automatic navigation and track guidance. In particular it looks at efforts to improve the accuracy of the mathematical model used in an integrated stystem which is to be used for navigation, guidance and collision avoidance. The paper commences with a brief description of the mathematical model and the state space equations developed from it. There then follows a description of the Kalman-Bucy filter being developed for use in a marine navigation system, together with the problems of accurately modelling a vessel in changing circumstances, when these circumstances affect the hydrodynamic coefficients upon which the model is based. It is then suggested that the accuracy of the model and indeed the inputs to it, which must be the same as the inputs to the actual system, are paramount to the use of filtering techniques in marine navigation. To overcome the problems of updating the model under operational conditions system identification techniques are introduced. This is achieved by augmenting the state vector by including sway and yaw coefficients derived from the hydrodynamic coefficients. This, in turn, involves extending the matix which represents the ship, but simplification methods are then introduced to reduce the computation times in the micro-processor based system used in the trials vessel. The paper goes on to explain the complete navigation and track guidance system, and concludes by discussing some of the results obtained, particularly where the technique has resulted in improvements in navigational accuracy.

2. INTRODUCTION

Chudley et al [1] formulate a mathmatical model and outline an application in marine simulation. Similiar models can be used to improve navigation of a vessel at sea, or perhaps

more importantly, while operating in confined waters; if this leads to improved accuracy of navigation it increases the safety margins of shipping using narrow channels and port approaches. Research at Polytechnic South West has been concerned with integration of navigation data with mathematical models using Kalman filtering techniques, a technique which is already established in the aerospace industries, and in some specialised maritime applications such as dynamic positioning systems, where navigational accuracy requirements dictate the need for precise measurements. For the average merchant vessel however, carrying typically less accurate systems giving a position fix with a random error of between 100 metres and 1 kilometre, forward speed through the water with a random error of 0.1 knots, and a heading to the nearest degree, improvements to navigation accuracy through integration are not so readily available, and may not be necessary. Work by Kalman and Bucy [2] targeted at the aerospace industry, showed how independant estimates of the state of a system can be combined to give the most probable, or minimum variance, estimate. This terminology implies a statistical inference, indeed the process assumes that random errors within the measurement systems are Gaussian and the standard deviations known. Dove [3] demonstrates the application of Kalman filtering to marine navigation, combining state estimates from measurements with those from a mathematical model. Trials conducted in simulation show promising results. In this work, however the model used to represent the vessel is also used within the filter. Any deviation between the two, or inclusion of an external forcing function, may lead the optimal estimate to stray from the true value. This suspicion was confirmed by tests conducted using data collected on board a vessel in the Solent (UK) [4]. Later studies directed towards overcoming these difficulties have included afloat trials in the Polytechnic's catamaran and current work involves the use of a 2000 tonne vessel engaged in the European coastal trade. The ship model which forms an integral part of the Kalman filter, and hence a part of the overall track guidance system, is formulated in three degrees of freedom. Central to the goodness of the model is the derivation of a set of coefficients which describe the motion of the vessel under consideration.

3. THE MATHEMATICAL MODEL

The model used in this investigation is based upon a Eulerian set of equations of motion. The forces and moments are derived in the usual way, as originally given by Abkowitz [5], with a modular approach as presented by Tapp [6] for use in marine simulation. Forces and moments are decomposed into contributions associated with the system elements, for example hull, propeller, rudder and disturbance terms. X and Y are the forces of surge and sway and N is the yaw moment, x, y and ψ are the corresponding displacements of the vessel and u, v and r are their derivatives. The rudder angle is denoted by δ, the propeller revolutions by n and the vessel moves on a grid (x_o, y_o) defined on the earth's surface, where x_o is the direction of true North, giving a reference from which heading (ψ) is measured.

In order to model the behavior of the hull it was first necessary to evaluate the derivatives used in the equations of motion. These hull constants are termed hydrodynamic coefficients and are usually obtained by conducting controlled tests on a scale model in a towing tank. Full-scale trials can be performed, but satisfactory control of the trials is difficult due to unknown forces such as wind, tide and current acting on the vessel and these results are more frequently used to validate the coefficients obtained from model tests. There are also some theoretical methods available for coefficient evaluation. Korvin-Kroukovsky [7] developed a method whereby the vessel's length is divided into strips; each strip is then treated as a buoyant cylinder of equal area, a form which has been well researched and coefficients established. Integration along the length of the vessel then gives some of the coefficients, originally those in heave, pitch and roll. The technique has been extended by Clarke [8] to include sway and yaw. This method is widely used by those concerned with ship handling, an application in which operators are not concerned with cycle time of the program, whereas one of the constraints of filtering is that the model must run in real time with a rapid update rate. This is particularly critical as the filtering theory used to date assumes that the system is linear between sampling intervals. Clarke [8] has evaluated sway and yaw coefficients for a number of vessels using towing tank and rotating arm test data and then, by regression analysis, produced formulae for evaluation of the linear coefficients directly from vessel dimensions of length, beam, displacement and block coefficient.

4. THE STATE EQUATIONS

Addition of first order differential equations to represent the steering gear and main propulsion, followed by rearrangement of equations of motion such that u, v and r are expressed in their canonical form, yields equation set (1). $X_1 \ldots X_8$, $Y_1 \ldots Y_8$, and $N_1 \ldots N_8$ are derived from the vessel's hydrodynamic coefficients.

$$\begin{bmatrix} \dot{\delta}_A \\ \dot{n}_A \\ \dot{x} \\ \dot{u} \\ \dot{y} \\ \dot{v} \\ \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_R} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_n} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ X_1 & X_2 & 0 & X_4 & 0 & X_6 & 0 & X_8 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ Y_1 & 0 & 0 & Y_4 & 0 & Y_6 & 0 & Y_8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ N_1 & 0 & 0 & N_4 & 0 & N_6 & 0 & N_8 \end{bmatrix} \begin{bmatrix} \delta_A \\ n_A \\ x \\ u \\ y \\ v \\ \psi \\ r \end{bmatrix} + \begin{bmatrix} -\frac{1}{T_R} & 0 \\ 0 & -\frac{1}{T_n} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_o \\ n_o \end{bmatrix} \qquad (1)$$

The eight first order differential equations are used to define the ship and can be can be written in matrx form as

$$\dot{\mathbf{x}}(t) = \mathbf{F}(t)\mathbf{x}(t) + \mathbf{G}(t)\mathbf{u}(t) \tag{2}$$

where **F** is the continuous time system matrix representing the ship. When tide, wind and current have to be considered it is convenient to partition the forcing matrix **G** into the control and disturbance forcing functions $\mathbf{G}_c$ and $\mathbf{G}_b$, giving

$$\dot{\mathbf{x}}(t) = \mathbf{F}(t)\mathbf{x}(t) + \mathbf{G}_c(t)\mathbf{u}(t) + \mathbf{G}_b(t)\mathbf{w}(t) \tag{3}$$

where **x(t)** is the state vector, **u(t)** is the control vector, and **w(t)** is the vector of disturbances. Integration of equation (3) yields the corresponding discrete solution

$$\mathbf{x}(k+1) = \mathbf{A}(k,k+1)\mathbf{x}(k) + \mathbf{B}(k,k+1)\mathbf{u}(k) + \mathbf{C}(k,k+1)\mathbf{w}(k) \tag{4}$$

where the matrices **A**, **B** and **C** can be obtained from:

$$\begin{aligned} \mathbf{A}(k,k+1) &= e^{\mathbf{F}(t)T} \\ \mathbf{B}(k,k+1) &= (e^{\mathbf{F}(t)T} - I)\mathbf{F}(t)^{-1}\mathbf{G}_c(t) \\ \mathbf{C}(k,k+1) &= (e^{\mathbf{F}(t)T} - I)\mathbf{F}(t)^{-1}\mathbf{G}_b(t) \end{aligned} \tag{5}$$

5. A FILTER FOR MARINE NAVIGATION AND GUIDANCE

While the vessel's position is of primary importance for marine navigation, the state of the vessel is likely to be passed to a control algorithm for track keeping. Further requirements thus comprise accurate heading to maintain course, and velocity information for feedback, or damping, of the control loop. The system process for the vessel described in equation (1) is tailored to suit these additional requirements. The system is not driven by white noise but by a deterministic control vector and noisy disturbances. Control is assumed to be stable and disturbances are taken as Gaussian processes with a non zero mean.

The theory of the Kalman-Bucy filter is well established and the equations used in the research described in this paper are given by Miller [10]. The filter used in the marine navigation problem is an extended Kalman filter. That is the non-linear system process is linearized about the most recent optimal estimate, while the measurement process is linear and the errors are Gaussian. As a ship constitutes a non-linear system, when parameters

such as large alterations of course and/or speed, shallow water effects, and trim are considered there must be some limitation to the technique. The linearization process assumes constant course and speed during each sample period. This is reasonable provided sample times are small when compared with such factors as ship time constants and time between waypoints. A block diagram of the filter is shown in figure 1. The filter quations are used recursively to obtain the state estimate at a future sampling.

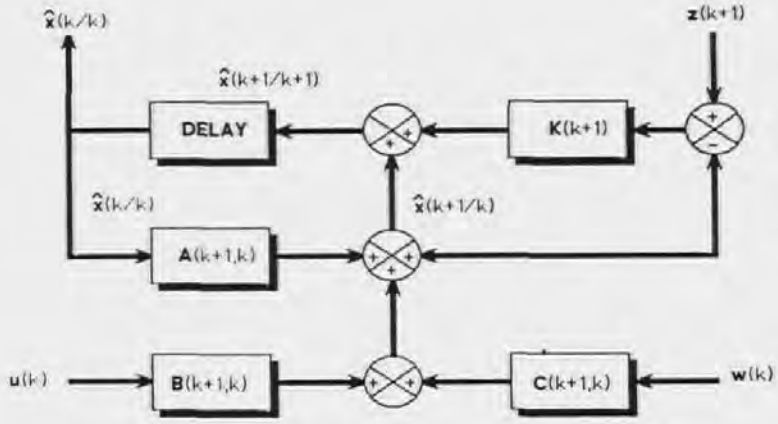

Figure 1. Block Diagram of the Optimal Filter.

Improvements can be made to the speed of the filter algorithm by considering the manner in which the equations are used. Figure 2 shows an iterative loop which commences each cycle by taking a measurement, initiates the covariance to the identity, then computes the Kalman gain and its error covariance. The iterations are used to obtain convergence of the filter. An improvement on this technique can be made by changing the order of these operations. In practice the system error covariance and Kalman gain can be computed prior to performing the measurement process. During this time the computer may well be idling, while awaiting the signal to initiate the measurement cycle, so a saving may be made in computer time. Furthermore, by computing the initial error covariance less iterations may be required.

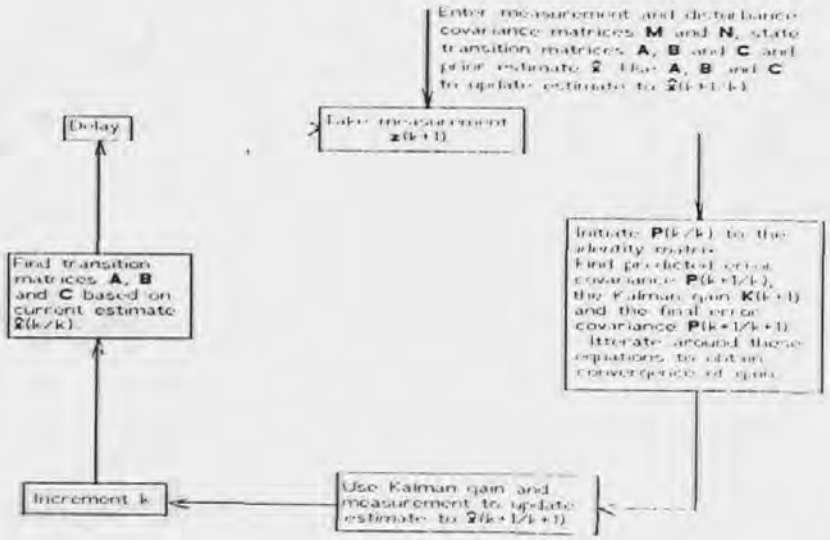

Figure 2. The Kalman Filter Loop

6. SYSTEM IDENTIFICATION

Much has been written of the difficulties of obtaining an accurate mathematical model of a ship. Experience has shown however that a good mathematical model is required in a maritime optimal track guidance system, and the accuracy of the filter is still further improved if it acquires both control and disturbance inputs, even though the disturbance inputs may only be estimate of the true values. There is the additional problem of changing hydrodynamic coefficients as circumstances change. For example, as the underwater surface of the hull is fouled with growth, when the vesel enters shallow water after an oceanic passage, or when the velocity is changed. This means that the X, Y, and N values in the system matrix will require updating. This may be difficult during routine commercial operations. It certainly would do little to enhance the sale of a filter based integrated navigation system if the potential owner were informed that the vessel would have to be periodically taken out of service to update the model. Established techniques for parameter identification, based upon various optimization criteria, would require new algorithms to be included into the Kalman filter recursive loop. These methods are usually time consuming and consequently are unsuitable for real-time applications. However Gelb [11]

proposes a method which can be easily implemented into the existing Kalman filter loop. This method has been applied to the track guidance system under development, optimizing parameters on the minimum variance estimation algorithms already in use.

6.1 Augmenting the State Vector

Let the unknown parameters be denoted by a vector **a**, having dynamics defined by the differential equation:

$$\dot{\mathbf{a}} = \mathbf{0} \tag{6}$$

with non-linear equations of motion, the system process can now be written:

$$\dot{\mathbf{x}} = \mathbf{f}(\hat{\mathbf{x}},\mathbf{a}) + \mathbf{Gu} \tag{7}$$

where both **a** and $\hat{\mathbf{x}}$ are to be estimated from the noisy measurement data. Combining **x** and **a** into a composite state vector denoted $\mathbf{x}^*$ such that:

$$\dot{\mathbf{x}}^* = \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{a}} \end{bmatrix} = \begin{bmatrix} \mathbf{f}(\mathbf{a},\hat{\mathbf{x}}) + \mathbf{Gu} \\ \mathbf{0} \end{bmatrix} \tag{8}$$

and applying this system process to the extended Kalman filter routine yields estimates for both states and unknown parameters.

6.2 The Modelling Process

Selecting the vector **a** to contain hydrodynamic coefficients for the vessel gives a large dimension augmented state vector and a large transition matrix. This formulation would then lead to cumbersome computations, defeating one of the prime objectives of this research. Furthermore, due to cross coupling, some coefficients cannot be isolated and are therefore unidentifiable. An alternative method was suggested by Robbins [12] who applied this method of parameter identification to aircraft, but used simplified mathematical models. To perform the identification process the system process was reduced to smaller components and controlled manoeuvres were performed. Then, assuming certain cross-coupling terms to be negligible under the control applied, for example when applying rudder to the aircraft surge and sway terms only are considered and the induced roll is neglected, a small number of parameters can be identified from each manoeuvre.

It is not economically viable to attempt to identify slowly varying parameters while on a voyage as the vessel may be delayed at great expense during identification manoeuvres. Furthermore, in order to keep the dimensions of the augmented state vector to minimum, maintain identifiability of parameters and to retain sparse population of the transition matrix it is necessary to identify the components of the latter directly. Initially only sway and yaw terms are considered, as these use the least accurate coefficients and were seen to give poorer results than the surge term. The augmented state vector can be written as:

$$\mathbf{x}^* = [\ \delta,\ n,\ x,\ u,\ y,\ v,\ \psi,\ r,\ Y_1,\ Y_4,\ Y_6,\ Y_8,\ N_1,\ N_4,\ N_6,\ N_8\ ]' \tag{9}$$

where the augmented parameters are shown in equation (1). These constants are dependent on the vessel states, and hence, assuming a slow transition time of the vessel in comparison to cycle time of the Kalman recursive loop, the parameters to be identified may be taken as having dynamics given by equation (6). The state transition matrix $\mathbf{F}^*$ is now of dimension 16 x 16, as shown in equation (10).

$$\mathbf{F}^* = \left[\begin{array}{cccccccccccccccc}
\frac{T_r}{T_m} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{T_m} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_1 & X_2 & 0 & X_4 & 0 & X_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hat{Y}_1 & 0 & 0 & \hat{Y}_4 & 0 & \hat{Y}_6 & 0 & \hat{Y}_8 & \hat{\delta} & \hat{u} & \hat{v} & \hat{r} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hat{N}_1 & 0 & 0 & \hat{N}_4 & 0 & \hat{N}_6 & 0 & \hat{N}_8 & 0 & 0 & 0 & 0 & \hat{\delta} & \hat{u} & \hat{v} & \hat{r} \\
\multicolumn{8}{c}{\mathbf{0}_8} & \multicolumn{8}{c}{\mathbf{0}_8}
\end{array}\right] \tag{10}$$

where $\mathbf{0}_8$ is the zero matrix of dimensions 8 x 8.

Writing this as a partitioned matrix of 4 sub matrices, each of 8x8 dimension.

$$\mathbf{F}^* = \left[\begin{array}{c|c} \mathbf{F} & \mathbf{E} \\ \hline \mathbf{0} & \mathbf{0} \end{array}\right] \tag{11}$$

The original 8 states of the system process are still described by equation (1). The discrete transition matrix is then given in partitioned form by:

$$\mathbf{A}^* = \left[\begin{array}{c|c} \mathbf{A} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{I}_8 \end{array}\right] \tag{12}$$

where $\mathbf{I}_8$ is the identity matrix of order 8, and $\mathbf{A}$ is the discrete solution to $\mathbf{F}$.

6.3 The Measurement Process

The original eight states of the measurement vector can be obtained as before but the augmented states are not measured. Y_1, Y_4, Y_6, Y_8, N_1, N_4, N_6 and N_8 can be obtained from the previous optimal estimates. The revious set of values for the sway and yaw coefficients are used in an iterative manner to obtain new values as given in equation set (13a). Solutions for the equations should be iterated to obtain convergence.

$$Y_1 = \frac{-Y_4 u - Y_6 v - Y_8 r}{\delta}$$

$$Y_4 = \frac{-Y_1 \delta - Y_6 v - Y_8 r}{u}$$

$$Y_6 = \frac{-Y_1 \delta - Y_4 u - Y_8 r}{v}$$

$$Y_8 = \frac{-Y_1 \delta - Y_4 u - Y_6 v}{r}$$

$$N_1 = \frac{-N_4 u - N_6 v - N_8 r}{\delta} \tag{13a}$$

$$N_4 = \frac{-N_1 \delta - N_6 v - N_8 r}{u}$$

$$N_6 = \frac{-N_1 \delta - N_4 u - N_8 r}{v}$$

$$N_8 = \frac{-N_1 \delta - N_4 u - N_6 v}{r}$$

The measurement matrix can thus be written

$$\mathbf{h} = \left[\begin{array}{c|cccccccc} \mathbf{X} & & & & \mathbf{0} & & & & \\ \hline & 0 & -\frac{u}{\delta}\gamma_4 & -\frac{v}{\delta}\gamma_4 & -\frac{r}{\delta}\gamma_4 & 0 & 0 & 0 & 0 \\ & -\frac{\delta}{u}\gamma_1 & 0 & -\frac{v}{u}\gamma_4 & -\frac{r}{u}\gamma_4 & 0 & 0 & 0 & 0 \\ & -\frac{\delta}{v}\gamma_1 & -\frac{u}{v}\gamma_4 & 0 & -\frac{r}{v}\gamma_4 & 0 & 0 & 0 & 0 \\ & -\frac{\delta}{r}\gamma_1 & -\frac{u}{r}\gamma_4 & -\frac{v}{r}\gamma_4 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{0} & 0 & 0 & 0 & 0 & 0 & \frac{u}{\delta}\Pi_4 & \frac{v}{\delta}\Pi_4 & \frac{r}{\delta}\Pi_4 \\ & 0 & 0 & 0 & 0 & \frac{\delta}{u}\Pi_4 & 0 & \frac{v}{u}\Pi_4 & \frac{r}{u}\Pi_4 \\ & 0 & 0 & 0 & 0 & \frac{\delta}{v}\Pi_4 & \frac{u}{v}\Pi_4 & 0 & \frac{r}{v}\Pi_4 \\ & 0 & 0 & 0 & 0 & -\frac{\delta}{r}\Pi_4 & -\frac{u}{r}\Pi_4 & -\frac{v}{r}\Pi_4 & 0 \end{array}\right] \qquad (13a)$$

where **X** is an 8 x 8 diagonal matrix with diagonal elements equal to the corresponding elements of the state vector. Then for the computation of the Kalman filter gain

$$\mathbf{H} = \left.\frac{\partial \mathbf{h}}{\partial \mathbf{x}^*}\right|_{\mathbf{x}^* = \hat{\mathbf{x}}^*}$$

6.4 Filtering

The filter must be modified to account for the additional terms included in the processes above. In order to estimate the prediction error covariance and hence the Kalman gain, $\mathbf{A}^*$ should incorporate the entire matrix $\mathbf{F}^*$:

$$\mathbf{A}^* = \left[\begin{array}{c|c} \mathbf{A} & \mathbf{D} \\ \hline \mathbf{0} & \mathbf{I}_8 \end{array}\right] \qquad (14)$$

The matrix **D** can then be obtained in a similar way to the discrete control and disturbance matrices and is then given by:

$$\mathbf{D} = (e^{\mathbf{F}(t)T} - \mathbf{i})\mathbf{F}(t)^{-1}\mathbf{E} \qquad (15)$$

The Kalman gain matrix, which now has dimensions 16 x 16, is computed as shown by Gelb [11].

7 CONTROL AND GUIDANCE

The theory of an optimal multi-variable control system has been developed to control simultaneously position and velocity of the vessel, and tested in simulation by Burns [13]. Deviation from the desired values were corrected by operation of the rudders and main engines. The cost function **(J)** is based upon the summation of the weighted errors over some time interval, perhaps over one stage of the voyage. In addition to minimise the errors in the output parameters, the optimal controller must also attempt to minimise the control effort, that is, to minimize rudder and main engine activity. The cost function is normally stated in the following quadratic terms:

$$\mathbf{J} = \int_{t_0}^{t_1} \{ (\mathbf{x}-\mathbf{r})\ \mathbf{Q}(\mathbf{x}-\mathbf{r}) + \mathbf{u}\ \mathbf{R}\mathbf{u} \}\, dt \qquad (16)$$

where **r** is the desired state vector and **Q** and **R** are usually diagonal matrices, with the values of the individual elements reflecting the importance of the parameters being controlled.

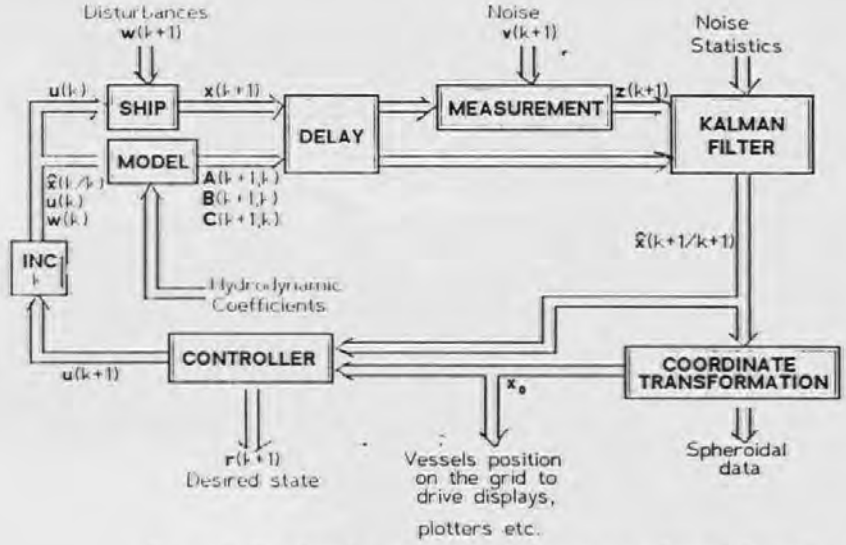

Figure 3. The Complete Integrated Navigation and Control System

An initial requirement of the controller is the desired state **r** at each sample time. This is obtained by entering a series of waypoints into the computer. In practice waypoint position is entered through the keyboard using either a cursor on the chart display driven by the arrow keys, or by typing in co-ordinates using the alpha-numeric keys. The program assumes that each pair of waypoints alternately define a straight line followed by a curve. Thus taking the first waypoint as the starting point, the second is the "wheel over" position at the start of the arc required to reach waypoint three. On reaching this point, the vessel is required to be on a steady course to waypoint four which is the next "wheel over" position and so on. With each waypoint either a speed for that leg of the passage or an estimated time of arrival is entered, so the desired state of the vessel can be computed at each sample time prior to starting the voyage. The overall integrated navigation system is shown as a block diagram in figure (3)

8. RESULTS AND CONCLUSIONS

Data sets used in earlier work were rerun using the filter algorithm with system identification. The overall track plot for a passage in to Plymouth showed a significant improvement. Part of a typical plot is shown in Figure (4), from which it can be seen that the filtered track follows closely the true position of the vessel. Figures 5 and 6 show the identified system coefficients. The rudder terms Y_r and N_r are seen to be noisy. These terms would be expected to reduce to zero when travelling in a straight line and increase during the use of rudders in a turn, which is seen to occur. Further noise is probably due to noisy rudder measurements. Y_v and N_v, the surge terms are close to zero. These terms influence the turning characteristics with speed and over the 6 to 7 knot speed range used during the trial have little influence.

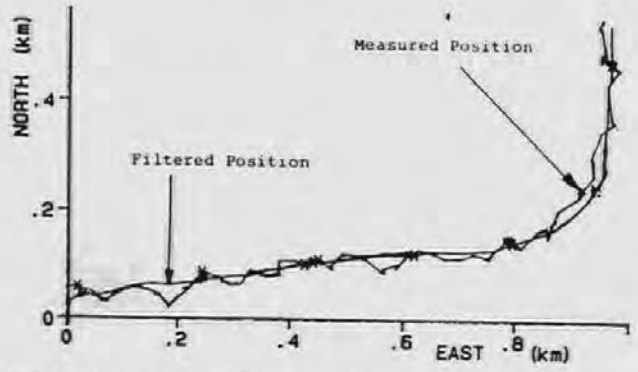

Figure 4. Comparison of Measured, Filtered and True Positions.

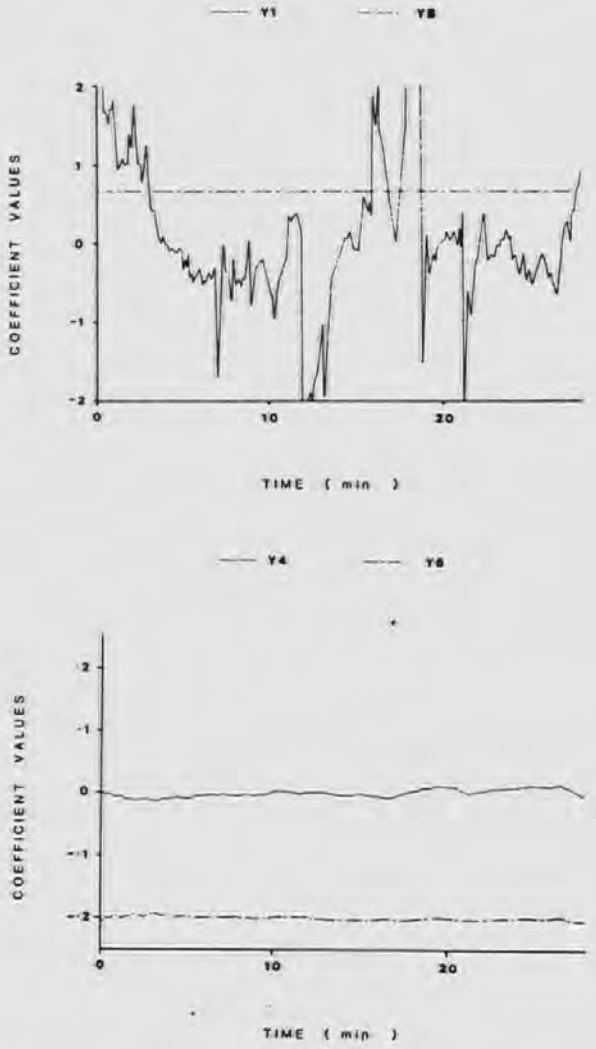

Figure 5. Sway System Coefficients.

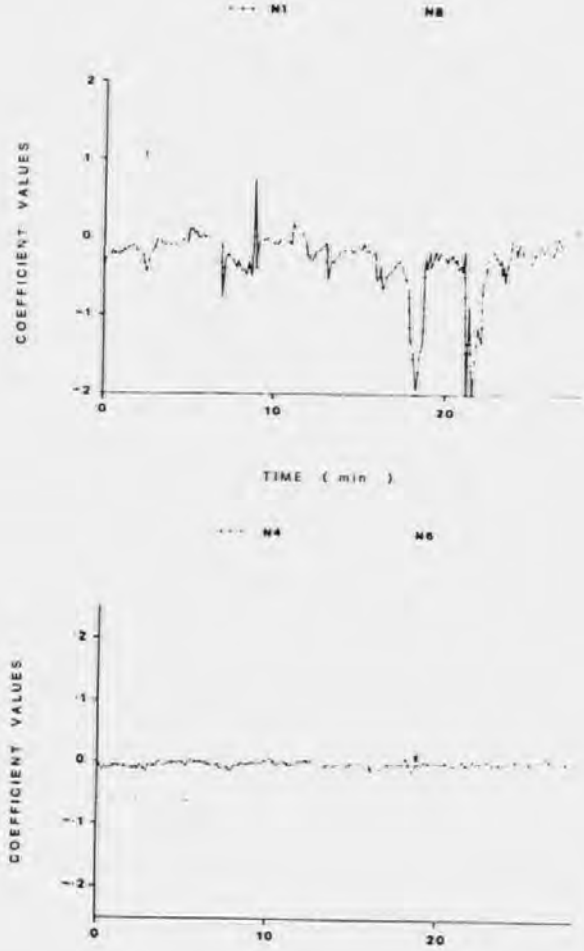

Figure 6 Yaw System Coefficients

A technique to overcome coefficient inaccuracies and variations by incorporating them in to the state vector has been introduced. Trials were undertaken for sway and yaw terms only as these were considered to be the most inaccurate and widely varying, but the method can also be applied to the surge terms. Trials to this end are now being undertaken. Resulting track plots of filtered position showed the vessel to remain within 20 metres of the demanded track. The filtering algorithm in use is intended to cope with random errors only, and fixed errors must be evaluated and either removed prior to filtering, or an allowance must be made for them. In this way the noise reduction achieved is a better assessment of performance. The ability of the system to maintain a position central to the noise of the position fixing system, in this case a Decca Navigator was used because it gave the best coverage of the approaches to Plymouth at the time the trials were undertaken, demonstrated that the filter was producing accurate outputs of displacement in the three degrees of freedom considered. It was shown previously [14] that inaccuracy in one, or all, of these outputs led to drift from true track. As values for velocity are fed back into the modelling process, any inaccuracy in their estimates leads to cumulative errors in the displacement outputs. The turn rate does however remain noisy and an improvement could be achieved by the use of a gyro input, which was not available in the test vessel. Finally the filtered output was fed to a control algorithm. Optimal control theory was used to establish the control parameters to maintain the vessel on track, in both along-track and cross-track directions.

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9th BIENNIAL SEMINAR ON

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A SURVEY OF AUTOMATIC NAVIGATION

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ABSTRACT

The paper commences with a very brief review of electronic navigation aids, and shows how the advent of larger less manoeuvrable VLCC's and faster container ships led to a requirement for more accurate position fixing and course keeping. It continues by tracing the development of integrated position fixing systems as being essential components of an automatic feedback system to guide the vessel safely from port to port.

The paper goes on to discuss the use of small powerful microcomputers in the integrated navigation and position fixing systems which started to appear in the early eighties. It will show the developments which have led to the use of real time computer programmes, with the digital computer at the heart of a sophsticated guidance system which controls the actions of propellers, thrusters and rudders to keep the vessel automatically on track, or on station at a fixed location.

The paper will conclude by giving examples of the use of automatic control and guidance systems in specialist ships such as Dynamic Positioning vessels used in the offshore industries.

Introduction.

The safe passage of a ship from port to port is the responsibility of the Master, who must use his skills and experience to ensure safe navigation. That none of these skills have been lost is shown in numerous feats of navigation which are frequently reported by the media. So why does the mariner need electronic navigation aids, integrated navigation systems, adaptive autipilots and other systems dependent upon the power of the microprocessor? Is there an argument for increased automation on the bridge? There are several factors which suggest that there is a requirement for moves in this direction, without completely eliminating the mariner from the command loop. This is the case in avionics, where the pilot retains ultimate control of his aircraft, even though automatic navigation and landing systems are being installed in the latest generation of airliners. It would be reasonable to suppose that the travelling public would wish this to continue, and the very existence of automatic systems on the flight deck allow the aircrew to undertake their tasks more efficiently.

Although modern land based marine electronic navigation systems are capable of fixing a vessels position to 50 metres at their best, coverage by many of these systems is restricted to small coastal areas outside of which accuracy is steadily reduced. Modern satellite navigation (Transit) can give a fix anywhere in the world to an accuracy of 100 metres, but satellite passes are infrequent, with up to four hours between fixes. The second generation satellite system (GPS) is gradually becoming available and will give complete coverage with high precision, but will this level of accuracy be made available to the commercial operator? The autopilots currently in use on ships simply maintain a vessel on course in the open sea. Whilst the technology is available to navigate an unmanned ship between ports, avoiding other vessels, with weather routeing and piloting, will the legislation be available to allow such developments, and is this what the operator and the public require?

Brief Survey of Marine Electronic Navigation Systems.

There is a Chinese legend that the Emporer Hoang Ti, who reigned about 4300 years ago, succeeded in persuing his enemy through a thick fog with the aid of a directional device. But Dr Joseph Nedham [1] suggests the earliest development of a compass in China, or anywhere else in the world, is no earlier than 1088 AD. The sextant and chronometer followed at much later dates, and these three were virtually the only instruments available to the mariner up to the turn of the century. After the development of wireless teleghraphy by Marconi and others it was soon realised that the early aerials used had directional properties and that this phenomenon could be used to obtain a bearing. There followed a period of much ingenious work by such pioneers as Marconi, Bellini and Tosi, and Round, to name but a few. The development of flight gave an

entirely new emphasis to the importance of navigation, and by 1914 radio direction finding systems, [2] , and the radio compass [3] were available. Air navigation between the two world wars was largely concentrated on developing radio beacons as the counterparts of marine buoys and lighthouses. This period and the rapid developments of radio navigation during World War 2 have been well documented by R V Jones [4] and many others.

The development of modern electronic navigation systems dates from the period 1939-1945. It was to meet the exacting demands of World War II, writes Fennessy [5], that a dramatic phase of development took place. This development was to form the basis of many of the systems in use today. The direct measurement of range using electromagnetic waves depends upon accurate measurement of the time taken taken for the radio signal to travel from transmitter to receiver. Prior to the development of frequency standards and atomic oscillators such measurement for a ship to shore system was impractical and hence the early systems tended to measure the difference in time of arrival of two radio signals, so that position fixes were related to hyperbolic position lines. The Loran system was an early example of such a system. Loran A was developed in the U.S.A. and was in use in World War II. In the United Kingdom naval scientists developed what was to become known as the Decca Navigator. Both Loran A and the Decca Navigator were in commercial use soon after the end of World War II. Since 1945 the use of electronic navigation aids has steadily increased; whilst in the period since 1970, with the appearance of minicomputers and microprocessors and the decreasing costs of electronic equipments, the growth has been more spectacular. In particular there has been a vast increase in the use of electronic navigation aids by small craft navigators .

There are two distinctly different satellite navigation systems available to the mariner. The first, known as Transit or NNSS (Navy Navigation Satellite System) was developed to the requirements of the US Navy and has been commercially available since 1967. Each satellite transmits at 150 and 400 MHz and the shipboard receiver measures Doppler shift to determine the relative velocity between satellite and receiver. Use is made of hyberbolic navigation and transferred position line principles to determine the ship's position so that only a single satellite is required for a fix. A single frequency receiver is adequate for most marine navigational purposes, but for highly accurate position fixing a dual frequency receiver is required. Such uses include hydrographic survey, land survey and the accurate positioning of off-shore platforms.

By 1975 a number of individual systems were thus available to the commercial operator. Each had its inherent advantages and disadvantages, so that no single system was completely satisfactory for navigation in all phases of a voyage. The Omega system, for example, provides world wide coverage, but is insufficiently accurate for inshore navigation. The Decca Navigator, or Decca Navigation System (DNS) as it is now being called, will provide accurate position data near the centre of a chain, but its accuracy

falls off with increasing range, due mainly to skywave interference. The Transit Satellite System is sufficiently accurate for survey work, provided a two frequency receiver is used, but the time between satellite passes makes it unsuitable for coastal navigation in most cases.

The 1980's have seen the development of the second satellite system, known as Navstar or Global Positioning System (GPS). The original specification was for the needs of the US Airforce because Transit is of little use for aircraft navigation. The advent of GPS may make all other position fixing systems redundant as it will give continuous 24 hour world wide cover with a high degree of accuracy. The advent of high accuracy crystal oscillators has enabled the system designers to produce a receiver which will give a direct measurement of range. Not all the satellites are yet in orbit and the development of the system was severely retarded by the American shuttle disaster. It might therefore be well into the 1990's before GPS is fully operational for commercial use. Public access will be provided by the Standard Precision Service (SPS) at a reduced accuracy of 100 metres for 95 per cent of fixes. The exclusively military system and the deliberately introduced degradation of accuracy will thus have some drawbacks. It is worth mentioning at this stage that the USSR Glonass satellite system will have approximately the same level of accuracy as GPS. Despite the global coverage and accuracy of GPS and Glonass, a number of European organisations see the need for alternative civilian satellite based navigation aids [6].

A typical fit in a merchant ship would now comprise a gyro compass with autopilot and repeater compasses, electromagnetic, pressure and/or Doppler log, Decca Navigation System or Loran C, together with Omega and/or Transit Satellite Navigation System. Increasingly there will be a demand for GPS, backed up by a standby system such as Loran C. This would give the navigator reasonable world wide coverage and sufficient accuracy for most of his needs. Radar, automatic radar plotting aid (ARPA) and direction finder would also be fitted. DNS and Loran yield comparable accuracies in the primary coverage areas. However, for coverage of a given area fewer Loran than Decca stations are required, giving lower operating costs for the latter. Unfortunately the basic accuracies of DNS, Loran and GPS are in many cases inadequate. A further point which needs emphasis, is that high risk transports require a degree of integrity which cannot be provided by any of these systems separately. Thus, even when GPS is fully operational, there will still be a need for alternatives.

The advent of GPS has led to a great deal of debate in Europe, and at least one conference, sponsored by the International Association of Lighthouse Authorities (IALA) in 1987, to discuss the need for a European back up system for GPS. One viewpoint being put forward is to extend the Loran coverage to those parts of European and Mediterranean waters not already covered, and to phase out the Decca chains. However there are a large number of small craft Decca users, including increasing numbers in the marine leisure industry. According to industry estimates, Dahl [7], some 100,000 DNS

receivers will be installed in leisure craft by 1990, with a further 30,000 Transit or Loran receivers, largely in the Mediterranean. It may thus be difficult to easily phase out any of these systems. Political, nationalistic and financial considerations will undoubtedly govern the final choice of an adequate back up system, rather than sound technological judgements.

Factors in the Development of Automatic Navigation.

The period 1945 to 1960 saw little change except that radars, electronic position fixing systems, and autopilots became more widely fitted in merchant vessels. There was also a move away from the towed log to electromagnetic and pressure logs. The 1960's saw the advent of twin radars, twin gyros, and dual channel steering systems, for obvious safety reasons, but there were no new concepts between 1945 and 1970.

By 1970 however it had become apparent that the advent of large VLCC's and fast container ships operating in increased traffic density, would require modern navigation systems. These demands, coupled with the dramatic achievements in the world of electronics, paved the way for the systems available today, but before dealing with them it is necessary to consider the requirements of the shipowner and the problems associated with the developments.

Ship owners and operators have, by the very nature of their business, been conservative. Tradition dies hard and there were none of the incentives which faced the aircraft industries in 1945. Ship design was stable, diesel engines were being widely fitted, equipment was largely satisfactory and efficient, and there were no spectacular disasters such as those which dogged the development of the world's first commercial jet airliner, the De Haviland Comet. Things remained that way for twenty years or more; perhaps this was a factor in the decline of European shipbuilding and ship operation, although it was by no means the major or only factor in this decline.

But by 1970 problems had started to arise. There was a widely held view that international shipping was not operated as safely as it might be, with the result that more accidents occurred than were acceptable. To the extent that even well found ships were <u>not</u> being equipped with the aids available to them, it could be argued they were being developed in advance of their demand. Furthermore advanced navigation aids were expensive, compared with the more traditional systems available, and there were no definable standards against which to measure improvements in safety. There were a variety of position fixing systems available, but none was completely acceptable,. Some of the reasons for this have already been mentioned in this paper. There were, and still are, difficulties in retaining high calibre trained staff at sea. There was, and still is, a decrease in job satisfaction. Furthermore the huge oil price increases in the early seventies were a major factor in increased operating costs, leading to a need for optimal operation of ships. Increasing traffic density, particularly in waters such as the Straits of

Singapore, increasing ship size and speed, leading to less manoeuvrability, were other contributory factors. Finally environmental factors started to emerge as early the as 1960's. For example the cost of clearing up the environment after the Torrey Canon [8] ran aground was in excess of the value of ship and cargo combined, and this accident saw a huge public outcry at the damage caused to wildlife and the UK coastline .

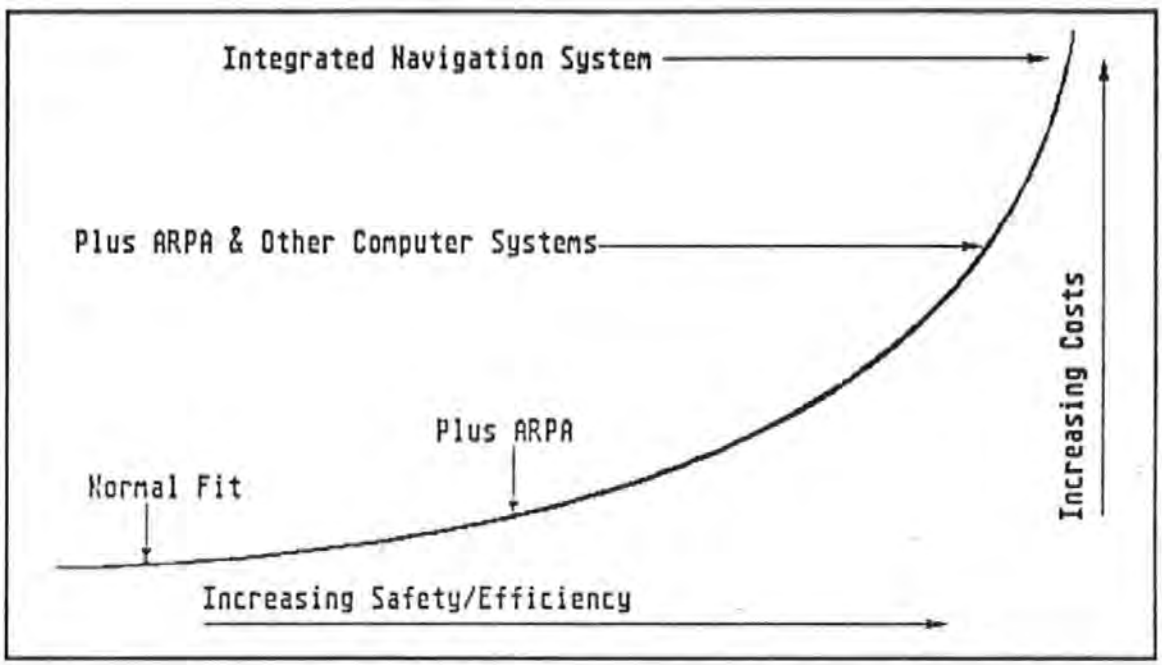

Figure 1. Costs of Navaids against benefits

Among other problems to be considered were the costs of development of a system, which must be set against the fact that the probability of a vessel completing a voyage is almost one [9] . Figure 1 is an early 1970's attempt to assess the costs of navigation aids against the improving benefits they might bring. Costs have dropped dramatically since then, but , for example, an early Transit satellite system would have cost in the order of 85,000 Singapore dollars for a dual frequency on board receiver. Any equipment developed has to be reliable, particularly in the hostile environmental conditions often encountered at sea, with shore maintenance and back-up facilities maybe over a thousand miles away. If the Automatic Radar Plotting Aid (ARPA) is unserviceable at a time when it is most needed, ie in the coastal phase of a passage, then there may be insufficient qualified personnel to provide good plotting at a crucial period in the passage, giving rise to the possibility of danger to ship and crew. Finally the automation process itself leads to further decreased job satisafaction for the highly trained personel who may wish to remain at sea.

However accidents do occur at sea. To quote just one statistic, Cockcroft [10] has

established that in the ten years between 1973 and 1982 0.084 per cent of trading ships were lost due to collisions. Marine accidents usually take the form of collisions or groundings and 90 per cent ot them occur in coastal waters. Such occurances have been reduced with the establishment of traffic separation zones, but it is not possible to establish these in all areas. Human error is almost invariably a factor, usually in the form of negligence, ignorance of the International Regulations for the Prevention of Collisions at Sea or improper use of equipment. It has been suggested [11] that 85 percent of marine groundings and collisions are due to human error, perhaps giving substance to the case for improvement of navigation and guidance systems for marine vehicles.

The problems which began to emerge in the 1970's may be divided into two distinct areas, namely the docking and anchoring of large displacement vessels, and the handling of large and fast vessels through restricted waters. An additional probem is associated with the emergence of oil and gas platforms and their siting in waters frequently used by trading vessels.

The docking problem was largely one of considering the ship's momentum. Limiting the momentum for a 250,000 tonne ship means the approach speed can only be ten percent of that for a 25,000 tonne ship. Put another way jetty damage was increasing with vessel size, and many port authorities were forced to employ permanent repair gangs for repair of jetties. The demand for decreased approach speed gave extra problems to Masters and Pilots. For example a normal person cannot sense a yaw rate of less than 0.005 degrees/second (3 degrees/minute). A major factor in solving this problem has been the development of Doppler Sonar and Radar devices, which are normally sited ashore. They measure the vessel's speed as she approaches the berth, after which the information is transmitted to the master and pilot. When the vessel is being manouevred into her berth the bow and stern speeds are measured, from which the operator can obtain the overall approach speed and yaw rate of the vessel.

One of the factors associated with the full speed problem was the emergence of too much data on the bridge, so that one man was increasingly unable to handle the increased information flow, whilst undertaking all the other duties required of the Officer of the Watch (OOW). For example he might have several sensors on the bridge, giving him heading (gyro compass), water speed (pressure log), ground speed (Doppler log), collision avoidance information (ARPA), navigational data (X band and S band radars), and positional information (Decca and Loran). The second factor also concerns the vessel's momentum. Large vessels at speed have large momentum and hence require long stopping distances and large diameter turning circles. This all requires more sea room at a time when the vessel's increased draft means the ship may have less space in which to manouevre.

The Use of Microprocessors on the Bridge.

Target plotting and tracking was very primitive in the 1950's and 1960's, and consisted mainly of the use of chinagraph pencils to mark a special reflection plotter, which is a detachable optical system, mounted on the front of the screen, and on which the position of other ships is plotted. With larger and faster ships came the demand that the OOW started plotting each target earlier; he was also required to plot more targets, a task which became increasingly difficult. All of this led to the development of Collision Avoidance Systems, (CAS), which were the first navigation aids to use micro computers and which led to the first integrated navigation systems in use at sea. These were later to be called Automatic Radar Plotting Aids. Essentially ARPA means interfacing the radar, or radars to a digital computer, which has software programs to solve the collision problem for a number of targets, and to present these solutions to the operator in a form, or forms, which can be easily and quickly interpreted. In order to calculate the true course and speed of each target then "own ship" speed and heading must also be inputs to the computer program. For collision avoidance speed through the water is required, because the international collision regulations require the give way' vessel TO ACT ON THE HEADING OF THE TARGET, AND NOT HER TRACK OVER THE GROUND. This entails the use of a pressure or electromagnetic log. However, if the software is to be used for navigation, then speed over the ground is required; this may be obtained from a 2 axis doppler log input to the computer. There are of course other methods available to find the ship's speed over the ground.

Once the computer was accepted as part of the bridge equipment, designers wished to use it for other navigational tasks. In the early 1970's the idea of interfacing navigation aids such as Decca and Loran were explored. With the advent of Transit further suggestions were made, and at least one developer produced an integrated system which not only integrated the navigational aids , but produced an output to control the steering through the autopilot, but the idea did not fully catch on with ship owners. Perhaps this was due to the conservatism referred to earlier. These concepts are illustrated in Figure 2.

While the completely integrated bridge system has not found favour in commercial trading vessels, single system deficiencies have led to the development of sytems in which the manufacturer has attempted to combine two or more receivers in to one equipment. For example Racal Marine Electronics have produced the MNS2000, which combines the Decca Navigator, Loran-C, Transit and Omega, while Sage and Luce [12] describe the use of a Kalman filter to combine Omega and Transit, or Omega and Loran. Many of these more sophisticated integrated navigation systems use techniques which have spun off from space navigation.

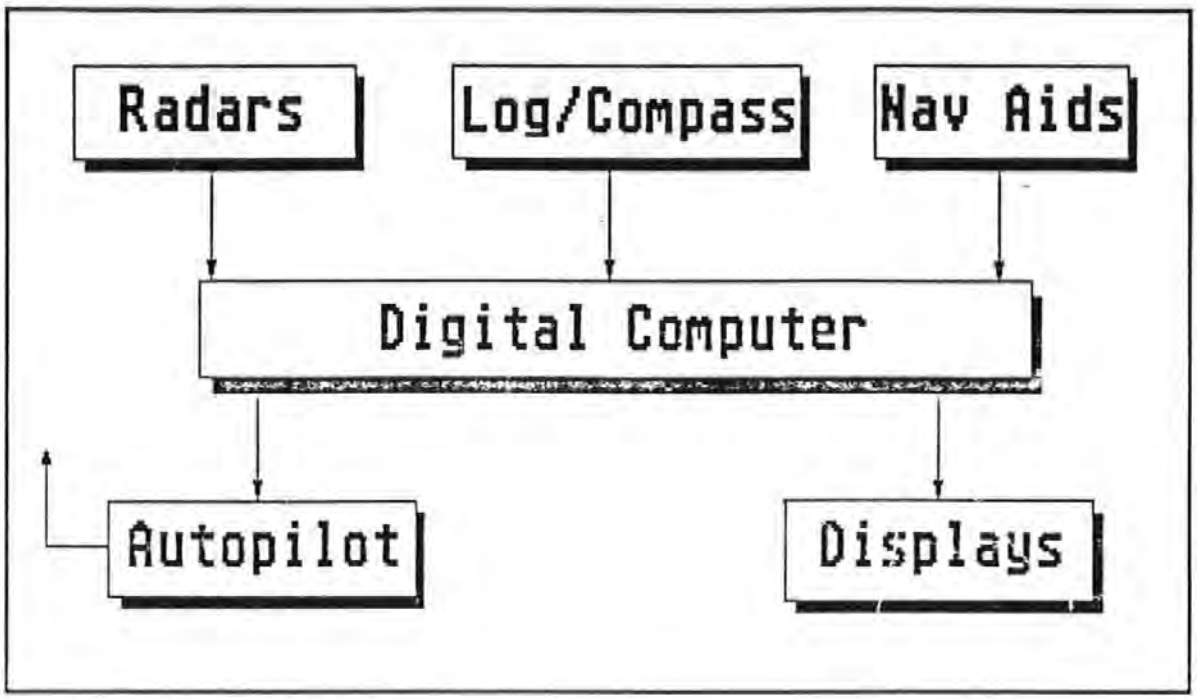

Figure 2. Automatic Navigation and Guidance

Integration of Navigational Data.

Returning now to the idea of integrated systems of which there are essentially two types, information systems and control systems [13]. A typical example of an integrated control system is that of a ship manoeuvring system for docking procedures. The integration of navigational data can be placed under the heading of an information system, the purpose of which is to provide accurate, current information by combining and processing data from a number of sources. This can be seen in Figure 3 [13].

To understand this consider the position of the OOW who wishes to fix the position of his vessel. He may plot a number of fixes obtained from different sources. For example, from log and compass, and a knowledge of the set and rate of the current, he can derive an estimated position from a previous fix, from radar information he may obtain a fix, and another fix from an electronic navigation aid such as GPS. Using his knowledge of the likely random errors in all three positions, he may take a weighted mean to establish the most probable position of the vessel. One of the requirements of an integrated navigation system then is to minimise in some way the random errors associated with the position fixing systems. The Decca Navigator Company [14] suggest that the a Gaussian distribution gives the best fit for the spread of random errors in radio navigation aids, so that the problem of minimising those errors can be treated as

one of minimising the variances. This concept has led to the development of Kalman-Bucy filters, which have been used extensively for aerospace, and latterly marine navigation.

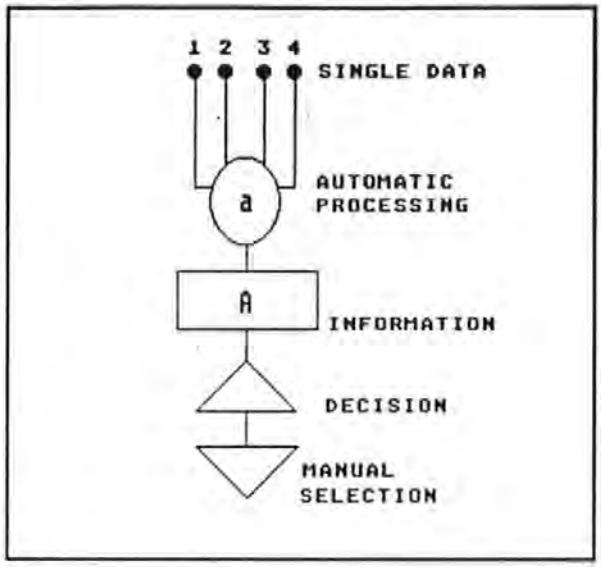

Figure 3. Integrated Information System

The ship is also acted upon by disturbances such as wind, tide and current. These disturbances may be random, as in a gust of wind for example. As the vessel moves sensors measure the position and velocity, but these measurements may be noisy, that is they contain random errors. Use of a Kalman filter will minimise such noise. The filter is a recursive algorithm which estimates the values of the variables of a stochastic system from measurements which contain randomly fluctuating noise. Optimal filtering, using a Kalman-Bucy filter, is a stochastic technique which combines noise corrupted measurements of a dynamic system with other known information about the system, in order to obtain best estimates of the variables, or states, which govern the system.

Marine Uses of Kalman Filters

The Kalman filter techniques have found a variety of uses at sea. Daniel [15] points out their uses in the off shore oil industry where dynamic positioning of survey and supply ships is an important illustration of the use of optimal techniques to maintain a stationary position. Dove and Miller [16] survey the uses of Kalman filters, whilst Liang et al [17] describe the operational features and configuration of a low cost marine integrated navigation system designed to enhance navigational accuracy, operational reliability and position reporting efficiency. Kalman filter techniques are being used extensively in a development of the GPS satellite navigation system. They are also being used in adaptive autopilots. Some of those uses will now be described.

Kalman Filter for a GPS Receiver.

The Global Positioning System offers a wide spectrum of positioning capabilities from navigation to precise surveying. A GPS receiver most commonly has a Kalman filter to process the raw pseudorange and range rate (or deltarange) measurement data obtained from the code tracker (Figure 4). An eight state filter is implemented to estimate position (3 components), velocity (3 components). and clock errors (clock bias and clock rate). Essentially the filter is being used to reduce the random noise to be found in the radio signals from the satellites. Filtered position and velocity values will be output at between 1 and 10 second intervals, while the estimated velocity is fed back to aid the code tracking logic.

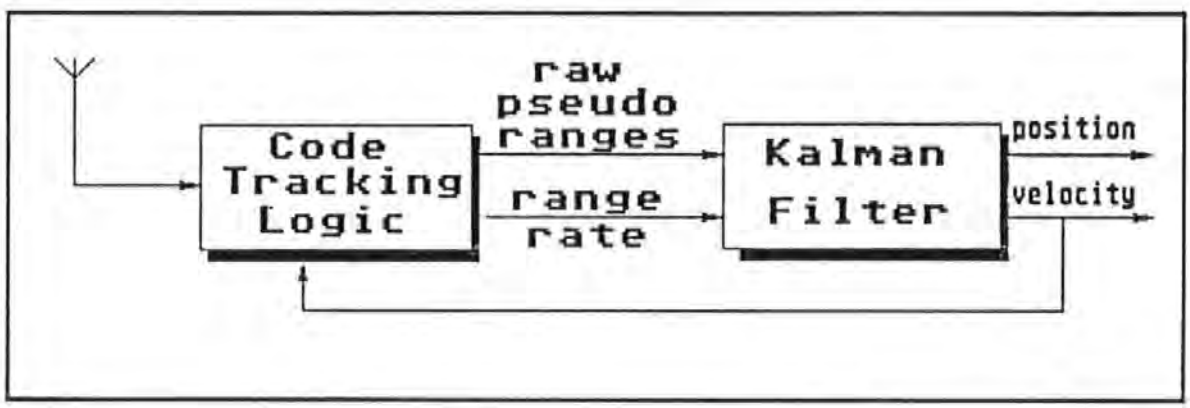

Figure 4. GPS Navigation Receiver

All Kalman filters require system models, and the one used here is based upon the vehicle kinematics. A constant velocity model disturbed by a constant acceleration between updates is used. The constant acceleration is modelled as an unbiased, normally distributed random forcing function. A full description is given by Napier [18], who also describes the integration of GPS with an inertial navigation system (INS) paticularly for aviation uses, where INS is commonly used. The use of Kalman filters in such a system is shown in Figure 5.

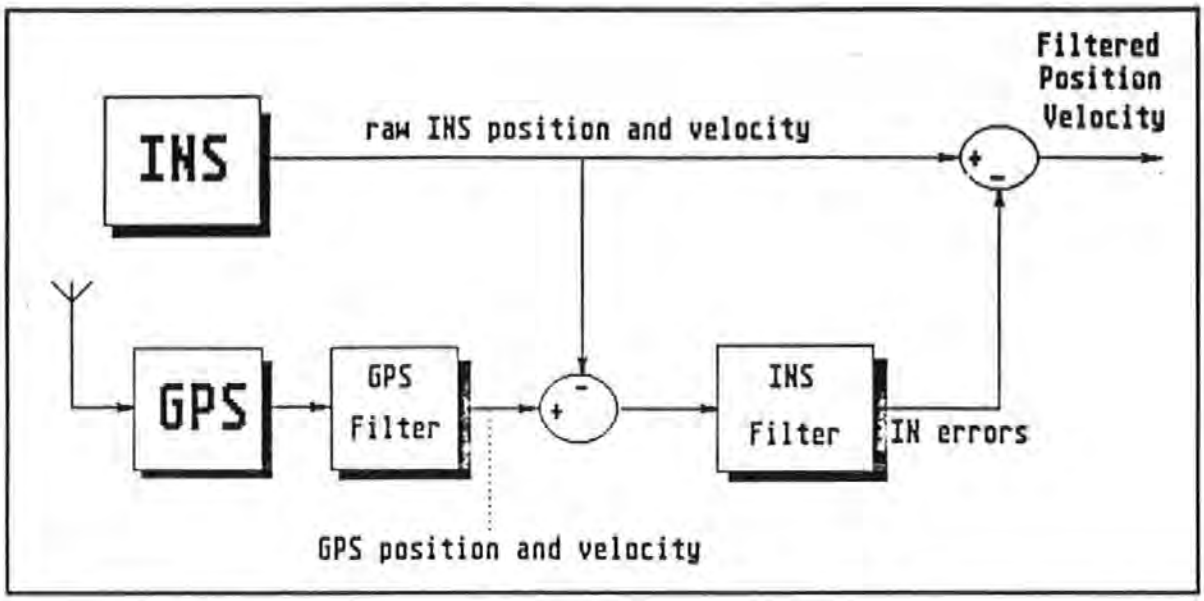

Figure 5. Kalman Filter for GPS/INS Integration

The Offshore Industries.

It has been increasingly realized that the seabed and the rock formations beneath it contain mineral sources that cannot be ignored. Oil and gas platforms are now familiar sights in coastal areas in many parts of the world, but the ocean floor is also a source of many substances, from gravel to manganese. As exploration depths have increased so there has been an increasing demand for accurate position fixing and position keeping systems. These requirements have led to the development of dynamic positioning systems. This is a technique to maintain the position of a vessel relative to a reference point without the use of anchors. The offshore industries required mobile vehicles to possess the mobility beyond the limitations of a moored vessel, but with the stability of the moored system [19]. There was also a need for rapid data processing, so the manual operator was to be replaced by an automatic control system. Dynamic Positioning (DP) thus maintains the position and heading of the ship automatically, using thrusters, together with the ship's rudders and propellers. DP must therefore use a digital computer to process the incoming information of position and heading plus information on wind, waves and curent, compare this information with the demanded values, and output control signals to thrusters in order to maintain the vessel within a watch circle, or enable her to follow a predetermined track, or to maintain station on another vessel such as a submersible. Only surge, sway and yaw of the vessel are controlled by the DP system. Roll, pitch and heave can however be damped by stabilisers fitted to the ship. The normal disturbances are wind, current and waves, but vessels engaged in pipelaying, drilling and similar activities have additional forces induced by these activities.

The variety of applications in which DP is being used include drilling and coring, pipelaying and pipe covering, diving support, remotely operated vessel (ROV) support, mining and trenching, semisubmersibles - including floatels, multi purpose vessels, supply, standby, rapid intervention, firefighting, survey and research vessels, and offshore loading tankers.

The major elements of a DP system are thus the sensors, which give position and heading, an optimal control and filtering system, and the thrusters, propellers and rudders to maintain the demanded position and heading. A simple description of a typical system follows, as it illustrates all the salient points of a completely automatic navigation and guidance system.

A Dynamic Positioning System.

To ensure a high degree of accuracy, position and heading data are filtered to minimise random errors and the best estimates are then fed to the controller, where they are compared with the demanded values. Signals are then sent to thrusters, rudders and main engines to ensure that the vessel is retained in the corect position at the correct heading. It is priority in DP systems to correct heading before allocating thrust to correct positional offset. This is particularly true for keeping head to wind in bad weather conditions. To further increase the system performance the wind force and direction is measured and fed forward as an input to the system.

Kalman filters require a mathematical model of the vessel. The known inputs which drive the system are also fed to this mathematical model. These are usually based upon Newton's laws of motion, and for DP ships, the model is often split into two parts, namely high and low frequency models. The low frequency model is able to estimate wind, current and wave forces, the vessel dynamics, the thruster forces and moments, and the intertaction effects between thrusters, hull and current flow. The high frequency model is used in obtaining estimates of the wave motion. The two parts of the model are then combined to give the total vessel motion in three degrees of freedom. The model outputs are then compared with the measured noisy values of position and velocity. The resulting differences are multiplied by the filter gains and fed back to appropriate parts of the model. The outputs from this optimisation process are the best estimates of position and velocity available. These values are the inputs to the controller. They are compared with the demanded values in order to establish the position and velocity errors. A block diagram of the filter is shown in Figure 6.

If the Kalman filter is allowed time to acquire sufficient history of both variances and weightings then the best estimate of the position and velocity becomes sufficiently accurate to allow direct useage in the computation of thrust commands. In other words no actual sensor input is neccessary for a limited period. This is a very important advantage of Kalman filtering techniques in the advent of sensor failure. It is standard practice for DP operators to activate the system thirty minutes prior to commencement of operations to allow the filter to stabilise.

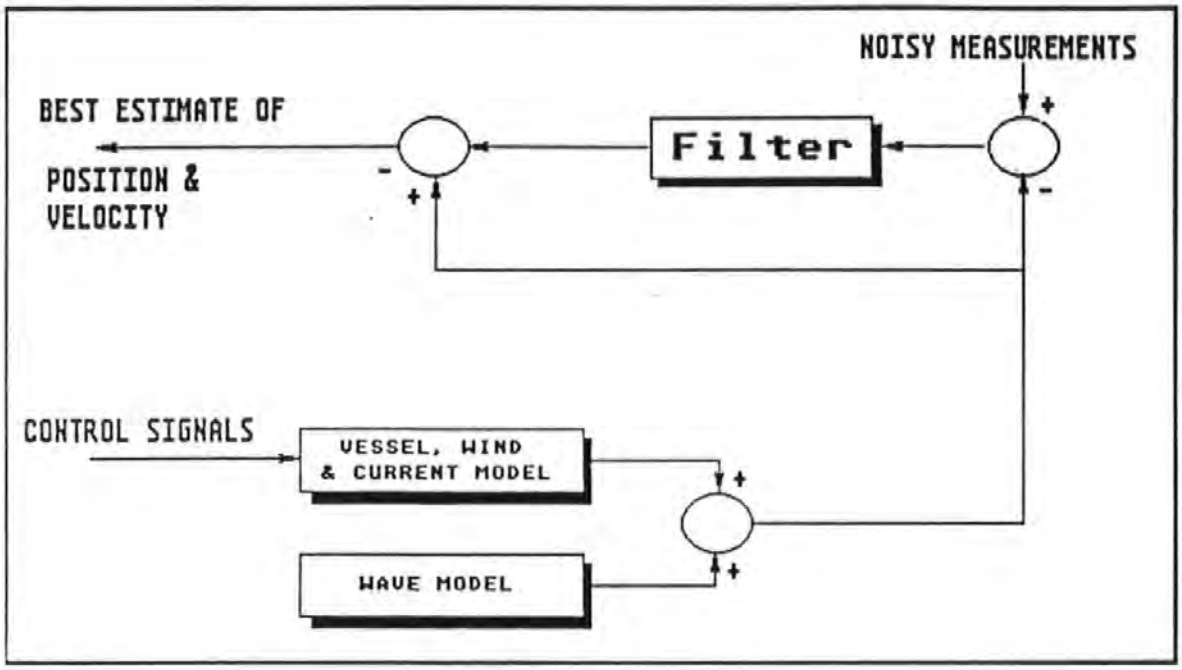

Figure 6. Kalman Filter Arrangements

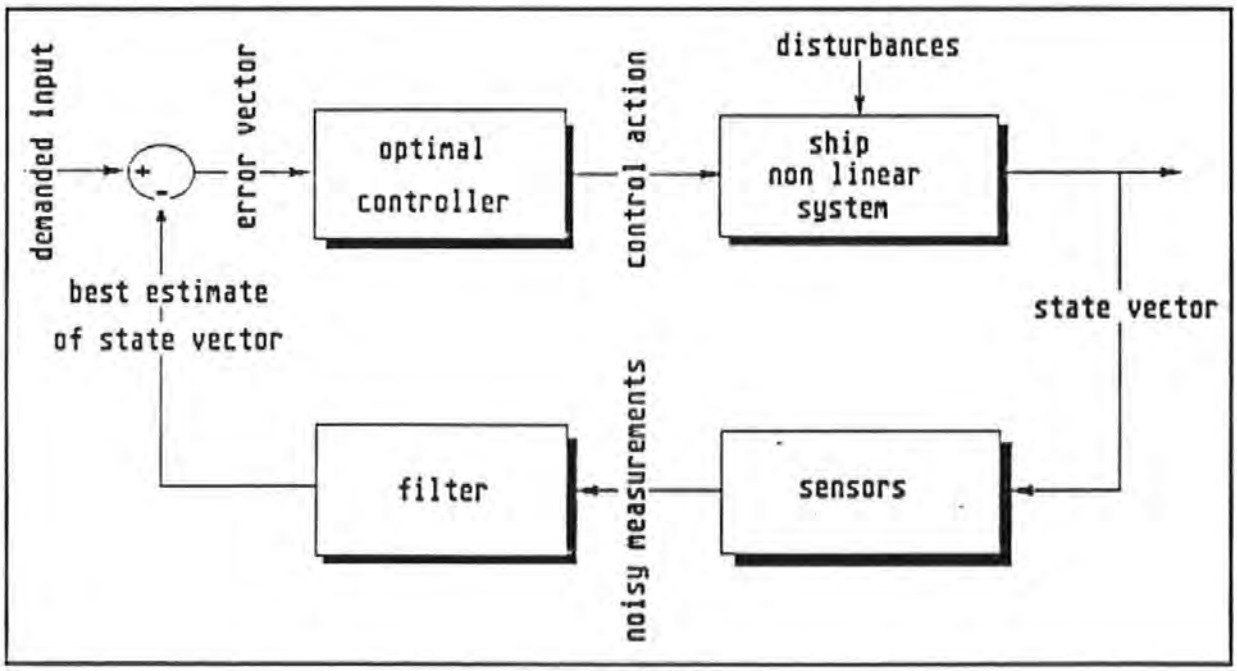

Figure 7. The complete DP system

Referring to Figure 6 the ship is guided by the use of the control vector (namely the action of rudder, thrusters and engines) to counter the disturbances such as wind and tide. As the vessel moves noisy measurements of position and velocity are obtained. The noisy measurements are filtered using an optimal filter to produce the best estimates of position and velocity. These estimates are used as inputs to the optimal controller, which produces new values for the control vector, thus completing the feedback loop.

Conclusions

The operators of today's ocean going and specialist vessels have numerous electronic aids available. The traditional role of each navigation aid has been one of a stand alone unit with the mariner, by his experience and training, coordinating the data from all the sources available to him in order to optimise vessel performance. As casualty statistics indicate however, when under stress or at times of peak work load, he may be a poor coordinator of information available, particularly when that information is from a number of different sources. The development of automatic navigation will therefore continue with evolution rather than revolution being the key. In West Germany, Japan, the Netherlands, the United Kingdom and France, projects have been undertaken on the "ship-of-the-future". These projects were largely attempts to optimize design, operations, maintenance, investments and energy consumption against the criteria of costs efficiency and safety. Not all of these studies have been successful, and not all of the conclusions have been in favour of increased automation of the navigation process. Automation today is not a question of whether a process can be automated, but whether it should be, taking into consideration various human factors. It is perhaps highly questionable whether total systems safety is always enhanced by allocating functions to automatic devices rather than to human operators [20].

Despite these findings there has been much progress. The Scandinavians require exceptionally high standards for automation in their luxury cruise ferries operating between Stockholm, Turku and Helsinki. These waters consist of a maze of islets which are ice-infested throughout the Baltic winter. During the course of a normal passage, ships may be required to make as many as 120 course alterations without significantly reducing speed [21]. As a direct result of this Krupp-Atlas developed the NACOS 25 navigation and command system, one such system is fitted on the bridge of Viking Line's *Athena* [22]. This is a development of the NACOS20 package developed by Krupp Atlas as part of its involvement in the West German *Schiff der Zukunf* (ship of the future) project and is a most sophisticated system. There are two radars with slave displays, a map storage system for the intended routes, an integrated echosounder, an adaptive track pilot, a nautical information display and doppler log.

Perhaps one of the most advanced integrated systems offered on the market place at

present is from Sperry Marine. Although at present international regulations only permit one man operation of vessels during daylight hours, and then only under certain conditions, the system has been approved by Det Norske Veritas for operation by only one person on the bridge day and night. Nine months ago the system was fitted on an 84000 dwt product carrier *Petrobulk Mars*, since then two sister ships, *Petrobulk Jupiter* and *Petrobulk Zaria*, have also been delivered with the system fitted [23]. Central to the integrated system is the 'touchscreen' controlled Rasterscan Collision Avoidance Radar (RASCAR)/ARPA. This is interconnected to the ADG autopilot, and a Voyage Management Station, all integrated by Sperry Marine's own Seanet Token Ring Data Network, which, in the event of a malfunction of one processor, does not make the whole system inoperative.

The majority of integrated systems are manufactured by a sole company and use all their own equipment; one drawback with this is that an operator might feel that the complete package does not offer all he may require. This is the feeling of the West German firm Anschutz whoes philosophy is to integrate equipment from other manufacturers for which the shipowner may have a preferance; this is useful for companies who may not offer a complete integrated system. One such company is Kelvin Hughes who do not at present offer an integrated navigation system based on their latest rasterscan ARPA, the Concept range. They do however realise this potential as the Concept series are equiped with standard interfaces capable of displaying navigation data and machinery data and could be part of a highly advanced bridge. Concept radars/ARPA are of the new generation type capable of carrying on screen map diagrams; once entered maps are maintained correctly in true motion by speed log input and by successive position fixes fed in from Transit, GPS, Decca, Loran-C or Glonass receivers via an RS423 interface to NMEA 0183 standard protocol.

In conclusion then it would seem that the specialist operators such as those engaged in offshore and survey operations are prepared to go for a completely automated navigation and guidance system, whilst the ferry, cruise liner and cargo operators are concentrating on developing ergonomic bridge designs with only a degree of automation in such functions as the autopilot, coupled with integration of two or more navigation aids. However manoeuvring vessels in confined waters is a very feasible application of DP. For example a vessel fitted with a cheap but reliable DP system would be able to forego the use of tugs. DP has established itself firmly in the offshore industries and will take an ever increasing role in this sometimes harsh environment. There is then a great deal of room for expansion in dynamically related operations which include enhancement of existing operations, together with applications of DP techniques to vessels in restricted waters and in the deep oceans where the next generation of offshore exploration will take place.

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MARINE AUTOPILOT DEVELOPMENT

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ABSTRACT

This paper discusses marine autopilots from the conventional 'proportional-integral-derivative' (PID) through to adaptive and 'linear quadratic gaussian' (LQG) controllers. It goes on to show some of the economic aspects which have stimulated research and development in this area of ship guidance. Rudder roll stabilisation is briefly considered.

In conclusion the paper considers some of the research currently being undertaken at Polytechnic South West, which is directed to automatic track keeping.

Introduction

The 1990's will be an unprecedented era for navigation particularly with the phasing in of the man made constellation called GPS (Global Positioning System). The anticipated 24 hour global coverage and the accuracy of GPS will bring the concept of automatic navigation closer to reality.

Autopilots are well established navigation aids in modern commercial and military shipping; in their basic form they will maintain a ship on course in the open seas. However, will either technology or legislation allow a marine vessel to sail unmanned from port to port? This would include automatically piloting the vessel out of a harbour, avoiding floating and submerged obstacles on route, weather routeing and piloting the vessel into another harbour. Undeniably futuristic? Indeed, the Ship Control Group at Polytechnic South West (formerly called Plymouth Polytechnic) has been undertaking research for many years in related areas such as high precision navigation, control and guidance of marine vehicles, mathematical modelling, weather routeing, automatic collision avoidance and control in port approaches. The immediate goal of the group is to produce a system that will assist the mariner as fully as possible.

Conventional Autopilots

Few ships of any size are built today without an autopilot. Shipowners recognize this equipment as an investment with a return on capital for many reasons. These include reduced manpower, improved fuel economy, accurate course keeping and less wear on machinery.

Automatic ship steering was introduced many years before control theory was applied to the design of autopilots (synonymous with autohelm or gyropilot). In 1922 both Minorsky [1] and Sperry [2] produced papers on automatic devices. Minorsky treated the problem of automatic steering mathematically, whereas Sperry considered it as a practical problem involving a gyrocompass. Both papers contributed towards the development of the modern autopilot.

Very early autopilots were based on mechanical construction and were able to provide rudimentary control of the rudder; today it is known as 'proportional' control. It is so called because the rudder is moved by an amount proportional to the heading error. Proportional control was adequate for the guidance of small craft such as torpedoes but unsatisfactory for the steering of large ships. This type of control would cause the vessel to continue to oscillate either side of the required course and the steering gear would be constantly hunting to keep the ship on the correct mean course. The vessel would eventually reach its destination but excessive wear in the rudder gears and

abnormally high fuel consumption restricted their use as course keeping devices. Both Minorsky and Sperry were aware of this problem. Early autopilots had other problems. For example, the hydraulic telemotor unit, a device used to control the movement of the rudder, was reported to malfunction because of a leakage [3] and an electrical system now replaces this device.

The controller concept since 1922 has hardly altered; developing technology only changed the hardware of autopilots from purely mechanical devices to electronic systems. Until the late 1970's most autopilot manufacturers used a control system based on the angular displacement, mentioned above, to control the course of the vessel. It was assumed that the ship had already developed a course error before the rudder was moved to correct the error. Certain vessels, such as oil tankers, were becoming very large. In 1980 Patterson [4] showed how this system worked satisfactory for course stable ships, but, proved to be unsuccessful on the very full tanker forms. A more appropriate method is to monitor the angular acceleration of the ship and use this as feedback to control the steering gear. However, almost all conventional, marine autopilots by 1980 were usually based on the simple 'proportional-integral-derivative' (PID) controller systems. Such systems take a signal proportional to the error between the actual and the desired course as the controlling input. This heading error signal is also electronically integrated producing integral control and differentiated producing derivative control data. The proportional, integral and derivative control signals are electronically blended together to produce a single control signal. To keep the ship on course, proportions of each of these three signals can be adjusted manually by a control panel containing three electrical potentiometers. Attempts to keep the ship on course were normally performed by trial and error: in fact this was one of its major criticisms. Nevertheless, PID autopilots do maintain a straight line course through the action of the ships rudder. In this respect, the composite control signal of PID autopilots was far superior to the single signal associated with proportional controlled autopilots.

Conventional, PID autopilots require manual adjustments to compensate for changes in the ship's environment; settings are seldom optimal for that ship. Adjustments for variations such as waves, wind and currents are tedious and time consuming. Furthermore, autopilots perform badly in rough seas as analysed for example, by Blanke in 1981 [5]. On such occasions manual steering has frequently been used in place of the autopilot, yet such circumstances require the use of automatic control. Further problems arise because of changes in the dynamics of the ship; for instance variations in the speed, draught or water depth. This explained the growing interest towards autopilots that could automatically adjust or 'adapt' themselves to these changes.

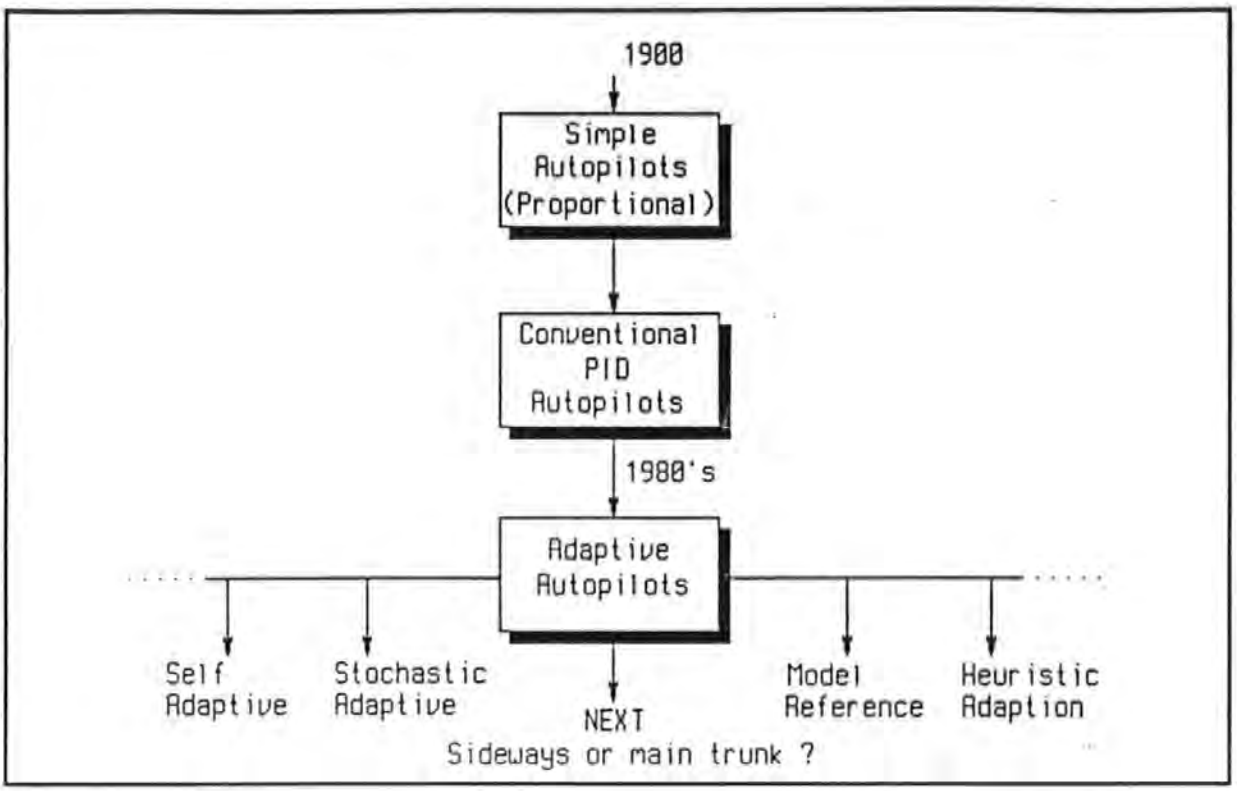

Figure 1. Development of autopilots

Adaptive Autopilots

Development towards adaptive autopilots has been rapid. In 1984 at least three different companies were marketing adaptive autopilots. Adaptive control appears to provide several benefits such as improved fuel economy, increase speed of vessel, reduced steering, reduced manual settings to compensate for wind, waves, currents, speed, trim, draught and water depth. Adaptive control also improves safety and makes the ship operation more convenient in all weather conditions. An example of such an autopilot is shown in figure 2.

There has been much research effort on the design of adaptive autopilots. Many suggestions were seen prior the 1980's. In 1975 Oldenburg [6] proposed to add adaption heuristically to ordinary PID autopilots; a similar approach was taken by Sugimoto and Kojima in 1978 [7]. A wide class of adaptive autopilots were also beginning to emerge according to modern adaptive and stochastic control techniques. Stochastic adaptive systems were proposed by Merlo and Tiano in 1975 [8]; Astrom in 1976 [9] and Brink et al in 1978 [10] had also introduced a stochastic approach to the analysis and control of the motion of a ship. Another approach, known as 'self tuning adaptive control', had been

investigated by Kallstrom and Astrom in 1977 [11] and two different autopilots were looked at in their paper. The simplest system used only heading measurements, while the more complex system was provided with a Kalman filtering of heading, sway velocity and yaw rate. The Kalman filtering was used to obtain reliable estimates of the three afore mentioned parameters. Self-tuning adaptive control was also considered in a paper by Brink and Tiano in 1981 [12]. This paper describes the simulation of a supertanker and a second generation containership. Results indicated that this type of adaptive autopilot was a feasible and efficient solution for automatic steering of a ship in main operational navigation situations.

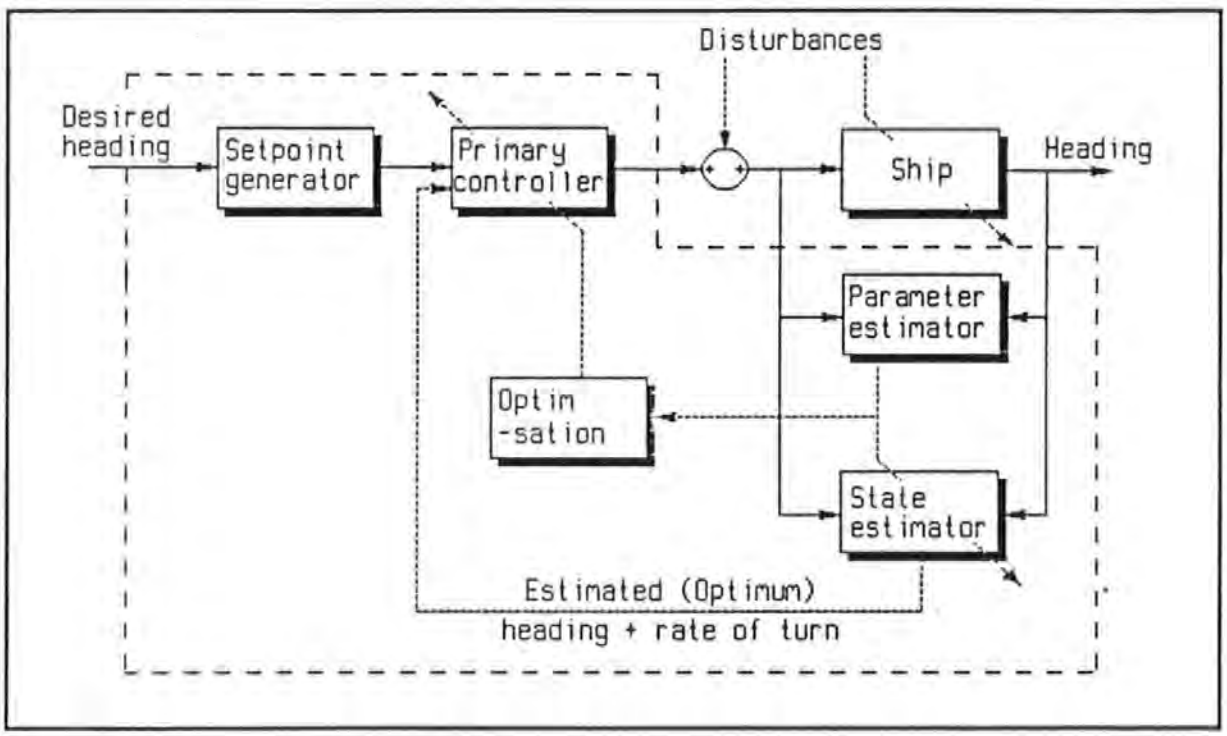

Figure 2. Adaptive autopilot (Adaptieve StuurAutomaat) as developed by Delft University of Technology

However, in 1976 the research of Amerongen [13] was committed to the implementation of an adaptive autopilot based on model reference techniques. The main requirement for such systems is an accurate mathematical model of the ship's steering dynamics and of the external environment. The ideal model is subjected to the same inputs as the actual ship. Inputs of the actual system such as the ship's heading, speed, rate of turn and rudder angle will be fed into a computer containing details of the model. If the response of the stored mathematical model differs from that of the actual system, the error between the two responses is subsequently used to adjust parameters of the real ship. For example, the computer may calculate the rudder angle required to minimise the course keeping errors in the optimum manner. The adaptive aspect in the system will

account for changes in weather, water depth and changes in the ship loading condition. A useful side effect of mathematical modelling is the ability to predict the path of the actual ship.

Research has been undertaken into the effects of the ship's natural yaw action in relation to the course to be steered. It has been found that a straight course is not necessarily the most economical and the ship's natural yaw action should not be smoothed out. The added resistance due to steering on a straight course has been analysed by Norrbin [14]. Disturbance levels and load conditions were shown by Astrom [15] to be factors in this process; adaptive control can minimize this loss. Reduced drag leads to fuel savings and speed increase; fuel savings of 1-3% and speed increases of 0.5-1.5% were observerved by Amerongen in 1984 [16]. The speed increases were mainly due to smoother rudder movements. Consequently, there would also be less wear and tear of the steering equipment, reinforcing the advantages of adaptive control. Earlier in 1979 Kallstrom et al [17] also confirmed a reduction in drag and the corresponding economic benefits of adaptive steering for tankers. Recently, Katebi and Byrne [18] suggested an autopilot using the LQG (linear quadratic gaussian) approach. It too minimised the added resistance due to steering. Additionally, an improvement in the course keeping performance in all weather conditions is suggested.

The 1980's have seen continuation of the work of the late 1970's. Emphasis is on the production of a generation of autopilots with energy saving capabilities. The availability of relatively inexpensive, fast digital microcomputers, the development of modern adaptive control and optimal theories has given the impetus to produce more sophisticated controllers. Thus, marginal savings in fuel consumption and accuracy in steering will continue to improve. Autopilot design in the future will continue to improve steering characteristics through the use of accurate filtering and modelling, and the improvement of both hardware and computer software.

Rudder Roll Stabilisation

A relatively recent development is where an autopilot is not only used to control the heading of the ship, but is used to reduce the roll motion as well. The rudder roll stabilisation (RRS) system has been mentioned in a number of recent papers [19-23]. On vessels such as ferries and naval ships as well as control of the heading, it is necessary that roll motion is reduced. Conventional roll reduction systems include passive and anti-passive rolling tanks and active and non-active stabilising fins. In general the control systems of these devices (if required) are designed without attention to the interaction with the heading control system. A possibility being investigated and indeed being used in the Dutch Navy is to use the rudder alone for controlling both the heading and reducing roll. This system offers advantages as it saves investments in expensive traditional roll stabilisation techniques while it requires only moderate additional investments in the

steering machine for the rudder. As a further advantage it may save fuel because the additional resistance caused by large rudder motions is only present when the roll reduction is really wanted. Fins give resistance whether they are in use or not.

Economic Aspects

In tracing the development of the marine autopilot, mention of some of the perceived economic benefits and implications would appear necessary to augment the technical discussion. In this respect, in viewing the autopilot operations of course changing and course keeping, it is the latter which in the main offers energy saving prospects. Here, the development of the adaptive autopilot has provided a particular milestone in improving course keeping. That is, as well as benefits provided through reduced manual adjustment compared with 'conventional' autopilots, the adaptive autopilot is able to steer the ship more economically. As previously mentioned, Amerongen in 1984 in applying model reference adaptive control (MRAS) to the automatic steering of ships pointed, in addition to safer operation, to decreased fuel costs of between 1-3%. Of course, the actual cost savings depend upon the price of fuel and today's fuel price stands at roughly what it was some 15 years ago. Thus, the economic benefits would not be as great as say in 1979-80 when a significant rise in fuel cost occurred and the fuel bill could occupy as much as 55% of all operating costs (excluding Capital costs) depending upon the type of vehicle and the mode of operation in the closed, semi-closed and the open market sectors. However, although the competitive edge provided by fuel saving devices has been blunted to some extent by reduced cost of fuel in the past few years it is interesting to note that Amerongen in 1986, referred to the fact that the value of 3% in fuel savings was still enough to repay the investment in less than one year.

In turning to the present day scene, and the energy saving capability of autopilots, Katebi in 1988 referred to adaptive autopilots based on the optimisation of a cost function which represents the energy used in maintaining a set heading. The cost function should ideally represent the added resistance due to steering and the elongation of distance sailed effects, due to sway and yaw motions. However, it would appear that many of the existing autopilots contain poor models of added resistance and that their validity has been questioned by Clarke [24] and Reid [25]. In fact the minimisation of these cost functions for adaptive autopilots may, it would appear, actually increase fuel consumption. Katebi [18] proposed an autopilot which would minimise the added resistance due to steering and additionally improve the course keeping performance in all weather conditions. This involved formulating a dynamic cost function optimised in a stochastic 'Linear Quadratic Gaussian' framework. This is the so called 'LQG adaptive autopilot' and it will be interesting to see a quantification of economic benefits compared with existing adaptive autopilots.

Finally, looking to the near future, it is expected that marine autopilot development will

move towards advanced track prediction and track keeping systems. Research has been directed towards this aspect at Polytechnic South West. This has been stimulated in part by consideration of the perceived economic benefits in reducing the distance sailed. This benefit was underlined by Meek [26] when it was estimated in a computer cost/revenue sensitivity study on a Panamax vessel that a 2% reduction in distance steamed was equivalent to reducing the crew cost by 10%. This involved the use of discounted cash flow techniques to generate NPV (Net present value) and RFR (Required freight rate) in order to quantify the relative merits of various savings in both operating and first cost factors and was of course pursued at a time of very high fuel cost. Never the less, this emphasised the importance to operators of shaving every possible nautical mile off a voyage by more accurate position fixing and more precise navigation as well as by track keeping referred to here. It is planned shortly to quantify the economic benefits which may be facilitated by the track keeping system developing at Polytechnic South West. An outline of this research programme is provided in the closing sections of this paper.

Research at Polytechnic South West

Development of a production system for fully automated ship control probably lies well into the future. The technology exists but there are other considerations governing the instrumentation installed on a vessel such as cost and legislation which may pose constraints in the immediate future. However, these may subsequently be relaxed. In connection with development towards automatic navigation, research at Polytechnic South West is underway to maintain the vessel not only on course but also on track. To undertake this, more than just positional information is required by the autopilot. That is, in particular velocity feedback in the two dimensions of surge and sway together with rate of turn are necessary in order to stabilize the system. While such measurement devices are available, they are rarely found in commercial shipping due to financial constraints. To overcome the problem of providing the appropriate measurements the use of Kalman filtering techniques may be adopted. Research in this area has been underway for a number of years and Dove [27] has shown the concept of Kalman filtering as applied to marine navigation; combining state estimates from measurements with those from a mathematical model. This has further been investigated by Miller [28].

The overall aim of the work is to investigate, design and develop an integrated navigation and collision avoidance system to provide advice to the master of the vessel. This is a large spectrum to cover and involves two full time research staff. A schematic diagram of the system is shown in figure 3. It will;

i) interface to the ship's navigational aids,
ii) perform the mathematical model computations,
iii) perform the filter computations,
iv) display an electronic chart showing ship status, desired track and information on target vessels,

v) Interface to the radar,
vi) run heuristics for collision avoidance (ACAS) and ship operations,
vii) make modifications to the mathematical model if necessary,
viii) present track information.

The project comprises of a team approach through the formation of the 'Ship Control Group' involving a wide range of disciplines including control and guidance, navigation, naval architecture, computing, artificial intelligence, mathematical modelling and signal processing. The prototype system will be fitted on board one of the Polytechnic's research vessels with the aim of having it operational within a period of two years.

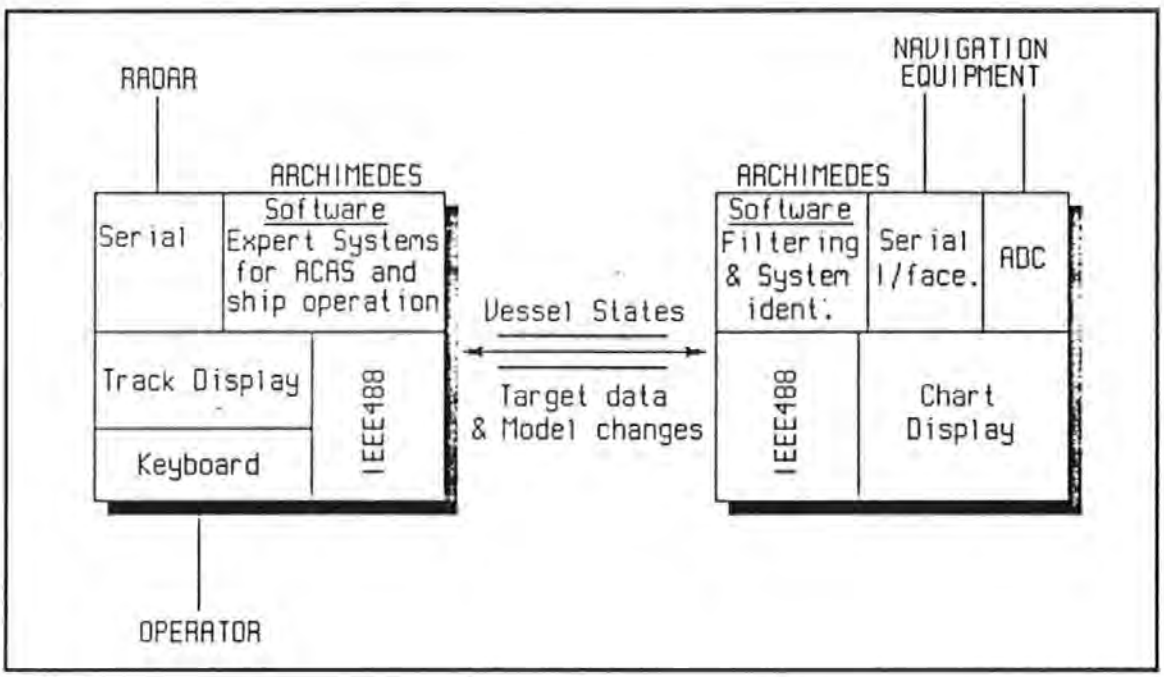

Figure 3. Prototype System Schematic

Conclusion

Whilst the majority of autopilots in use today are of the course keeping mode, automatic station keeping and track keeping systems are starting to emerge in specialist vessels used in the offshore industry and in Hydrographic Surveying. Until a highly accurate, 24 hour, position fixing system such as Navstar is available world wide, course keeping using adaptive autopilots will remain as standard.

A full economic study on what benefits adaptive autopilots do offer when compared with traditional autopilots needs to be undertaken as results shown at present seem to be inconclusive. Is it enough to save 1-3% of fuel now that the price of fuel has dropped to

its present level and is this figure accurate now that we are seeing the models of added resistance being questioned? When considering the economic benefits of a track keeping system there can be no denial that savings will be made by reducing sailing distance; however, the question of how much saving still remains.

Figure 1 showed the development of autopilots and asks the question what is next? The work being undertaken at Polytechnic South West and at many other institutions in the world will add another dimension to autopilots with the development of automatic navigation and guidance systems. These are described in a companion paper to this one [29] and explain the concept of an automatic track keeping system to guide the vessel along a predetermined track. The addition of an automatic collision avoidance package will further enhance the system; perhaps we are closer to the unmanned ship than we would care to think!!

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A Review of Ship Simulator Models Past, Present and Future

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ABSTRACT

This paper sets out to describe the use of mathematical models in maine simulators. It commences by describing categories of simulators and explains that Newtons second law of motion forms the base for the model equations. Four types of mathematical model are suggested; these are the input-output model, the holistic model, the force model and the modular model. After briefly describing these the paper goes on to give a more detailed explanation of the modular model, its development from an holistic model at Polytechnic South West, and the reasons why the Polytechnic's Ship Control Group are developing it for use in further research programmes. Each module is described in turn and the paper then goes on to give details of work undertaken to simulate the 278000 deadweight tonnage tanker Esso Osaka, and shows that the simulations compare well with ship trial results. The paper concludes by out lining future research at Polytechnic South West and the increasing role the mathematical model is taking in marine research and development.

INTRODUCTION

Marine simulators have been used successfully over a number of years to enable mariners to gain experience of ship operations. This enables the mariner to undertake general navigation training including situations that hopefully, he may never have to encounter.

There are many types of ship manoeuvring simulators installed in maritime training and research establishments throughout the world. Dependent on their usage, the complexity of these simulators range from small desk-top simulators for training or examination in some specialised part task, to highly sophisticated full manoeuvring simulators employing high level technology for maximum realism and which may be used for maritime research as well as training.

Common to all simulators is the mathematical model of the system on which training is to be based. The performance of say, a ship simulator, depends on the sophistication of the inherent ship mathematical model. The model accepts commands implemented by a student on the bridge and produces outputs representing the dynamic behaviour of the ship in response to these commands and to the various environmental influences input by the instructor, at that particular phase of the training exercise.

Mathematical models of ship dynamics are required for many different purposes but can generally be split into three categories, namely;

a) Ship Manoeuvrability Analysis.
   i) Ship Design.
   ii) Waterway Improvement and Port Facilities.
   iii) Safety Regulations and Casualty Studies.

b) Training and Research Simulators.

c) Shipboard Manoeuvring Predictors.

The need for reliable mathematical models which can be used to perform a variety of studies associated with ship manoeuvrability has been long understood by specialists in the field. At Polytechnic South West the Ship Control Group has developed over a number of years various mathematical models to simulate specific requirements.

EQUATIONS OF MOTION

The development of the mathematical model starts with a set of generalised equations to express the dynamics of a rigid body in a fluid medium. The equations are derived from Newton's second law of motion, namely;

Force = mass x acceleration (1)

These equations are then extended to model the complex hydrodynamic forces and moments experienced by a hull manoeuvring in response to the control inputs of rudder and propeller. By integrating through small time steps the motions of the vessel can be simulated. Further forces and moments are then introduced in response to the disturbance inputs of wind and tide. Figure 1 schematically shows the physical components involved in a typical ship manoeuvring system [1].

The equations of motion for ships are well documented in a number of papers and are not present here. Abkowitz [2] is considered to be one of the classical papers in this area.

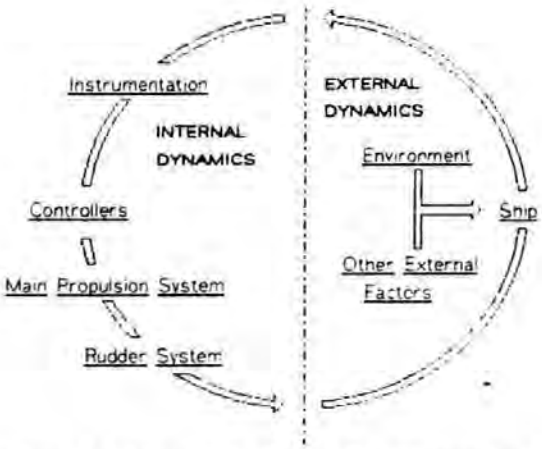

Figure 1. Schematic of a Typical Ship Manoeuvring System

TYPES OF MATHEMATICAL MODEL

The type and complexity of the mathematical model, will depend entirely on the purpose for which the model is to be used. In the past comparisons of simulator mathematical models have been made by McCallum [3] and Case et al [4]. Between different reseach establishments there is little commonality of ship manoeuvring mathematical models and hydrodynamicists have over the years developed models of various forms and fidelity. The major reason for this is the complexity of the flow phenomena around the hull, propeller, and rudder particularly on the subject of generation and losses of vorticity and surface waves [5]. The mathematical model designed for ship manoeuvring must be capable of representing a wide range of ship types and configurations, machinery and propulsion/steering devices.

The many differing types of mathematical model, can generally be placed under one of four headings, namely:

i) Input-Output relationship model.
ii) A holistic model.
iii) A force mathematical model.
iv) A modular manoeuvring model.

Each of these will be briefly described in the following sections.

The Input–Output relationship model

When using this type the researcher starts with the simplest possible model and then tries to fit the model response with the response to the real system. When fitting is not accurate enough, the model can be extended until a fit has been achieved with desired accuracy [6]. If the system requires a non-linear model, the parameters can be derived from full scale trials or from trials with scale models. The simplest model in the input-output approach is the first order Nomoto model governing yaw response to rudder motion. By taking Laplace Transforms and assuming the initial conditions are zero a transfer function can be obtained relating rudder angle to heading. Representation of the transfer function between heading and rudder angle, derived from the first order Nomoto model, is shown in figure 2.

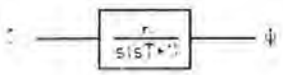

Figure 2. Transfer Function

The first order Nomoto model can be expanded to a second order differential equation as described by Bech [7], who then went on to note that the second order differential equation could only accurately describe ship manoeuvres in a very small range of heading and rudder angle. He rewrote the equation to include non-linearities [8]. The same approach can be followed in order to estimate the sway speed.

For use in simplified simulations this type of model for ship manoeuvring will indeed be adequate, but for simulating manoeuvres where high order non-linearities occur its performance is not sufficient. Modern thought is that the input-output relationship model should not be used for ship manoeuvring predictors, but can be used in applications to ship control [9].

The holistic model

This type of model has proven to be highly successful and is installed in many ship simulators in use today. Racal SMS Systems Ltd, as a marine simulator manufacturer, used this form of ship modelling in early versions of their MRNS9000 navigation simulator. The holistic model has been adopted and refined by many institutions with interests in hydrodynamics.

This type of model is highly formal and systematic. It treats the hull-water interface as a black box and models the system as a complete entity. It is based on the premise that a manoeuvre is a small perturbation from an equilibrium state of steady forward motion at a nominal service speed. It has been used successfully for the simulation of ship manoeuvres by the application of rudder control by Strom-Tejsen [10] and in a modified form has been applied to engine manoeuvres by Crane [11] and Eda [12], despite the fact that such manoeuvres can hardly be described as small perturbations. Dand [13] describes this type of model as:

" A model which performs satisfactorily when taken as a whole, but does not allow individual elements to be changed readily as the design is changed "

The Ship Control Group at Polytechnic South West has used this model in past research. The selection of the important non-linear terms were made by reviewing the work of Strom-Tejsen, Lewison [14], Gill [15][16] and Eda and Crane [17]. The non-linear functions of the control

parameters (rudder and propeller) were also required in the final non-linear equations of motion.

The complete set of the holistic model non-linear equations of motion as used by the Ship Control Group has been described in various papers [18-20] and has been shown to give accurate representation of the three degrees of ship motion in all manoeuvring situations. A comparative evaluation of the mathematical model was made with full scale measurements taken by Morse and Price for the USS Compass Island [21]. The USS Compass Island was constructed with a Mariner type hull form, and a complete set of hydrodynamic coefficients for this class of vessel have been measured by Chislet and Strom-Tejsen [22] using the Planar Motion Mechanism Test.

Although this model gives accurate simulations of ship manoeuvring it does not allow rudder, propeller or hull geometry to be changed with ease. Modern day requirements of mathematical models do require the model to be adaptable.

The force mathematical model

This type of model was first proposed by McCallum [23] and essentially treats the hull as a lifting surface inclined at a drift angle to the water flow, thus generating lift and drag forces, as on an aerofoil section. McCallum postulates that a linear relationship exists between the lift force on the hull and the angle of incidence, up to an angle of about one radian, whilst the drag force increases quadratically from some minimum value at a zero angle of incidence. The rudder, also being a higher aspect ratio aerofoil section is also modelled in the same manner. It is not to be expected that a simple model of this sort will be able to give accurate manoeuvring predictions over the very wide range of operating conditions experienced.

Fig 3 shows the forces and moments acting on the vessel. From these McCallum developed the three equations of motion in the following form.

For the surge equation, the total mass m_x may be expected to change with the direction of fluid flow.

$$m_x\dot{u} = [\, T_p + L_H\sin\alpha - D_H\cos\alpha - L_R\sin\alpha_R - D_R\cos\alpha_R + m_y vr \,] \quad (2a)$$

The sway equation may be similarly written.

$$m_y\dot{v} = [\, -L_H\cos\alpha - D_H\sin\alpha + L_R\cos\alpha_R - D_R\sin\alpha_R - m_x ur + F_p \,] \quad (2b)$$

The yaw equation is obtained by taking moments about the centre of gravity.

$$I_z\dot{r} = [\, -N_V - L_H d_1\cos\alpha - D_H d_1\sin\alpha + L_R d_2\cos\alpha_R - D_R d_2\sin\alpha_R + d_3 F_p \,] \quad (2c)$$

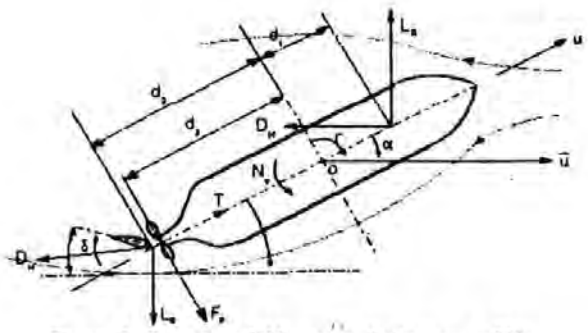

Figure 3. Forces and Moments Acting on a Ship

Research work is still continuing to refine this type of model and to investigate different methods of calculating the hydrodynamically generated forces by both slender-body theory and wind tunnel experiments, for example by Pourzanjani [24]. The later versions of the Racal Marine Systems Ltd MRNS9000 navigation simulator employ models based on this approach and incorporates a basic ship's editor to enable other ship types to be modelled.

The modular manoeuvring model

Current research on ship manoeuvring modelling tends to favour this type of model. The Mathematical Model Group (MMG) of the Society of Naval Architects of Japan, first published a paper describing a model of this type in 1978 [25]. This was subsequently followed by various papers on the subject [26][27], and a further refined model in 1984 to simulate various ship manoeuvring motions in harbour [28]. Research in Germany, by Oltmann and Sharma [29], is based on the modular concept, as is the modular manoeuvring model developed at British Marine Technology Ltd (BMT) between 1983 and 1984.

A modular manoeuvring model is one in which the individual elements, such as the hull, propeller, rudder, engines, and external influences, of a manoeuvring ship are each represented as separate interactive modules. Each module, whether it relates to hydrodynamic or control forces or external effects is self-contained. The modules are constructed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and expressing their interaction by other physical expressions.

The equations of motion for a modular manoeuvring model are generally expressed by;

$$\begin{aligned} mu - mrv &= X_H + X_P + X_R + X_E \\ mv - mru &= Y_H + Y_P + Y_R + Y_E \\ I_z r &= N_H + N_P + N_R + N_E \end{aligned} \quad (3)$$

where the suffixes H, P, R and E denote components of hull, propeller, rudder and external forces.

The model arranged in this way lends itself to a number of applications. For example it allows research on one particular module and the effect that module has on the system model as a whole. This is invaluable when trying to determine the effect of various rudder areas on the manoeuvring performance of a vessel. Previously a series of captive model tests had to be undertaken to select optimal rudder area. Advances in any particular field of related research can be incorporated into a module and into the system as a whole without having to alter other system modules. Other advantages of this approach are the expansion facilities it allows. In addition to the modules shown in equation set (3) extra modules can be employed to simulate bow thrusters and stern thrusters for example. Hence the model can be tailored to suit a number of applications and such effects as ship to shore and ship to ship interaction can be investigated. Gradually a very sophisticated model incorporating all of the more specialised attributes can be developed.

MATHEMATICAL MODELLING AT POLYTECHNIC SOUTH WEST

Mathematical modelling has been undertaken by the Ship Control Group at Polytechnic South West for a number of years, culminating in a modular manoeuvring model, developed for use in a marine simulator by N.J. Tapp [30]. In the sections following each of the modules in the equation set will be examined in turn.

Hull Forces and Moments

The hull forces and moments module contains all the hydrodynamic data which is specific to the hull alone. They can be expressed by the following equations:

$$X_H = X_{\dot{u}}\dot{u} + X_{vr}vr + X_{vv}v^2 + \frac{u}{|u|}X_{rr}r^2 + R_H$$

$$Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + \frac{u}{|u|}Y_r r + Y_{vvv}v^3 + Y_{vrr}rv^2 \quad (4)$$

$$N_H = N_{\dot{r}}\dot{r} + N_{\dot{v}}\dot{v} + N_r r + \frac{u}{|u|}N_v v + N_{vvv}v^3 + N_{vrr}rv^2$$

The equations are a further development of previous research work on the holistic type model with the important non-linear terms being similar to enable comparisons of the models to be made. The multiplier $\frac{u}{|u|}$ included in some of the terms is to correct the sign of the derivative, during astern motion of the ship.

The term R_H in the surge equation represents the ship's resistance on a straight course and is modelled by the following expression:

$$R_H = X_u u + \frac{u}{|u|}X_{uu}u^2 + X_{uuu}u^3 \quad (5)$$

Propeller Forces and Moments

In order to model the motion of a ship for both ahead and astern motion it is important to determine correctly the propeller forces and moments. Tapp, to cover all manoeuvring regimes, adopted the method of modelling the propeller forces and moments published by Oltmann [29] and Mikelis [31]. This method is based on the knowledge of the thrust coefficient:

$$C_T^* = \frac{2T_p}{\rho A_p(up^2 + cp^2)} \quad (6)$$

for the whole range of the advance angles ε for the propeller.

Propeller Forces and Moments for a Single Screw Ship

$$X_p = (1 - t_p)T_p$$

$$Y_p = Y_{\dot{v}}n^2 \quad (7)$$

$N_p = N_{\dot{v}}n^2$ where $N_{\dot{v}} = Y_{\dot{v}}x_p$ assuming that the screw is located at a distance x_p from the lowest centre of gravity.

Propeller Forces and Moments for a Twin Screw Ship

Obviously the modelling of a twin screw ship is a more complex problem than a single screw. It is not the intention of this paper to present these equations as the results that will be shown are based on a single screw vessel. Basically, the surge term is a summation of the effect of both propellers as is the yaw term. The sway term is dependent on a number of factors including rotation of propellers and their operating condition i.e. port propeller ahead and starboard propeller astern.

Rudder Forces and Moments

In common with the propeller modelling it is important to calculate accurately the rudder control forces and moments in order to model correctly the turning and course keeping performance of the ship. From Hirano et al [32], using Tapp's adopted sign convention, the forces and moments induced on the ship due to rudder action are given by:

$$X_R = -(1 - t_R)F_N\sin(\delta)$$

$$Y_R = -(1 + a_H)F_N\cos(\delta) \quad (8)$$

$$N_R = -(1 + a_H)F_N x_R\cos(\delta)$$

where:

F_N is the normal force produced by the rudder. a_H and t_R are correction factors to adapt the open-water characteristics of the rudder to behind-hull conditions. a_H can be determined from knowledge of the form factor of the hull, C_B. The value of t_R can be estimated from the reduction in forward speed of the ship when turning.

External Disturbance Forces and Moments

A number of modules can be used to describe various external effects which, in keeping with the modular structure, are treated simply as additional forces and moments imposed on the basic hull hydrodynamics. The required complexity and operating conditions of the

model determines the external force modules needed. These can include, for example, such effects as wind, tide, thrusters, bank effects, tugs, anchorage, ship to ship interaction, and squat. Tapp's model, for use in a marine simulator, had external force and moment modules for wind and tide, the wind module being based on research by Isherwood [33].

RESULTS OF THE ESSO OSAKA MATHEMATICAL MODEL

Exxon International published a report in 1979 detailing the performance of a modern supertanker [34][35], describing full-scale trials of the 278000 dwt Esso Osaka. The modular model outlined was verified by using it to simulate the full scale results given in the above papers. Hydrodynamic coefficients that were not readily available were estimated using some of the formulae outlined previously and by using methods from refernces [27][36][37][38] and [39]. The values were then converted to 'Bis' non-dimensional form. The following figures show a comparison of simulated and full scale results in varying depths of water;

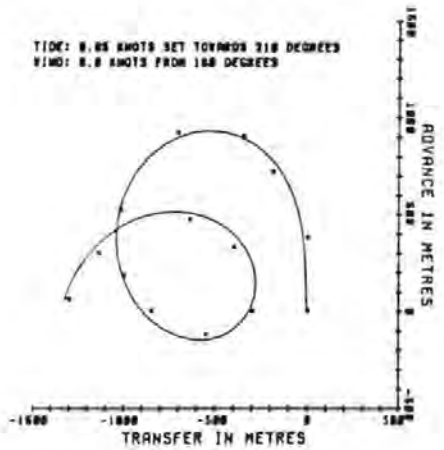

Figure 4. Deep Water 35° Port Turning Circle

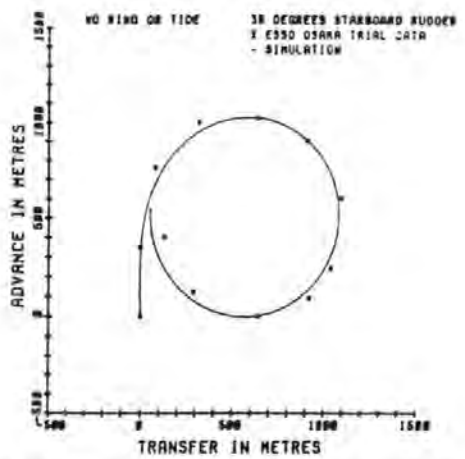

Figure 5. Medium Water Depth 35° Starboard Turning Circle

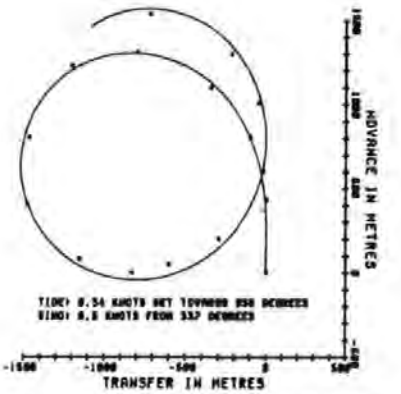

Figure 6. Shallow Water 35° Port Turning Circle

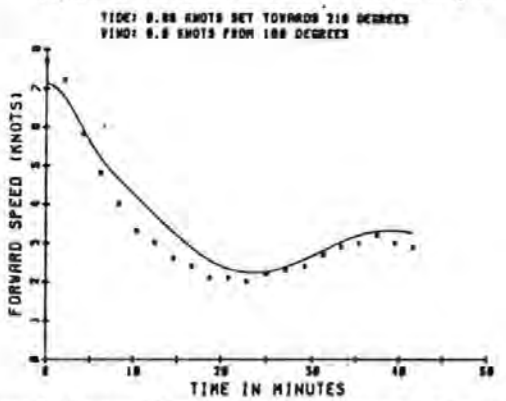

Figure 7. Forward Speed / 35° Port Turn in Deep Water

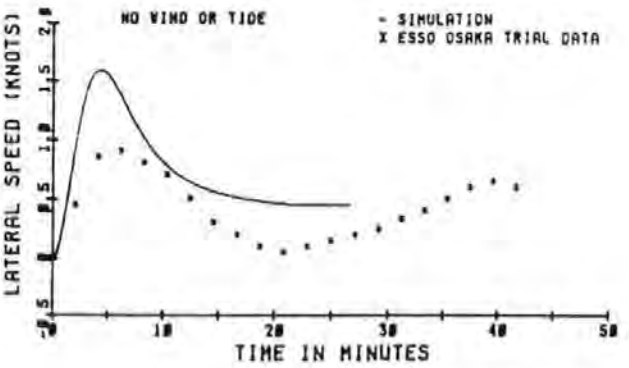

Figure 8. Lateral Speed / 35° Port Turn in Deep Water

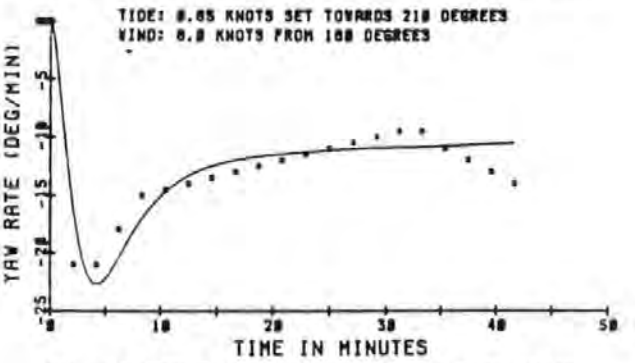

Figure 9. Yaw Rate / 35° Port Turn in Deep Water

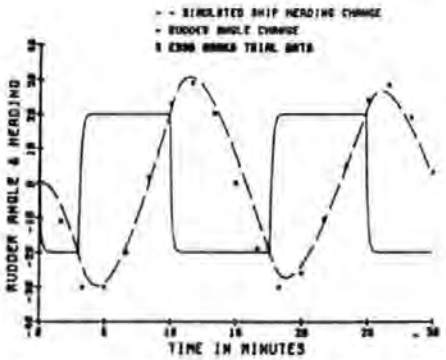

Figure 10. 20° Kempf Manoeuvre in Medium Depth Water

With reference to figures 4-10, it can be seen that the simulated results are comparible with the full scale trials results. Simulations were carried out at varying water depths and with wind and tide influences. It was noted that on some simulated turning circles and Kempf manoeuvres the model tended to respond slowly to rudder angle alterations, particularly in the deep water simulations, when compared with the same manoeuvres of the ship. This aspect of the model performance is being investigated in the next phase of the research programme.

CONCLUSIONS

This paper has attempted to provide an overview of differing types of mathematical models in use in marine simulators. Recent research at Polytechnic South West favours the modular type of mathematical model and the results are shown from one such series of model tests. The ultimate aim of the research being undertaken is to investigate, design and develop an integrated navigation and collision avoidance system of which the model forms an integral part. The model in use at present is required to be expanded to simulate more complex situations such as stopping in narrow channels.

This work is central to the overall research at Polytechnic South West. It is intended to improve the model in use at present, to not only use in simulations, but also to implement it on the Polytechnics research vessel so that the software can be tested under operational conditions. The complete integrated navigation system will ultimately be fitted in the research vessel. The system will display the required data on VDU's thus creating a central navigation console.

NOMENCLATURE

A_o	Propeller Disc Area
cp	Tangential propeller velocity
d_1	Distance CG to hull centre of pressure
d_2	Distance CG to rudder centre of pressure
d_3	Distance CG to propeller plane of rotation
D_h	Hull hydrodynamic drag
D_r	Rudder hydrodynamic drag
F_s	Propeller sideways force
I_z	Moment of inertia about z axis
L	Ship length between perpendiculars
L_h	Hull hydrodynamic lift
L_r	Rudder hydrodynamic lift
m	Mass of ship
n	Propeller revolution rate
N	Hydrodynamic turning moment
N_v, N_r, etc	Yaw hydrodynamic coefficients
r	Yaw rate
T_p	Propeller thrust
u	Forward velocity
$\bar{u}$	Vector velocity of ship CG through water
up	Axial propeller velocity
v	Lateral velocity
X	Hydrodynamic surge force
X_u, $X_{\dot{u}}$, etc	Surge hydrodynamic coefficients
Y	Hydrodynamic sway force
Y_v, $Y_{\dot{v}}$, etc	Sway hydrodynamic coefficients
α	Drift angle
α_e	Effective drift angle
δ	Rudder angle
ψ	Ship heading
ρ	Density of sea water

In this paper shorthand notation has been adopted:

$$Y_v = \frac{\partial Y}{\partial v} \quad \text{and} \quad \bar{Y}_{\dot{v}} = \frac{Y_{\dot{v}}}{\frac{1}{2}\rho L^4} = \frac{1}{2}\rho \frac{\partial^2 Y}{\partial \dot{v}^2}$$

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