THE EFFECTS OF AERATION ON WAVE IMPACTS.

by

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

PHILOSOPHIAE DOCTOR

School of Civil and Structural Engineering
Faculty of Technology
in collaboration with the
Single Layer Armour Club (SLAC)
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Dedicated to the memory of Alexander Griffiths

"Stand shadowless like silence, listening
To silence"

Autumn. Thomas Hood.
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ABSTRACT
In order to determine the effects of aeration on wave impacts, both model scale and field measurement of pressure and aeration were conducted over a period of three years. Aeration quantification techniques deployed in laboratory experiments included fluid impedance measurement which were also used in the field and acoustic methods. The most common form of impact observed was due to hydrostatic pressure variation, referred to as Class I impacts in the text.

Apart from this, two distinct impact classifications have been identified. The first of these classifications is referred to as Class II impacts in the text and arises due to water wave action. Two discrete categories occur within Class II impacts: compression waves and shock waves. Compression type impacts have long rise times, typically hundreds of milliseconds, and are produced by waves which tend to have much lower impact velocities and present much larger contact angles upon impact. These waves tend to be spilling breakers which may transport much entrained air due to interfacial turbulence. Rise times are a strong function of both void fraction and mean bubble size.

Shock waves, with rise times typically less than 20 milliseconds, occur when conditions are such that the local velocity of sound is exceeded. Appropriate conditions for shock waves exist when water impacts on structures with a high velocity and narrow approach angle. Although shock wave generation requires the presence of some air in a wave in order that the local speed of sound might be exceeded, in practice void fractions of less than 20% are needed. When characterising Class II shock waves there is strong correlation between the bubbly shock wave theory and Taylor's incompressible jet impact theory.

The final class of impact is referred to as Class III in the text. Such impacts result from compression and oscillation, or direct collapse of trapped bubbles/air pockets alone. Class III impacts arise when air pockets, trapped as waves break at the wall or at some distance from a structure, collapse and transmit shock waves through the water. Class III impacts may accompany Class I or Class II impacts but it is more likely for the direct collapse of air pockets to accompany Class II shock waves and for the air pocket oscillations to accompany Class II adiabatic compression waves.

The resultant impact pressure magnitudes are functions of wave height and velocity for hydrostatic events whilst pressure magnitudes are functions of impact velocity, mean bubble size and void fraction for Class II compression waves. Peak pressure levels for Class II shock waves are dependent upon impact velocity and void fraction. Class II shock waves and Class III bubble impacts generate the highest peak pressures (typically in excess of 30kPa) whereas Class II compression wave impacts are of smaller magnitude but larger duration.

Aeration does affect peak pressures and pressure rise times but relationships between impact pressure, rise times and aeration are also dependent upon the impact regime and wave type.
"Our campaign against the sea must be waged with the same care that we would take against any other enemy threatening our boundaries".

US Army Corps of Engineers. 1964.

The influence of aeration upon breaking wave impact pressures and rise times has posed a vexed question for many years, if not centuries. Two principal schools of thought exist; one contends that aeration is a major determinant, whilst the opposing view is that impact spectra may be characterised in terms of incompressible flow theory alone.

High impact pressures with short rise times have been observed in many laboratory experiments, usually with model scale waves. When scaled up to equivalent waveheights observed at sea, model test results greatly overestimate peak pressure magnitudes, whilst Conversely underestimating most impact rise times (with the notable exception of field data from Rouville et al, 1938).

Wave breaking phenomena are of great importance to engineers who design coastal defences and to scientists involved with modelling the effects of sea level rise. It is assumed that sea level rise per se would not be the principal problem around the British Isles. Associated effects such as storm surges resulting in violent wave action would pose a severe problem even in the UK, let alone countries such as Bangladesh, where increased incidence of storm surges could prove catastrophic.

It has been predicted that a mean sea level rise of 15cm around the UK would result in a 1 in 150 year wave breaking event becoming a 1 in 40 year event, while for an 80cm rise the probability would increase to an annual event.

With reference to coastal defence design: most seawall and breakwater designs are tested using model waves and implications are that scaling for peak pressures is incorrect. By contrast the rise time criterion might be too conservative with respect to time thus biasing any adverse effects, eg resonance, to small components rather than larger armour units or sections of walls.

It is apparent that the relative influences of all parameters pertinent to breaking waves need clarification. This provides the rationale for the work described in this thesis.
GLOSSARY OF TERMS.

\( a_0 \) constant relative to area
\( a_n \) general coefficients
\( A \) surface area
\( A \) ratio of bubble pressure to inertial pressure
\( A \) attenuation
\( A_1 \) bubble interface surface area
\( A_n \) general coefficients
\( A_o \) initial surface area
\( A_x \) excess surface area

\( b^A_{ab} \) radiation/thermal/viscous dissipation coefficients
\( b_n \) general coefficients
\( B \) constant proportional to mass transfer
\( B \) ratio viscous to inertial pressure
\( B \) summed force term (Navier-Stokes)
\( B \) magnetic induction
\( B_T \) magnetic induction in toroid

\( c \) general velocity/celerity term
\( c_{g/l} \) speed of sound in gas/liquid
\( c_{hf/lf} \) "high frequency"/"low frequency" speed of sound
\( c_o \) speed of sound in bubble free water
\( C \) ratio of surface tension to inertial forces
\( C_{g/l} \) specific heat at constant pressure (gas/liquid)
\( C_s \) saturation concentration
\( C_a \) ambient concentration far from bubble

\( d \) diameter
\( d \) mean diameter
\( d_b \) breaking wave water depth
\( d_e \) effective bubble diameter
\( D \) Rayleigh dissipation function
\( D \) length of air pocket (Bagnold)
\( D_{g/l} \) diffusivity (gas/liquid)
\( D_o \) bubble cloud diameter
e exponent
ε aspect ratio
E elasticity
E elastic constant of air
Ei induced electric field intensity
EMAX maximum value of electric field intensity
Eo Eotvos number

f general frequency term
f0 dummy frequency term
fcloud bubble cloud resonance frequency
fd drive frequency
fc center frequency
f0 resonance frequency
F general force term
FD drag force

G acceleration due to gravity

H general height term
H waveheight
Hb breaking waveheight

I impulse
I intensity
I electric current
Im imaginary component of complex number
Is scattering intensity

j exponent power
j0 induced current density

k shape oscillation parameter
k wave number (2π/λ)
k0 stiffness parameter
k' real component of shock wave rise
k'' imaginary component of shock wave rise
K Boltzmann's constant
K time averaged mass transfer coefficient
K length of fluid cylinder (Bagnold)
K(ωc) thermal diffusivity (gas/liquid)
K HI Harkins correction factor
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<td>$l$</td>
<td>length of Rayleigh-Taylor instability</td>
</tr>
<tr>
<td>$l$</td>
<td>acoustic path length</td>
</tr>
<tr>
<td>$L$</td>
<td>Lagrangian</td>
</tr>
<tr>
<td>$L_b$</td>
<td>breaking wavelength</td>
</tr>
<tr>
<td>$m$</td>
<td>exponent power</td>
</tr>
<tr>
<td>$m$</td>
<td>general mass term</td>
</tr>
<tr>
<td>$m_{b eff}$</td>
<td>effective bubble mass</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$M_{d/u}$</td>
<td>downstream/upstream Mach numbers</td>
</tr>
<tr>
<td>$M_{HF/LF}$</td>
<td>&quot;high frequency&quot;/&quot;low frequency&quot; Mach numbers</td>
</tr>
<tr>
<td>$M_o$</td>
<td>Morton number</td>
</tr>
<tr>
<td>$M_s$</td>
<td>Mach shock propagation</td>
</tr>
<tr>
<td>$n$</td>
<td>dissolved gas concentration</td>
</tr>
<tr>
<td>$n(r)$</td>
<td>bubble concentration</td>
</tr>
<tr>
<td>$N$</td>
<td>number of bubbles per unit volume</td>
</tr>
<tr>
<td>$N_T$</td>
<td>number of turns in magnetic coil</td>
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<tr>
<td>$p_{n(r)}$</td>
<td>bubble size probability</td>
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<td>$P$</td>
<td>general pressure term</td>
</tr>
<tr>
<td>$P_a$</td>
<td>acoustic pressure</td>
</tr>
<tr>
<td>$P_b$</td>
<td>bubble pressure</td>
</tr>
<tr>
<td>$P_{d/u}$</td>
<td>downstream/upstream pressure</td>
</tr>
<tr>
<td>$P_o$</td>
<td>atmospheric pressure</td>
</tr>
<tr>
<td>$P_{\text{MAX}}$</td>
<td>maximum peak pressure</td>
</tr>
<tr>
<td>$P_s$</td>
<td>shock pressure</td>
</tr>
<tr>
<td>$P_{\text{WH}}$</td>
<td>water hammer pressure (von Karman)</td>
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<tr>
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<tr>
<td>$Q$</td>
<td>quality factor</td>
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<td>$Q$</td>
<td>thermal energy</td>
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<td>$Q$</td>
<td>volumetric flow rate</td>
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<tr>
<td>$Q_{\text{cl}}$</td>
<td>heat capacity of gas/liquid</td>
</tr>
<tr>
<td>$Q_o$</td>
<td>unloaded quality factor</td>
</tr>
<tr>
<td>$r$</td>
<td>general distance or radius term</td>
</tr>
<tr>
<td>$r_{d/u}$</td>
<td>downstream/upstream bubble radius</td>
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<tr>
<td>$r_s$</td>
<td>surface tension radius</td>
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<td>$r_{\text{res}}$</td>
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<tr>
<td>$Re$</td>
<td>real component of complex number</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynold's number</td>
</tr>
<tr>
<td>$R_m$</td>
<td>resistance of bubble mixture</td>
</tr>
<tr>
<td>$R_{\text{MAX/MIN}}$</td>
<td>maximum/minimum bubble radius</td>
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</table>
R \sub{Ro}  mean bubble radius
R_{p}     probe resistance
R_{w}     resistance of still water

s       displacement
s       entropy
S       trapped air volume
S_{r}   bubble radial stress term

t       general time term
t_{a}    time for growth of Rayleigh-Taylor instability
t_{g}    minimum time necessary for growth of Rayleigh-Taylor instability
t_{r}    impact pressure rise time
T       general temperature term

u       general flow velocity term
u_{d/u} downstream/upstream velocity
u_{w}   normal velocity
u       tangential velocity
u(r)    gas content in interval r to r+\delta r
u_{i}   impact velocity
u_{r}   recirculation velocity
u_{rel} relative velocity
U       internal energy
U_{o}   ambient flow velocity

v       general volume term
v       dimensionless velocity gradient
v_{s}   shock velocity term
v'      complex bubble volume amplitude
V       change in volume
V       relative velocity of jet
V_{B}   bubble volume
V_{s}   volume occupied by gas
V_{m}   measured voltage
V_{o}   initial volume

w       width of bubble cloud
W       work/mechanical energy
W       frequency ratio

x       general spatial coordinate
x       bubble coating factor
X       jet expansion length (Fuhrboter)
y       general spatial coordinate
z general spatial coordinate
Z shear rate

GREEK SYMBOLS,

α attenuation
α₁₂ bubble stiffness index parameters
α₁₂ functions of air pocket length (Bagnold)

βₓᵧ₀ void fraction (downstream/upstream/equilibrium)

γ(pv) ratio of specific heats constant pressure/volume
γᵧᵧ eff effective ratio of specific heats/polytropic index
Γ gamma function
Γ mathematical function varying as β

δ general damping constant
δ shock width
δᵣᵣᵣ radiation/thermal/viscous damping
δᵣᵣ total damping constant
Δ small quantity of

ε sum of shear stresses

θᵣᵣ incident/scatter angles

κ maximum to minimum bubble diameter ratio

λ general wavelength term
λᵣᵣᵣ characteristic diffusion lengths (gas/liquid)

μᵣᵣᵣ molecular viscosity (gas/liquid)

νᵣᵣᵣ kinematic viscosity (gas/liquid)

ρ general density term
ρᵣ fluid density
ρᵣᵣᵣ gas/liquid density
ρᵣᵣᵣᵣ water density
\( \sigma \) \hspace{0.5cm} \text{general surface tension term}

\( \sigma_{\text{abs}} \) \hspace{0.5cm} \text{bubble absorption/extinction/scattering cross sections}

\( \sigma_m \) \hspace{0.5cm} \text{electrical conductivity of gas/water mix}

\( \Sigma \) \hspace{0.5cm} \text{summation}

\( \Sigma_{e/s} \) \hspace{0.5cm} \text{total extinction/scattering cross sections}

\( \tau \) \hspace{0.5cm} \text{characteristic diffusion time}

\( \tau \) \hspace{0.5cm} \text{bubble collapse time (Rayleigh)}

\( \tau_{\text{rel}} \) \hspace{0.5cm} \text{relaxation time or rise time}

\( \tau_m \) \hspace{0.5cm} \text{mean bubble surface lifetime}

\( \phi \) \hspace{0.5cm} \text{general angle term}

\( \Phi \) \hspace{0.5cm} \text{velocity potential}

\( \Phi \) \hspace{0.5cm} \text{thermal damping function}

\( \chi \) \hspace{0.5cm} \text{compressibility}

\( \chi \) \hspace{0.5cm} \text{gas to liquid viscosity ratio}

\( \chi_{(\rho \gamma)} \) \hspace{0.5cm} \text{thermal conductivity (gas/liquid)}

\( \psi \) \hspace{0.5cm} \text{volumetric shape parameter}

\( \psi_{(\phi \omega)} \) \hspace{0.5cm} \text{downstream/upstream shock deflection angle}

\( \omega \) \hspace{0.5cm} \text{general angular frequency term}

\( \omega_0 \) \hspace{0.5cm} \text{centre angular frequency}

\( \omega_r \) \hspace{0.5cm} \text{resonance angular frequency}

\( \Omega \) \hspace{0.5cm} \text{solid angle}
## WAVE IMPACT CLASSIFICATIONS

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
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<tbody>
<tr>
<td>I(a)</td>
<td>hydrostatic</td>
</tr>
</tbody>
</table>
| I(b) | hydrostatic with harmonic components  
      | ie when pressure sensor well below SWL |
| I(c) | hydrostatic at oblique impact |
| II(a) | fluid compression waves where bubble oscillation  
      | period >> pressure rise time |
| II(b) | fluid compression wave - adiabatic P-t curve |
| II(c) | bubbly fluid shock wave |
| III(a) | air pocket/bubble impacts with subsequent substantial  
      | volume oscillation |
| III(b) | collapsing air pocket/bubble impacts giving rise to air shocks |
CHAPTER 1

REVIEW OF CURRENT MODELS FOR WAVE IMPACTS

INTRODUCTION

The problem of waves impacting on coastal structures has been under serious consideration for the last 150 years. It is clear that normal wave action will result in changes of the hydrostatic pressure which will vary as the wave velocity. The resultant pressure impacts may last for several seconds and will be of a form shown in Figure 1.1. Such impacts are also referred to as the "bourrage". The earliest recorded successful measurement of pressures due to wave breaking were those of Stevenson[1] at Skerryvore Hebrides in the 1840's. Since then two principal schools of thought have emerged to explain the processes occurring during impact. The 2 major transient hypotheses are:

a) Transients arise due to the collapse of trapped air pockets and the piston effect of encroaching fluid. Compression of the fluid is of paramount importance.

b) Transients arise due to phenomenally high vertical fluid accelerations. The fluid is treated as incompressible.

Taylor's jet impact theory, the simplified forerunner to the complex and elaborate theory covered by (b) above is discussed later in Section 1.3, and is applied in subsequent chapters.

1.1 THE EFFECT OF TRAPPED AIR POCKETS UPON WAVE IMPACTS

1.1.1 Bagnold

The first comprehensive attempt to obtain formulae for impact pressure and pressure rise time was made by Bagnold in 1939 [2]. He postulated that pressure shock waves resulted from the collapse of trapped air pockets at the wave/jet front. Assuming that adiabatic gas laws are obeyed, then the equation of motion for a cylinder of fluid in the x direction is given by:

$$\rho_0 \frac{D}{\rho_{0}} \frac{d^2 x}{d t^2} - P_0 \left[ \frac{D}{\rho_{0}} \right]_{x} + P_0 = 0 \quad (1.1)$$
where $D$ is the length of the air pocket; $K$ is the "active" length of fluid cylinder as shown in Figure 1.2.

The maximum possible momentum per unit area of the fluid cylinder is given by:

$$I = \rho u K$$  \hspace{1cm} (1.2)

where $u$ is the fluid velocity.

Bagnold performed measurements on breaking waves in a 36 foot long model wave tank and obtained the following expression for peak shock pressure:

$$P_s = 2.7 \rho_F u^2 \frac{K}{D}$$  \hspace{1cm} (1.3)

where $P_s$ is the peak shock pressure above atmospheric.

Bagnold postulated an expression for the pressure rise time based upon complete adiabatic compression of the air pocket. He observed an approximate relationship between the parameter $K$ and the wave height $H_b$ such that $K \approx \frac{H_b}{5}$; thus (1.3) may be rewritten:

$$P_s \approx 0.54 \rho_F u^2 \frac{H_b}{D}$$  \hspace{1cm} (1.4)

1.1.2 Denny

Denny[3] repeated Bagnold's experiments in 1951. He found that the wave breaking process was highly position sensitive. Only breaking waves yielded intense shock pressures and millisecond rise times, although on collision with a wall, both breaking and non-breaking waves were forced up the wall as high velocity jets before collapsing into reflection waves. These measurements reinforced the belief that wave breaking is a stochastic process with the most probable shock pressure directly proportional to wave height. The maximum pressure observed during the investigation was 110 times the wave height and Denny concluded that extrapolation in 10 foot sea waves would result in shock pressure maxima in excess of 3,000kPa. The probability of such magnitudes is unlikely since ripples of dimension $H_b/10$ result in halving of the shock pressure due to the enhanced probability of enclosing air pockets.

1.1.3 Mitsuyasu

Mitsuyasu[4] performed impact pressure measurements for a uniform train of 10.5cm
waves in a laboratory tank of dimensions 22m(L) x 0.6m(W) x 0.35m(D). Bagnold's compression model was modified to fit the results thus (in the absence of air leakage):

\[ P_S = 1.2 \left( \frac{\rho_F U_0^2 K}{D} \right) \pm 1.18 \left( \frac{\rho_o U_o^2 K P_o}{D} \right)^{1/2} \quad (1.5) \]

and when air leakage occurs, assumes a form

\[ P_S = Q_0 e^{-\alpha t} \sin \omega t \quad (1.6) \]

\[ \omega \] is a form of resonance frequency for an effective radius \((kD)^{1/2}\) to account for air pocket oscillation and \(\alpha\) is an attenuation term to account for the leakage.

Mitsuyasu believed that were the front face of an incident wave perfectly regular, then water hammer pressures would result. The trapping of air pockets was assumed to arise due to velocity dispersion where the wave crest is travelling with greater velocity than the trough.

1.1.4 Muraki

Muraki [5] conducted field tests on Hokkaido and obtained wave pressure, wave run-up and breakwater oscillation data. He classified wave pressure curves into four categories as shown in Figure 1.3. Curves A to C represented non-breaking "clapotis" type wave pressures and that curve D was representative of breaking waves which produce "shock" pressures or "gifles". Typically the time for "gifles" observed by Muraki was approximately 70 milliseconds.

1.1.5 Lundgren

Lundgren [6] identified three shock regimes when predicting forces and deformations on breakwaters.

Lundgren also attempted a definition of the term shock pressure as "a pressure of substantial magnitude the rise time of which is of the order 100 milliseconds or less".

i) ventilated shock

Ventilated shocks occur when a wave is incident on a structure such that all or most of the intervening air escapes prior to collision as shown in Figure 1.4(a). The rise time for the shock pressure is given by [6]:

1-3
\[ t_r = \frac{S}{(H_b \cdot C)} \quad (1.7) \]

where \( C \) is the wave celerity, \( S \) is the volume of the trapped air per unit length of structure, likewise the shock pressure may be expressed:

\[ P_s = \frac{\rho_F \cdot C^2}{2S} \cdot H_b^2 \quad (1.8) \]

Ventilated shocks are affected by gravitational and inertial forces only, allowing Froude law scaling between model and prototype, since there are no terms involving compressibility or the local speed of sound.

ii) Compression Shock

When a wave crest is travelling with greater velocity than the bulk of the wave, a concave profile results due to entrapment of air, see Figure 1.4(b). Lundgren postulated that some fraction of the wave's kinetic energy was converted into bubble/air pocket motion, the rest of the kinetic energy caused vertical run-up. The collapse of the air pocket may effect an audible acoustic signal and water splash. Lundgren suggested that scaling from model to prototype might be feasible, (based on empirical data), using a dimensionless parameter \( H^* \) such that:

\[ H^* = r^{2/7} - 1.4 + 0.4 \cdot r^{-5/7} \quad (1.9) \]

where \( r = \frac{P_s}{P_0} - 1 \)

When the value of \( H^* \) is approximately 0.2 then the maximum shock pressure is linear with respect to waveheight and Froude law scaling is appropriate.

iii) Hammer Shock

When a mass of water strikes a structure normally, a high intensity short duration pulse may result. If the system were bounded then the incident shock pressure could be obtained from von Kármán's formula

\[ P_{WH} = \rho_\varphi \cdot u \cdot c_\varphi \quad (1.10) \]
where \( c_g \) is the local speed of sound.

He believed that hammer type shocks may be observed in concert with compression shocks due to the action of a well formed wave crest (Figure 1.4(c)).

1.1.6 **Fuhrbörter**

Shock pressures generated by water jet impact were investigated by Fuhrbörter [7] using high speed jets. The aim of the investigation was to simulate shock pressures on rigid walls such as breakwaters by reproducing the conditions necessary for shocks to occur. A jet of 20cm diameter impacted on a measurement surface for incidence angles in the range 30° to 90°. Observed rise times were in the range 1 to 2 milliseconds with corresponding fall times of 2 to 4 milliseconds. Maximum pressures were observed for an incidence angle of 82.5° with minimum pressures resulting for 30° incidence. Typically the maximum pressure measured was about 400 kPa but turbulence effects in the water also help to reduce maxima. Fuhrbörter derived an expression for peak pressure as a function of the elasticity ratio between liquid and gas thus:

\[
P_S = \left[ 1 + \left( \frac{E}{E_a} - 1 \right) \frac{D}{X} \right]^{-1} \quad (1.11)
\]

where \( D \) is analogous to Bagnold’s parameter and denotes the effective air layer thickness over the impact area and \( X \) is the length of the expansion area of the jet axis (compared to Bagnold’s \( K \)).

\( E/E_a \) is the ratio of elasticity of liquid to air (=15500).

1.1.7 **Oumeraci and Partenscky**

Oumeraci and Partenscky have conducted both small scale and large scale laboratory investigations into the effects of breaking waves on vertical structures such as breakwaters [8,9]. They indicated two principal breaking regimes and the choice of expression depends on whether travelling waves may be characterised by Miche’s expression [10]:

\[
\frac{H_b}{L_b} = 0.142 \tanh \left( 2\pi d_b/L_b \right)
\]  

(1.12)

where \( H_b \) and \( L_b \) are the local waveheight and wavelength at the critical breaking depth \( d_b \).

or this expression for standing waves which break when [11]:
In stormy conditions wave mismatches arise due to collision of incident and reflected waves and breaking occupies a region between (1.12) and (1.13). There is a tendency toward (1.13) for increased mismatch. Analogous to Muraki [5], Oumeraci and Partenscky [8] identified 4 wave classifications:

i) Turbulent Bore (Spilling breaker):
The wave has already broken and a convex foam covered bore approaches a structure and is vertically deflected.

ii) Advanced Plunging Breaker with large air pocket:
The wave crest overturns at the structure entrapping a large volume of air resulting in an audible signal as the pocket collapses and the jet rushes up the wall.

iii) Young Plunging Breaker:
The trapped air pocket is very small and compression of the air cushion results in a higher frequency acoustic signal than in (ii) and the trapped air is entrained as bubbles in the bulk fluid while the body of water rushes up the wall.

iv) Upward deflected breaker:
There is a very rapid vertical rise of the waterline with no air entrainment.

The resultant forces expected from each of these wave categories is given in Figure 1.5.

Oumeraci and Partenscky investigated the effect of air entrapment on the dynamic response of a structure [9]. They found that the air pocket of an incident breaker may perform volume oscillation with the period of the oscillation directly proportional to the waveheight. If the onset of bubble oscillation occurs within the first or the last quarter cycle of the structure's natural oscillation period then there will be a cumulative response and if the bubble oscillation frequency is close to the structure's natural resonance frequency the implications could be serious.

1.2 THE EFFECT OF HIGH FLUID ACCELERATION UPON WAVE IMPACTS

The alternative school of thought with respect to wave impacts is that which maintains that the observed "shock" pressures result from rapid vertical acceleration of the incident wave. There are two principal models for characterising this phenomenon -
numerical modelling with finite boundary computations and solving analytically using the theory of pressure impulses.

Numerical Solution
Dold and Peregrine[12] devised boundary integral computations describing free surface motion resulting from irrotational inviscid flow. Laplace's equation for the velocity potential is evaluated on the boundaries with the effective mesh controlled by Bernoulli's equation. An outline of the procedure is (see [12] for further details)

i) Specify initial conditions: x,y position co-ordinates and the initial velocity potential;

ii) Using Laplace's equation solve for the gradient of the velocity potential at the free surface;

iii) Time step values of the surface velocity potential using Bernoulli's equation, assuming zero pressure at the free surface;

iv) Time step the position of the free surface using:

\[
\begin{align*}
\frac{Dx}{Dt} &= \frac{\partial \phi}{\partial x} \\
\frac{Dy}{Dt} &= \frac{\partial \phi}{\partial y}
\end{align*}
\]  

(1.14)

Analytical Solution
If the effects of viscosity, gravity and fluid convection are negligible compared to fluid acceleration then the Navier–Stokes equation simplifies to Newton's second law thus:

\[
\dot{u} = \frac{1}{\rho_f} \nabla P
\]  

(1.15)

(1.15) integrated over the impact time interval will give the pressure impulse, the divergence of which satisfies Laplace's equations

\[
\nabla^2 I = 0
\]  

(1.16)
The pressure impulse remains unaffected by turbulence. Cooker and Peregrine [13] have specified wave impacts using three parameters: $U_n$, the velocity normal to the structure, $H_b$, the waveheight and $\mu$ which is a fraction in the range 0 to 1 such that $\mu H_b$ characterises the height of the impact zone. They obtained an expression for the impulse such that:

$$I(x,y) = 2\rho_F U_n H_b \sum_{n=0}^{\infty} \frac{(\cos \mu \lambda_n - 1)}{\lambda_n^2} \sin \left( \lambda_n y/H_b \right) \exp \left( -\lambda_n x/H_b \right)$$  \hspace{1cm} (1.17)

where $x > 0$, $-H_b \leq y \leq 0$ and $\lambda_n = \frac{(n+1) \pi}{2}

They indicated that the peak pressure contours will have a similar distribution to those of the impulse, enabling the modelling of transient pressure gradients.

Impact Mechanism

Cooker and Peregrine [13] have shown through their modelling that for maximum impact pressure there is no direct impact due to the water surface, rather the effect of rapid acceleration of the water level vertically up the wall causes a "flip-through" mechanism, as illustrated in Figure 1.6, resulting in an upward splash. The maximum computed rate of change of pressure is $3000 \rho g \frac{1}{2} H_b^{3/2}$ and the maximum water acceleration is $10^4$ times that due to gravity.

1.3 SIMPLIFIED JET IMPACT THEORY

Some of the theory covered in section 1.2 was derived from work conducted by Taylor [14] with expansion and modification of the boundary problems evaluated by Vinje and Brevig[15].

Taylor's jet impact model states that when a jet of water with normal velocity $U_\perp$ impacts a plane surface at an oblique angle it produces a thin layer of high pressure which deflects streamlines away from the impact region thus reducing the pressure. The maximum stagnation pressure integrated over the area of impact is $\frac{1}{2} \rho U_\perp^2$, as in the Bernoulli expression. This stagnation pressure may be greatly exceeded for oblique impacts (since the impact zone ceases to be symmetric but assumes a skewed distribution as shown in Figure 1.7) and becomes very peaked and tends to infinity as the impact angle tends to zero. It is at this point where the model outlined in Section 1.2 assumes relevance.

The maximum allowed shock pressure is given by Von Karman's 'Water Hammer' expression (1.10). It is possible to exceed even this value at points across a narrowing impact zone, but the pressure integrated across the whole impact zone cannot exceed water hammer values.
If the jet's frame of reference travels at \( U_L \sin \Phi \) with respect to the impact zone and the relative velocity between plate and jet is \( V \) then the maximum impact pressure is given by the expression:

\[
P_s = \frac{1}{2} \rho \ell \left( V + \frac{U_L}{\sin \Phi} \right)^2
\]

(1.18)

The resultant high pressures travels across the impact zone at speeds typically equal to or greater than the local speed of sound. The subsequent jet of water upon impact experiences a tangential velocity given by the expression

\[
U_{11} = U_L \left[ \frac{1}{\tan \Phi} + \frac{1}{\sin \Phi} \right] = \frac{U_L}{\tan \Phi/2}
\]

(1.19)

which is the sum of impact and parallel water surface velocity components.

These expressions are the simplest description equations governing the behaviour of an incompressible fluid in contact with a solid boundary. A pictorial representation of the action is given in Figure 1.8.

The above model is highly applicable to breaking waves of the plunging type, where the angle of approach changes constantly in close proximity to coastal structures.

For plunging waves at the point of breaking, the impact angle \( \Phi \) reduces rapidly thus offering the necessary conditions for very high impact pressures i.e. large values of \( U_L / \sin \Phi \).

1.4 SUMMARY

Wave impact models proposed by a range of researchers have been discussed. All of the models covered above fall into one of two regimes, namely compressible systems where the effects of any gas phase must be included in pressure calculations and incompressible systems where high pressures arise due to impact or acceleration of high velocity fluids alone. Two models have been looked at in greater detail and applied to laboratory and field results in Chapter's Four and Five.

A different approach to the propagation of pressure waves through bubbly fluids is considered in Chapter Three and it will be shown in subsequent chapters that there is some overlap between compressible models and the incompressible Taylor jet impact theory.
**FIGURE 1-1.** TYPICAL WAVE PRESSURE SPECTRUM.

**FIGURE 1-2.** BAGNOLD'S COMPRESSION MODEL.

**FIGURE 1-3.** LUNDGREN'S WAVE IMPACT MODELS.

**FIGURE 1-4.** MURAKI'S WAVE CLASSIFICATIONS.

**FIGURE 1-5.** OUMERACI'S WAVE CLASSIFICATIONS.

**FIGURE 1-6.** COOKER/PEREGRINE "FLIP-THROUGH" MODEL.
FIGURE 1-7. VARIATION OF IMPACT PRESSURE AS JET ANGLE ALTERS. (TAYLOR)
impact pressure $= \frac{1}{2} \rho (v + u / \sin(\phi))$

**Figure 1-8. Oblique Impact of Jet on a Plane Surface. (Taylor's Theorem)**

(a) Jet impact on plate

(b) Breaking wave - analogous to situation (a)
REFERENCES - CHAPTER ONE.


2.1 BUBBLE GENERATION AND CHARACTERISTICS

2.1.1 DEFINITION OF A BUBBLE

A bubble may be defined as a gas filled cavity enclosed by a liquid envelope. Bubbles occur in the environment due to a varied range of circumstances a sample of which are listed below.

a. Entrapment of air due to wind/wave action at sea.

b. Entrapment of air around vessels leading to wake production.

c. Cavitation due to large negative pressures near ship propellers, ie. change in volume due to change in pressure at constant temperature.

d. Chemical changes eg effervescence; electrolysis.

e. Boiling ie change in volume due to change in temperature at constant pressure.

2.1.2 "BIRTH" AND GROWTH OF BUBBLES

Bubbles may be viewed as living systems with distinct inception and termination processes. Whatever natural method or artefact is used to generate bubbles the basic physics remains the same. Liquid is "torn apart" and gas rushes into the cavity from either a discrete gas phase ie air above the sea or from gas/vapour in the fluid itself.

Mass transfer occurs between liquid and gas phase and if bubble formation is rapid then the momentum of the gas phase is large and internal circulation of gas within the bubble ensues. If however bubble formation is slow then internal circulation will not arise.
There are 2 models which explain adequately mass transfer and growth:

a. surface stretch model

b. fresh surface model

a. assumes that interfacial components remain invariant and the bubble surface becomes stretched upon expansion, whereas b. allows for the increase in bubble dimensions by the addition of new fluid at the interface.

The interfacial area may be expressed thus:

\[ A = A_x + a_0 t^m \]  \hspace{1cm} (2.1)

where \( A_x \) is the excess surface area left after growth and \( A \) the resultant surface area. \( a_0 \) is a constant and the power \( m \) has been evaluated as 2/3 by Ranz et al [1] and 1 by Heertjes [2]. The mass transfer factor for gas bubbles in liquid is given by Clift et al. [3]

The time averaged mass transfer coefficient area product may be expressed:

\[ \bar{K}A = 2 B A_0 (D/\pi \tau)^{1/2} \]  \hspace{1cm} (2.2)

The constant \( B \) has a different value dependent upon which model is adopted: \( A_0 \) is the initial surface area of the bubble.

From [3] the following expressions are obtained:

**surface stretch model**

\[ B = \frac{1}{(2n + 1)} \left[ 1 + \frac{2n}{n + 1} \left( \frac{A_x}{A_0} \right) \left[ 1 + n \left( \frac{A_x}{A_0} \right) \right] \right]^{1/2} \]

**fresh surface model**

\[ B = a_1 + (1-a_1) \frac{A_x}{A_0} \]

where \( a_1 = \frac{\sqrt{\pi}}{2} \frac{\Gamma(n+1)}{(n+1/2)\Gamma(n+1/2)} \)

It is evident however that the models are in reasonably good agreement and that the time averaged mass transfer coefficient is a weak function only of the power \( m \).
2.1.3 "DEATH" AND BREAK-UP OF BUBBLES

Decay of bubbles is controlled by external conditions and 4 major regimes exist:

static conditions; turbulent flow; velocity gradients and resonance.

2.1.3.1 Static Conditions

Bubble deformation occurs due to Rayleigh–Taylor instabilities forming at the leading edge of a bubble. Indentations occur and these deepen with time. Grace et al [4] derived an expression for the time available for a disturbance $\mathcal{G}$ to grow thus:

$$t_d = d_{be} \frac{(2+3\chi)\ln(\cot(\ell/4d_{be}))/4u}{4d_{be}}$$

(2.3)

where $d_{be}$ is the effective bubble diameter (equivalent sphere) $u$ is the fluid velocity and $\chi$ is the viscosity ratio of the dispersed to continuous phase.

Experimental evidence indicates a relationship between the available time and the requisite growth time $t_g$ as derived by Plesset and Whipple [5]. Splitting for gas bubbles occurs when $t_d > 3.8t_g$ [4] consequently an upper limit is established for the maximum stable effective spherical bubble diameter of a single bubble unaffected by any other forces, which for air in tap water assumes the value 4.9cm.

2.1.3.2 Turbulent Flow Fields

Turbulent flow fields are extremely complex thus problematic to model. Stability criteria may be determined using the Hinze model [6].

a. Shear forces in concert

The combination of shear stress components in liquid acts to deform a bubble surface. If the shear stress components exceed the combined effects of liquid viscosity and bubble surface tension then mass is lost from the bubble to the surrounding liquid and bubble collapse ensues. The collapse criterion may be expressed thus:
where $\epsilon$ is the sum of viscous shear stresses around the bubble resulting from turbulence, $\sigma$ is the bubble surface tension, $\mu_g$ is the bubble viscosity and $\rho_g$ the gas density.

b. Large turbulent eddies

In most circumstances turbulent eddies act as transport mechanisms only and owing to their relatively large dimensions have minimal influence upon bubble collapse. However when a turbulent eddy is of comparable or smaller magnitude that a bubble's effective diameter then collapse is highly probable.

2.1.3.3 Velocity Gradients

Bubbles burst when velocity gradients within the bubble and at its surface are of sufficient magnitude to exceed bubble surface tension. A bubble which is initially spherical will undergo volume oscillations when exposed to a constant velocity gradient and will eventually assume an ellipsoidal shape predicted thus [7]:

$$
\frac{1 - \epsilon}{1 + \epsilon} = \frac{5 (19\psi + 16)}{4 (\psi+1) \left(19\psi \right)^2 + \left(\frac{20\sigma}{r_o Z \mu_g} \right)^2}^{\frac{1}{2}}
$$

(2.5)

where $r_o$ is the mean bubble radius, $\epsilon$ is the bubble aspect ratio, $\psi$ is the dimensionless velocity gradient and $\psi$ is a volumetric shape parameter, $\mu_g$ is the liquid viscosity and $Z$ the shear rate.

The relaxation time of the oscillation is approximated thus:

$$
\tau \sim r_o \mu_g/\sigma
$$

(2.6)

The limiting case occurs for fluid particles in steady state shear flow as derived by Taylor [8] [9].

Experimental evidence shows that bubbles burst when $\epsilon<0.26$ [10] and that bursting occurs within a shape parameter window thus: $0.005 < \psi < 3$ [11].
2.1.3.4 Resonance

It is possible that bubble bursting may result when the characteristic turbulence frequency is close to or equal to the bubble's natural resonance frequency [12]. Subharmonic excitation may also cause break up particularly for large bubbles since shape oscillations are easily activated by subharmonics and these lead to bubble deformation. This last point is covered in more detail in section 2.3.2.

2.2 LINEAR BUBBLE DYNAMICS

2.2.1 BACKGROUND

There are many aspects to the study of the acoustic properties of bubbles, such as resonance behaviour, damping, dispersion and attenuation; which can be characterised by linear second order differential equations of motion or with the inclusion of higher order terms by nonlinear equations of motion. The theory included in this chapter attempts to cover the salient features of both linear and nonlinear bubble characteristics and in addition such transient characteristics particular to bubbles resulting from cavitation.

This section is devoted to the linear behaviour of bubbles - volume pulsations, resonance, the constituents of the damping constant and their relative importance and frequency dependence, the transition between adiabatic and isothermal values of the damping coefficient and stiffness parameter or 'spring constant', etc.

2.2.2 INTRODUCTION TO LINEAR THEORY

In its simplest form the motion of a pulsating gas bubble in a liquid is that of a monopole radiator, i.e. there is volume pulsation of the bubble without deformation. Thus the equation of motion for the bubble is analogous to that of a mass on a spring - simple harmonic motion (shm), with some damping or dissipation. Consequently, the bubble expands and contracts with a definite frequency and an inertial force results from the surrounding liquid causing vibration. Such a monopole radiator exhibits a sharply defined resonance peak at the frequency:

\[
fr = \frac{1}{2\pi r_0} (3\gamma P_0/\rho g)^{\frac{1}{2}}
\]

(2.7)
where \( r_0 = \) mean bubble radius, \( P_0 = \) static pressure for bubble radius \( r_0 \), \( \gamma = \) ratio of specific heats (adiabatic), \( \rho_g = \) density of water/liquid. The correct density expression which should be used in (2.7) is the sum \( \rho_g + \rho_g \) but \( \rho_g \ll \rho_g \). The other assumption made is that the system is adiabatic. Equation (2.7) was originally derived by Minnaert [13]. Bubbles pulsate when they are created and on coalescence; vibration also occurs when a free stream of liquid containing entrained gas bubbles passes by an object eg. waves, or passes through a constricted vessel, and most pertinent to our investigations when the surrounding liquid is insonified by an incident sound wave. The degree of sound damping increases with the gas content or void fraction of the liquid. Even a void fraction of \( 10^{-12} \) can produce an observable effect upon acoustic transmission loss and when bubble clouds are present the liquid tends to acoustical opacity with transmission losses of 100dB/m or greater.

2.2.3 SIMPLE HARMONIC MOTION

For a linear equation of motion, the amplitude of the volume pulsation must be small. If the inertial reaction of the liquid is ignored, then the instantaneous pressure at the surface of a bubble may be expressed:

\[
P_b = P_S \exp(j\omega t) = P_o
\]

(2.8)

where \( P_0 = \) static pressure (dc term), \( P_S \exp(j\omega t) \) sinusoidally varying pressure (ac term).

Equilibrium is only achievable in this alternating pressure field if the bubble is also vibrating. Assuming that no dissipation occurs, the equation of motion for the system may be expressed in terms of the lagrangian (kinetic energy – potential energy) \( L \), such that [14]:

\[
(d/dt) \left( \frac{\partial L}{\partial \dot{V}} \right) - \frac{\partial L}{\partial V} = 0
\]

(2.9)

where \( V = \) change in volume.

If a generalised force \( F \) is present which is not derived from a potential, then \( F \) [equation 2.9] becomes:

\[
(d/dt) \left( \frac{\partial L}{\partial \dot{V}} \right) - \frac{\partial L}{\partial V} = F
\]

(2.10)

The liquid surrounding the bubbles vibrates as the bubble undergoes expansion.
and contraction and the maximum kinetic energy of the liquid is reached when the bubble is restored to its equilibrium value $V_0$. A velocity potential exists, since the liquid flow is irrotational, i.e. $\omega \Delta v = 0$ [15]

The velocity potential at a distance $R$ from the bubble centre is given by:

$$\phi = V/4\pi R \quad (2.11)$$

It can be shown [16] that with the above conditions, the lagrangian may be written:

$$L = \frac{\rho g (8\pi r_0)}{(2.12)} (\dot{V}^2) - (\gamma P_0/2V_0) V^2$$

thus:

$$(\rho g/4\pi r_0) \ddot{V} + (3\gamma P_0/4\pi r_0) V = P \quad (2.13)$$

In the presence of a resultant pressure force $P \exp(j\omega t)$, the change in pressure, equation (2.13) may be rewritten in the form of a linear differential equation of motion for a spring:

$$m_b \ddot{V} + kV = P \quad (2.14)$$

where $m_b$ is the effective mass of the bubble and $k$ is the stiffness coefficient. Most springs undergoing SHM have a dissipation term which is derived with respect to Rayleigh's dissipation function $D$ [17]:

$$D = [\beta \dot{V}^2]^{1/2} \quad (2.15)$$

$\beta$ is the dissipation coefficient. Equation (2.14) may be amended to include damping thus:

$$m_b \ddot{V} + b\dot{V} + kV = P \quad (2.16)$$

the resonance frequency of the spring may be expressed thus:

$$\omega_0 = (k/m_b)^{1/2} \quad (2.17)$$

compare equation (2.7)
When there is no resultant change in pressure and $P$ is zero then the bubble motion is that of a damped exponential sinusoidal oscillation. The number of cycles required for the amplitude of oscillation to reach $\pi^{-1}$ of its initial value represents the $Q$ of the bubble system. When the damping component has small magnitude, the $Q$ value may be represented thus [18]:

$$Q_o = \frac{\omega_o m b}{b} \quad (2.18)$$

In the presence of a driving force which results in a change of pressure, the expression for the $Q$ value becomes:

$$Q_o = \frac{\omega_o}{\Delta f} \quad (2.19)$$

The system damping constant for the bubble system is defined as:

$$\delta_{TOT} = 1/Q_o$$

In calling $\delta$ a constant, it is implicitly assumed that only its resonance value will be used. The sharper the resonance peak (greater the $Q$), the less damping. Thus the smaller $\delta_{TOT}$ is, the more acceptable it becomes to use the damping value at resonance – hence the term damping constant.

### 2.2.4 DAMPING

The total damping constant has three components:

1. thermal damping due to heat conduction between gas and liquid;
2. radiation damping due to the radiation of spherical sound waves;
3. viscous damping due to the presence of viscous forces at the gas–liquid interface.

The above damping components are affected by a range of parameters. Thermal damping is particularly sensitive to the presence of contaminants in the fluid which leads to coating of bubbles. Radiation damping is affected by multiple scattering contributions when bubble clouds are very dense. These problems are discussed later in this Chapter.
2.2.4.1 Thermal Damping

The equations derived earlier assume an adiabatic equation of state. In a purely adiabatic system (ideal), the pressure and volume fluctuations are in phase, hence the heat efflux during the compression phase is equal to the heat flow into the bubble during expansion. Real bubble systems are not quite so simple to analyse. The gas which is in contact with the liquid is better represented by an isothermal equation of state, because of the large specific heat and thermal conductivity of the surrounding liquid. Toward the bubble centre, the adiabatic equation of state is more appropriate because there is low thermal conductivity in this region. Consequently, the bubble does not obey a single state equation, but the actual thermal process is polytropic and this results in a phase difference between the specific pressure and volume changes of the bubble. In deriving the simplest expression for thermal damping of a bubble system, several assumptions are made:

i. pressure, volume and temperature oscillations are small – hence linear;
ii. density and specific heats are constant (both are linear functions of temperature);
iii. temperature at the bubble centre is finite i.e., no temperature discontinuities which result from shock wave production. The effects of shock wave passage through a bubbly medium are addressed in Chapter 3;
iv. no temperature changes at gas/liquid interface;
v. conduction is the sole heat loss process – convection is neglected.

If convection terms are included then an additional current term would need to be added to subsequent equations. This current term would be a function of specific heat capacity at the fluid/gas interface. Convection currents do occur in large unstable bubbles with resultant internal circulation.

The process by which heat is conducted to the liquid obeys the first law of thermodynamics, which stated in differential form is:

\[
\begin{align*}
\frac{dU}{dt} &= \frac{dW}{dt} + \frac{dQ}{dt} \\
\frac{dW}{dt} &= -(P_b/\sigma v) (\partial \sigma v / \partial t) \\
\frac{dU}{dt} &= \rho g \gamma_v (\partial T / \partial t)
\end{align*}
\]

(2.20)

where \(U\) is the internal energy which is a function of the local temperature gradient, \(W\) is the work, \(Q\) is the thermal energy, \(v\) is a small volume element, and \(\gamma_v\) specific heat at constant volume. The rate of transfer of heat energy flow per unit volume from a small volume element for a conduction process can be expressed thus [19]:
\[
\frac{dQ}{dt} = \chi \cdot ^2T \tag{2.21}
\]

where \( \chi \) is the thermal conductivity of air and \( \chi_g = D_g \rho g \gamma_P \) where \( D_g \) is the diffusivity of air/gas, \( \gamma_P \) is the specific heat at constant pressure.

Substituting equation (2.21) in spherical co-ordinate form into equations (2.20) yields:

\[
(\rho g \gamma_P / r) \left[ \frac{\partial (rT)}{\partial t} \right] = (\chi_g / r) \left[ \frac{\partial^2 (rT)}{\partial r^2} \right] - (P_b / \omega \nu) \left( \frac{\partial \nu}{\partial t} \right) \tag{2.22}
\]

From consideration of the ideal gas laws\[19\], we get:

\[
P_b \nu = \omega m R (T_0 + \Delta T) \tag{2.23}
\]

where \( \omega \) is the mass of gas in volume element, and \( R \) is the universal gas constant.

Differentiation of equation (2.23) and substitution into equation (2.22) produces a linear differential equation for the temperature distribution within the bubble.

\[
\frac{\partial (rT)}{\partial t} = D_g \left[ \frac{\partial^2 (rT)}{\partial r^2} \right] + j \left( \omega / \rho g \gamma_P \right) P_s \exp[j \omega t] \tag{2.24}
\]

The boundary conditions for equation (2.24) are:

i. \( T \) is finite at the bubble centre;

ii. \( T = 0 \) at the gas/liquid interface, but with a finite gradient.

Several methods exist for solving equation (2.24), the most physically acceptable being to use a successive approximations technique. However, the simplest method, while not physically complete, is mathematically viable and assumes a sinusoidal temperature variation. Thermal damping expressions comprise two principal terms, a heat transfer term plus a sinusoidal temperature variation at the gas/liquid interface. Impulse terms such as those resulting from shock wave generation have been ignored. This model is simplistic in that the deformation resulting from shape oscillations in large bubbles and the effects of coalescence which would result in dipole oscillations have been ignored. The model simplifies bubble response to isothermal behaviour for very small bubbles (micron size) and adiabatic behaviour for bubbles with dimensions of hundreds of microns. For very large bubbles i.e. the millimetre and larger size range, then the response of the bubble is polytropic, adiabatic at the centre and isothermal at the gas/liquid interface. It thus becomes possible to obtain an expression for the change in
bubble volume based on the above assumptions [20].

\[ V = \frac{V_0 P_s \exp(j\omega t)}{\gamma P_0} \left[ 1 + \frac{3(\gamma - 1)}{\psi g r_0 \coth(\psi g r_0) - 1} \right] \]  \hspace{1cm} (2.25)

and \[ \psi g = (j\omega/D_g)^{1/2} \]  \hspace{1cm} (2.26)

It is now possible to express the equation of motion in the form of equation (2.20):

\[ m_b \ddot{V} + b_t \dot{V} + kV = -P \exp(j\omega t) - P_s \exp(j\omega t) + m_b \ddot{V} \]  \hspace{1cm} (2.27)

where \( b_t \) is the dissipation due to thermal contributions.

By differentiation of (2.25) and substitution into (2.27) we obtain:

\[ \frac{1}{k + j\omega b_t} \frac{V_0}{\gamma P_0} \left[ 1 + \frac{3(\gamma - 1)}{\psi g r_0 \coth(\psi g r_0) - 1} \right] \]  \hspace{1cm} (2.28)

It is necessary to eliminate the imaginary part of (2.28) by the substitution:

\[ \psi g = (1 + j)k_g \]  \hspace{1cm} (2.29)

where \( k_g = (\omega/2 D_g)^{1/2} \). At resonance, the expression \( k_g r_o \) varies as the mean pressure inside the bubble and equation (1.27) may be rewritten [21].

\[ \frac{\gamma P_0}{k V_0} = \left[ 1 + \left( \frac{\omega b_t}{k} \right)^2 \right] \left[ 1 + \frac{3(\gamma - 1) \left( \sinh(2k_g r_o) - \sin(2k_g r_o) \right)}{2k_g r_o \left( \cosh(2k_g r_o) - \cos(2k_g r_o) \right)} \right] = \alpha_1 \]  \hspace{1cm} (2.30)(a)

For bubbles of radius \( \sim 20 \mu m \) \( k \) approaches the value for a purely adiabatic system and the dimensionless stiffness index \( P_0/k V_0 \) may be approximated thus:

\[ \frac{\gamma P_0}{k V_0} = \left[ 1 + \frac{3(\gamma - 1)}{2k_g r_o} \right] \left[ 1 + \frac{3(\gamma - 1)}{2k_g r_o} \right] = \alpha_2 \]  \hspace{1cm} (2.30)(b)

For 'small' sub micron bubbles, the value of \( k \) tends to its isothermal limit. The stiffness parameter is modified by \( \alpha_1 \) or \( \alpha_2 \) of equations (2.30)(a) or (b). Thus we obtain:
with \( m = 1 \) or \( 2 \) and where \( f_r \) is the resonance frequency.

An additional modification to \( k \) is required, since the instantaneous pressure inside the bubble is not equal to that on the surface. The effect of surface tension causes the pressure inside the bubble to increase above the pressure at the bubble surface. Surface tension is inversely proportional to radius, thus the effect is significant for small bubbles, but becomes negligible for large ones:

\[
k = - \left( \frac{\partial P_g}{\partial V_g} \right) \tag{2.32}
\]

The pressure inside the bubble is now:

\[
P_g = P_s + \frac{2\gamma r}{r_g} \tag{2.33}
\]

For an adiabatic system and for a polytropic system [21][22]:

\[
P_g = \left[ P_o + \frac{2\gamma r}{r} \right] \left[ \frac{V_o}{V_g} \right] \tag{2.34}
\]

From equations (2.32) and (2.34) a new expression for \( k \) results:

\[
k = \left( \frac{\gamma P_o}{\rho_o \alpha_m V_o} \right) \beta \tag{2.35}
\]

where \( \beta = 1 + \left( \frac{2\gamma}{P_o r_o} \right) - \left( \frac{2\gamma}{3P_o r_o} \right) \tag{2.36} \)

Once again the expression for the resonance frequency of equation (2.31) is modified by the correction factors for thermal damping and surface tension and now becomes:

\[
f_r = \frac{1}{2\pi r_o} \left( \frac{3\gamma P_o \beta}{\rho_g \alpha_m} \right)^{1/2} \tag{2.37}
\]

Equation (2.36), the second term indicates that for large bubbles surface tension is negligible hence \( \beta \) tends to unity.

The thermal damping constant is given by the expression:

\[
\delta t = \frac{\omega b_t}{k} \tag{2.38}(a)
\]

and it has been shown [21] that the damping constant has the form:
\[
\delta t = 2 \left[ \frac{16}{9(\gamma-1)^2} \left( \frac{f_C}{f_r} \right)^2 - \frac{3(\gamma-1)}{3(\gamma-1)} \left[ \frac{f_C}{f_r} - 4 \right] \right]^{1/2} (2.38) (b)
\]

where \( f_C \) is the frequency corresponding to a given pressure such that
\[
f_C = \left( \frac{3\gamma P_0}{4\pi \rho L D_g} \right)^{1/2}.
\] (2.39)

2.2.4.2 Radiation damping

Bubbles in a compressible liquid which undergo volume pulsations dissipate some energy by radiating spherical sound waves, assuming that the bubble acts as a monopole radiator and that its radius is small compared to the acoustic wavelength of the radiated sound, it is possible to determine the radiation damping constant. For a sinusoidal source in a compressible liquid, the velocity potential may be expressed.

\[
\phi = j\omega V^1/4\pi R \exp [j\omega(t - \frac{R}{c_w})] (2.40)
\]

where \( c_w \) is the velocity of sound in water/liquid, \( R \) is the radial distance from the source, \( V^1 \) is the complex amplitude of the change in bubble volume.

\[
V^1 = V^1 \exp(j\omega t) (2.41)
\]

The acoustic pressure of the system is defined as \( [23] \).

\[
P_a = \rho L (\partial \phi / \partial t) (2.42)
\]

thus the acoustic pressure at the bubble surface becomes:

\[
P_a = -(\rho L \omega^2 V^1/4\pi r_o) \left[ 1 - j(\omega r_o/c_L) - \frac{\omega^2 r_o^2}{2! c_L^2} + \frac{j \omega^3 r_o^3}{3! c_L^3} + \ldots \right] (2.43)
\]

The acoustic pressure at the bubble surface is associated with the pressure difference between the 'ac' driving pressure and the change in pressure at the bubble surface which results from the change in bubble volume.

\[
P_a = -(P + kV^1) \exp(j\omega t) (2.44)
\]
In the linear approximation terms with order higher than \( r_o / c_q \) are neglected, thus equation (2.44), after rearrangement and substitution, becomes:

\[
\frac{(\rho g/4\pi r_o)}{V} + \frac{(\rho g \omega^2/4\pi c_q)}{V} + kV = -P \exp(j\omega t) \quad (2.45)
\]

For situations where the bubble radius is much less than the wavelength of radiated sound, the first term of equation (2.45) corresponds to the first term of equation (2.14), thus the generalised motion term assumes the same value in the presence of a compressible liquid as it does or the 'incompressible' mass on a spring approximation. The coefficient of radiation dissipation is given by the second term in equation (2.45).

\[ b_r = \frac{\rho g \omega^2}{4\pi c_q} \quad (2.46) \]

thus the radiation damping constant at resonance is given by:

\[ \delta_r = \frac{b_r}{\omega_0 m_b} = \omega_0 r_o / c_q \quad (2.47) \]

For large bubbles, where the effect of surface tension is negligible and the thermodynamics are those of an adiabatic system, the radiation damping constant becomes frequency independent.

(c) Viscous damping

In a viscous liquid there is a transfer of momentum from an element of liquid with a high velocity to a region with lower velocity. The characteristic equation for expressing Newton's second law for a fluid of constant density is the Navier-Stokes equation, which may be expressed thus [24]:

\[ \rho g \frac{Dr}{dt} + -\nu P_o + \mu^2 \omega^2 \left[ \frac{dr}{dt} \right] + B \quad (2.48) \]

where \( \mu \) is the coefficient of viscosity, \( B \) is the sum of forces acting over the fluid volume.

If the assumption is made that the liquid is incompressible, then \( B = 0 \); similarly, the viscous term \( \mu^2 \omega^2 (dr/dt) \) is zero, because the flow is assumed to be irrotational and the velocity may be expressed as the gradient of a scalar potential.
Although the sum of viscous forces in the liquid is zero, there is a net viscous force acting on the bubble surface which results in an excess pressure. For a small spherical shell of liquid at the bubble surface, there is distortion upon expansion and contraction due to viscous stresses, which results in a net energy loss since more energy is required to compress the bubble than is regained during the expansion phase i.e. an hysteresis effect. An expression for the radial stress at the bubble surface has been determined thus [25]:

\[ S_r = - \left( \frac{\mu V}{\pi r_0^3} \right) \]  \hspace{1cm} (2.49)

Thus the equation of motion for the bubble becomes:

\[ m_b \ddot{V} + \frac{\mu}{\pi r_0^3} V + kV = P \]  \hspace{1cm} (2.50)

where \( \frac{\mu}{\pi r_0^3} \) is equivalent to \( b_v \), the viscous dissipation coefficient, and

\[ \delta V = b_v/\omega_m = \left( \frac{8\pi \mu f_r}{3\gamma P_0} \right) \left( \alpha/\beta \right)^{\frac{1}{3}} \]  \hspace{1cm} (2.51)

Thus the resonance value of the viscous damping constant is directly proportional to the resonant frequency.

Total damping

The total damping constant is the sum of the individual damping constants of radiation, thermal and viscous origins.

\[ \delta_{TOT} = \delta r + \delta t + \delta v \]  \hspace{1cm} (2.52)

Figure 2.1 shows the variation of all three components and the total damping constant with resonance frequency [20]. Thermal damping is the dominant component and peaks at 250 kHz. The radiation damping constant is almost frequency independent with a mean value of \( \sim 0.013 \). Viscous damping may be neglected at low frequency, but assumes significance at 100 kHz and has equal weighting with thermal damping at 1 MHz. The total damping constant has a value of \( \sim 0.03 \) at 1 kHz and reaches a maximum plateau \( \sim 400 \) kHz. The expressions for the three components of the damping constant are for a linear system, most higher order expressions were lost or ignored. For accurate bubble system models it will be necessary to take nonlinearities into account.
2.2.5 SCATTERING, ABSORPTION AND TRANSMISSION

2.2.5.1 Scattering and Absorption

For bubbles which are insonified by the pressure amplitude of an incident sound wave it can be assumed that the pressure throughout the bubble volume is constant, provided that the bubble radius is \( << \) than the sound wavelength. The impact of the incident sound wave causes forced vibrations of the air inside a bubble, which expands and contracts in contact with the surrounding water. The forced vibration results in emission of a spherically symmetrical sound wave from the bubble. This scattering process redistributes the sound energy and is accompanied by absorption/dissipation. The scattering cross section for an actual bubble has the form [26].

\[
\sigma_s = \frac{4\pi^2 r^2}{\left[ (f_r^2/f^2 - 1)^2 + \delta_{\text{TOT}}^2 \right]}
\]  

whilst the absorption cross section is given by:

\[
\sigma_a = \frac{4\pi r^2}{2\pi r} \left( \frac{\delta_{\text{TOT}}}{(f_r^2/f^2 - 1)^2 + \delta_{\text{TOT}}^2} - 1 \right)
\]  

The sum of the two cross sections gives the extinction cross section, \( \sigma_e \).

Transmission

In the presence of bubble clouds, the velocity of sound through a medium is altered, hence the overall compressibility of the system changes. Since the velocity has a complex value, there is an exponential attenuation of sound intensity through the bubble cloud. Assuming that bubbles are of a single size, then the sound intensity at any point \( R \) may be determined thus:

\[
I(R) = I(0) \exp \left( -\sigma_e \int_0^R n(r) \, dr \right)
\]

(2.55)

where \( n \) is the bubble concentration. It is uncommon to find clouds of identically sized bubbles, thus expression for the extinction cross section was modified by Wildt [26].

\[
\Sigma_e = \frac{4\pi r^2 n(r) (\delta_{\text{TOT}}/2\pi r)}{(f_r^2/f^2 - 1)^2 + \delta_{\text{TOT}}^2} \int_0^\infty \, dr
\]

(2.56)

The above integral is easily evaluated provided that \( n(r) \) does not change rapidly
for radii near to resonance. A further assumption is made that the absorption due to non-resonant bubbles can be neglected. This assumption is not necessarily valid, since the damping 'constant' for non-resonant bubbles is not known: this problem is commented upon later. Thus for resonance \( n(r) \) and \( \delta_{TOT} \) (\( \delta_{TOT} \)) may be taken outside the integrals:

\[
\Sigma e = 2r_r n(r_r) \delta_{TOT} \int_0^\infty \frac{dr}{(f_r^2/f^2-1)^2 + \delta_{TOT}^2}
\]  

(2.57)

By using the approximation that the only contributions to the integral are from frequencies/bubble sizes near resonance, the lower limit of the integral may be taken to \(-\infty\). \( f_r/f \) may be replaced by \( r_r/r \) and equation (2.57) solved using the following substitutions and approximations:

\[
-a = r_r/r - 1 \quad (r_r/r = 1)
\]

\[
(r_r^2/r - 1) = a^2(0 + 2)^2 - a^2 = 4a^2,
\]

since \( r_r/r - 1 = 0 \)

\[
da = -r_r/r^2 dr,
\]

thus \( dr = (r/r_r)^2 r da = r_r da \), since \( (r/r_r)^2 = 1 \),

thus:

\[
\Sigma e = 2r_r^2 (r_r) \delta_{TOT} \int_0^\infty da/4a^2 + \delta_{TOT}
\]

(2.58)

\[
\Sigma e = \pi r_r^2 n(r) \lambda
\]

(2.59)

If we define \( u(r) \) dr as the total volume of gas/air for bubble with radii in the interval \( r \) to \( r + dr \) then:

\[
\Sigma e \approx (3\lambda/4r_r^2) u(r_r)
\]

(2.60)

It is now possible to obtain values for the attenuation of sound passing through a non-uniform bubble size distribution. The determination of scattered sound intensity is, however, more complex, especially if the effects of multiple scattering are to be included. The basic equation for sound scattered from a volume \( dV \) at a distance \( R \) is given by [26]:

\[
dI_s = \frac{n\sigma_{sdV}}{4\pi R^2} l(o) \exp [-\sigma_e \int_0^R n(r)dr]
\]

(2.61)

for bubbles of the same size and:

2.17
\[ \frac{\Delta s}{\Delta \omega} = \sum s \frac{dV}{4\pi R^2} I(0) \exp(-\Sigma e) \]  

\[ (2.62) \]

for non-uniform bubble distributions.

In order to facilitate the solution of (2.61) & (2.62) it is assumed that for bubbles with radii > 250 \( \mu m \), the absorption process at resonance is an order of magnitude greater than the scattering process, thus multiple scattering is five orders of magnitude less than the absorption process and as such becomes insignificant. Figure 2.2 illustrates scattering from a bubble screen [26]. Using the parameters from Figure 2.2, equation (2.61) may be expressed thus:

\[ \frac{\Delta s}{\Delta \omega} = \sigma_s / \sigma_e \frac{\cos \theta_i}{4\pi \cos \theta_i + \cos \theta_s} (1 - \exp[-\sigma_e (\sec \theta_i + \sec \theta_s)] \int_0^w n(r) dr) \]  

\[ (2.63) \]

where \( w \) is the width of the bubble cloud.

There are two limiting cases for equation (2.63), namely very high and very low transmission loss respectively. For high transmission loss, (2.63) becomes:

\[ \frac{\Delta s}{\Delta \omega} = \frac{d\Omega}{4\pi TOT^2} \]  

\[ (2.64) \]

and for low transmission loss:

\[ \frac{\Delta s}{\Delta \omega} = \sigma_s \frac{d\Omega}{4\pi} \sec \theta_s w \bar{n} \]  

\[ (2.65) \]

where \( \bar{n} \) is the average bubble concentration.

For bubble ensembles of different sizes when it is considered satisfactory to include only those bubbles near resonance, the scattering cross section is written thus:

\[ \Sigma_s = 4\pi r^2 / \left( (\Gamma r^2 / \Gamma^2 - 1)^2 + 4\pi (\Gamma r^2) \right) \]  

\[ (2.66) \]

Equation (2.64) is valid for bubble clouds of different sizes and high transmission loss, but the low transmission analogue of (2.65) for different sized bubbles is:

\[ \frac{\Delta s}{\Delta \omega} = \Sigma_s \frac{d\Omega}{4\pi} \sec \theta_s w \]  

\[ (2.67) \]
2.2.6 SUMMING RESONANT AND NON-RESONANT BUBBLE CONTRIBUTION

A computer program was devised for determining acoustic scatter and extinction cross sections for a cloud of known bubble sizes by J Griffiths based upon previous programs of A Cowley* and damping expressions and polytropic index from Clay and Medwin [27]. A flow chart for the program is given in Appendix A. Modifications were made to accommodate off resonance contributions. Acoustic scattering redistributes energy and is accompanied by absorption and dissipation.


The radiation damping term is almost frequency independent and unaffected by bubble resonance, since it is a function of geometrical cross section and wavelength. The thermal damping component was assumed to show a square law relationship with frequency as discussed in section 2.2.4.1 and the non-resonant bubble damping was assumed to vary thus:

\[ \delta_t = \delta_t(\text{RES}) W^2 \]  \hspace{1cm} (2.67(a))

where

\[ W = \frac{f}{f_r} \quad \text{for} \quad f < f_r \]
\[ = \frac{f_r}{f} \quad \text{for} \quad f > f_r \]

likewise the viscosity term was projected as varying thus:

\[ \delta_v = \delta_v(\text{RES}) W^J \]  \hspace{1cm} (2.67(b))

where

\[ J = 2 \quad \text{for} \quad f > f_r \]
\[ J = \text{ext} \left(2(1/W-1)\right) \quad \text{for} \quad f < f_r \]

The above expressions were computed from single bubble responses and neglect any bubble interaction terms. Contributions from nonresonant bubbles tend to values comparable from fluid or solid spheres when the bubble is far from its resonant frequency.

The signal attenuation in dB/m due to a cloud of different sized bubbles may be
expressed thus:

\[ A = 4.343N \sum_{n} p_n(d_n) \sigma_{en} \]  

(2.68)

where \( N \) is the total number of bubbles \( m^{-3} \) and \( p_n(d_n) \) the probability of occurrence of a bubble diameter \( d_n \).

Commander and Moritz [28] recognised the need to include off resonance contributions when determining global cross section figures. They noted that summing resonant contributions alone led to serious overprediction of bubble numbers. In response to this problem they concluded that it was necessary to solve the inverse scatter equation which involved the use of Fredholm integral equations.

2.3 NON-LINEAR BUBBLE DYNAMICS

2.3.1 HIGHER HARMONICS

2.3.1.1 Introduction

The acoustic properties of bubbles examined throughout Section 1.2 relied upon many assumptions in order ultimately to provide linear equations for characterising bubble behaviour. There are nonetheless several sources of nonlinearities which must at least be recognised and preferably included in the analysis of bubble behaviour. Nonlinearities result from bubble vibration, the passage of sound through a medium and in sound wave generation. This section examines the form which these nonlinearities take and comments on their relevance as a potential tool in the study of bubble acoustics.

2.3.1.2 Nonlinear Bubble Vibration

Equation (2.16) gave the linear equation of motion for a mass on a spring which for the present, we will assume analogous to bubble motion. In equation (2.16) \( k \) — the stiffness constant, is single valued for each solution. However, in practice, the equation of motion is of the form:

\[ m_0 \ddot{V} + b \dot{V} + k_1 V + k_2 V^3 + k_3 V^5 + \ldots \ldots = P \]  

(2.69)
If terms to second order only are retained - which is a reasonable assumption, since third order effects are typically three orders of magnitude down to second order ones, then with rearrangement, (1.69) becomes

\[ m_b \ddot{V} - b \dot{V} - k_1 V + k_2 V^3 + \ldots = P \]  \hspace{1cm} (2.70)

Assuming that \( V \) takes the form \( V = V_1 \cos \omega t \) and that \( P \) takes the form \( P = P_1 \cos \omega t + P_2 \sin \omega t \), then:

\[
\begin{align*}
\dot{V} &= -\omega V_1 \sin \omega t \\
V^3 &= V_1^3 \cos^3 \omega t = V_1^3 \left( \frac{1}{4} \cos \omega t + \frac{3}{4} \cos 3 \omega t \right) \hspace{1cm} (2.71)
\end{align*}
\]

Hence equation (2.70) becomes:

\[
\ddot{V} = (P_2 + \delta_{TOT} V_1) \sin \omega t + (P_1 - \omega_0^2 V_1 - \frac{3}{2} \alpha V_1^3) \cos \omega t - \frac{1}{4} \alpha V_1^3 \cos 3 \omega t \]  \hspace{1cm} (2.72)

where \( \delta_{TOT} \) is the total damping constant \( \delta_{TOT} = \omega_0^2 m_b \), \( \omega_0^2 = k_1/m_b \), \( \alpha = k_2/m_b \).

In order to obtain a second order solution for the equation of motion, the modified volumetric strain \( V^* \) given by [28]:

\[
\ddot{V}^* + \omega^2 V^* = -\frac{1}{4} V_1^3 \cos 3 \omega t - \omega^2 \delta_{TOT} \sin \omega t + \left( (\omega^2 - \omega_0^2 V_1^3 + P_2 \right) \cos \omega t \]  \hspace{1cm} (2.73)

First order solutions are the form \( \dot{V}^* = \omega^2 V^* = 0 \), which correspond to the \( \cos \omega t \) and \( \sin \omega t \) parts on the right of equation (2.73). Thus the second order solution of equation (2.73) is

\[
\ddot{V}^* + \omega V^* = -\frac{1}{4} \alpha V_1^3 \cos 3 \omega t \]  \hspace{1cm} (2.74)

It is expected that the solution to equation (2.73) would have the form:

\[
V^* = A_1 \cos \omega t + A_2 \sin \omega t + A_3 \cos 3 \omega t \]  \hspace{1cm} (2.75(a))

thus

\[
\begin{align*}
\dot{V}^* &= -\omega^2 A_1 \cos \omega t - \omega^2 A_3 \sin \omega t - 9 \omega^2 A_3 \cos 3 \omega t \\
\omega^2 V^* &= \omega^2 A_1 \cos \omega t - \omega^2 A_2 \sin \omega t - \omega^2 A_3 \cos 3 \omega t
\end{align*}
\]  \hspace{1cm} (2.75(b))

Solving (2.75)(b) simultaneously, we get:
\[ V' + \omega^2 V' = -\frac{1}{2} \alpha V_1^3 \cos 3\omega t = -8\omega^2 A_3 \cos 3\omega t \]  \hspace{1cm} (2.76)

Therefore

\[ A_3 = \frac{\alpha V_1^3}{32\omega^2} \]  \hspace{1cm} (2.77)

It is possible to obtain higher order solutions of the form by manipulation of equations (2.69) to (2.76) [29]:

\[ V' = A_1 \cos \omega t + A_2 \sin \omega t + A_3 \cos 3\omega t + A_4 \cos 5\omega t + A_5 \cos 7\omega t + \ldots \]  \hspace{1cm} (2.78)

Consequently, the nonlinear equation for a mass on a spring/bubble with damping may be evaluated.

2.3.1.3 Nonlinearities of Sound Passage through a Medium

The equation of motion for particles in an acoustic field of small amplitude signals is approximated by the Helmholtz equation:

\[ \varphi^2 s = \frac{1}{c^2} \frac{\partial^2 s}{\partial t^2} \]  \hspace{1cm} (2.79)

where \( s \) is the displacement and \( c_0 \) is the local velocity of sound in the medium.

Now:

\[ c_0^2 = \frac{\partial P_a}{\partial \rho} \]  \hspace{1cm} (2.80)

where \( P_a \) is the acoustic pressure. For an adiabatic system:

\[ P_a = P_0 \left( \frac{\rho}{\rho_0} \right)^\gamma \]  \hspace{1cm} (2.81)

Thus:

\[ c_0^2 = \frac{\gamma P_0}{\rho_0} \left( \frac{\rho}{\rho_0} \right)^{\gamma - 1} = \frac{\gamma P_0}{\rho_0} \frac{1}{(1 + \gamma \tau)^{\gamma - 1}} \]  \hspace{1cm} (2.82)

2.22
When the displacement is small:

\[ c g^2 = \chi / \rho_0 \]  \hspace{1cm} (2.83)

and \( \chi \) is the compressibility. However, the compressibility, which is analogous to
the mass on a spring situation, is not a single order term, but rather consists of
a series of harmonics of the form [29]:

\[ \chi = a + \frac{b}{2!} V + \frac{c}{3!} V^2 + \frac{d}{4!} V^3 + \ldots \]  \hspace{1cm} (2.84)

where \( V \) is the volumetric strain and the coefficients are temperature dependent.
Thus the relationship between pressure and volumetric strain is of the form

\[ P_a = aV + \frac{b}{2} V^2 + \frac{c}{24} V^4 + \ldots \]  \hspace{1cm} (2.85)

Consequently, any expression for pressure, such as those in previous sections must
include higher harmonics, especially in the presence of gas/air bubbles which alter
the compressibility of the medium. It has been shown[30] that the void fraction
required to affect the first order component of volumetric strain is \( \sim 10^{-4} \), yet to
affect the second order component a void fraction of only \( \sim 10^{-8} \) is necessary.
Typically the equation of motion for a gas bubble in a liquid medium, driven by
a pressure force will be of the form:

\[ m_b \ddot{V} + b \dot{V} + k_1 V + k_2 V^3 + k_3 V^5 + \ldots = \sum_{n=0}^{N} P_n e^{i \omega t} \]  \hspace{1cm} (2.86)

It is apparent that variation in the harmonics will prove useful in the analysis of
bubble cloud behaviour.

### 2.3.2 SUBHARMONICS

There is a threshold pressure requirement for the generation of subharmonic
oscillation in bubbles. The critical amplitude is achieved only when damping
levels are overcome. The generation of radial subharmonic oscillations is
connected with spherical instability and may be attained over a fixed frequency
bandwidth only, which itself is a function of the driving pressure amplitude.
Once subharmonic oscillation has been activated surface oscillations or
deformations may set in which result in bubble breakup and collapse. The larger
the bubble the lower the threshold for surface deformation and subsequent
collapse. Small bubbles are less prone to surface deformation consequently
subharmonics are more difficult to initiate but once established are more stable
than in larger bubbles.

2.3.3 NONLINEARITIES IN THE BUBBLE DAMPING MODE

Properetti [31][32] and Prosperetti and Crum [33] have shown that the standard
treatment for characterising bubble dynamics is flawed in its use of polytropic
index. They have shown that an "effective" viscosity term was necessary to
combat multiple oscillation and non-periodic effects. Prosperetti[32] showed that
the bubble oscillation pressure has both real and imaginary components in phase
with the radial oscillations and the time derivative of the radial oscillations
respectively.

\[ P_b = -\text{Re}\Phi R - \text{Im}\Phi R \]  \hspace{1cm} (2.87)

where \( \Phi \) the thermal damping function is given by the expression:

\[ \Phi = 3\gamma/(1-3(\gamma-1)j\chi[(j/\chi)^{3/2}\coth(j/\chi)^{3/2}-1]) \]  \hspace{1cm} (2.88)

and

\[ \ddot{R} + A(B+\text{Im}\Phi)\dot{R} + A(\text{Re}\Phi-C)R = -AP(t) \]  \hspace{1cm} (2.89)

which is a damped harmonic oscillator equation with:

natural frequency \( A(\text{Re}\Phi-C) \)
damping component \( A(B+\text{Im}\Phi) \)

\( A \) is the ratio equilibrium bubble pressure/inertial pressure; \( B \) is the viscous
pressure component/equilibrium bubble pressure; \( C \) is the surface
tension/equilibrium bubble pressure.

If a straight polytropic relation were adopted then the resonance frequency would
be:

\[ A [3\gamma_{eff} - C] \]

2.24
and the damping component would be:

\[ AB \]

Thus the polytropic model may be unreliable in accounting for the dissipation of energy by thermal processes especially at large incident pressure amplitudes.

Prosperetti's formulation of bubble dynamics is based upon a direct evaluation of the internal pressure within a bubble and the resultant radial oscillation curves differ markedly from their polytropic analogues with respect to energy dissipation in the large amplitude regimes.

In the linear regime it appears that the polytropic model is adequate to describe bubble motion.

2.4 BUBBLE INTERACTION AND ITS EFFECT ON BUBBLE DYNAMICS

2.4.1 BJERKNES INTERACTION

The motion of two spheres in a fluid is analogous to coulombic interaction with velocity potential the analogue of voltage. This effect was noted by Stokes as early as 1842. The resultant hydrodynamic force due to interaction of two oscillatory bodies in a fluid was investigated and explained by father and son C.A. and V.B. Bjerknes [34].

The full equation of motion for a radially oscillating bubble is given by [17]:

\[
\rho g \frac{r}{r^3} + \frac{4 \rho g r^2}{2r} + \frac{4 \mu r}{2r} + \frac{2 \sigma}{r} = P_b(r, t) - (P_o t) + (P_o t) \quad (2.90)
\]

If the system may be assumed to be adiabatic then:

\[
P_b(r) = P_o \left( \frac{r_o}{r} \right)^3 \gamma \quad (2.91)
\]

and for constant pressure inside the bubble we may obtain a Rayleigh solution for the radial bubble motion:
\[ r^2 = \frac{2}{3} \frac{(P_b - P_\infty)}{\rho \ell} (r_o^3 - r^3) \]  
(2.92)

where \( r \) and \( r_o \) are expressed by elliptical functions in time such that:

\[
t = \left( \frac{\rho \ell}{2P} \right)^{\frac{1}{2}} \int \frac{r_o^3}{r} \left( \frac{r^3}{r_o^3 - r^3} \right)^{\frac{1}{2}} dr
\]
(2.93)

which upon integration over one period of oscillation yields:

\[
\tau = r_o \left( \frac{2\rho \ell}{3P} \right) \left[ \frac{5}{6} \right] \left[ \frac{1}{2} \right] \left[ \frac{4}{3} \right] = 0.915 \ r_o \left( \frac{\rho \ell}{P} \right)^{\frac{1}{2}}
\]
(2.94)

The Bjerknes force exhibits a dipole radiation field since a simple source of radius \( r \) moving through a fluid at velocity \( u \) may be likened to a dipole source located at the same centroid and with source strength \( 2\pi ur^3 \). The interaction between two spheres may be either "attractive" i.e. bubbles oscillating in phase, or "repulsive" i.e. bubbles oscillating in antiphase. The magnitude of the resultant hydrodynamic force obeys an inverse square law.

It is the Bjerknes force which adds the first multipole contribution to scattering terms since the interaction of two bubbles causes mutual volume distortion and establishes a cylindrical symmetry compared to spherical symmetry due to the simple monople radiator; there is also an angular dependence.

### 2.4.2 MULTIPOLe RESONANCES

As shown in 2.2 bubbles exhibit well defined resonances when operating as monopole radiators. As the void fraction increases opportunities for multipole scatter and higher order resonances rise concomitantly until a regime is reached where wave reflection and refraction dominate and scattering concepts no longer apply.

Multipole monopole scattering is negligible at or near resonance typically \(~10^{-4}\) down on single scatter and \(~10^{-7}\) down on absorption; but it may assume significant proportions for non-resonant scatterers, especially large bubbles, whose scattering and extinction cross sections are almost equal.
Interference between scattered sound waves results in an effective incoherent scatter value which overestimates bubble numbers because of multiple scatter interference. Typically for a 20% void fraction, the overestimate could reach a maximum of about 30% if all bubbles are large and insonified well above resonance. Likewise for a 10% void fraction the overestimate under similar conditions would give a 20% overestimate.

It is possible to characterise sound propagation through a bubbly medium for void fractions up to 20% if dipole and quadrupole contributions are included. Higher order multipole components may assume significance for large bubbles. Berger and Twersky[35] derived expressions for dipole and quadrupole contributions for underwater sound propagation in bubbly fluids up to 20% void fraction. Typically for $R << \lambda$ then the relative contributions go as:

\begin{align*}
\text{monopole} & \quad 1 \\
\text{dipole} & \quad 10^{-2} \\
\text{quadrupole} & \quad 10^{-4}
\end{align*}

As bubble numbers and sizes increase the relative contributions of multipoles rise thus for $r \sim \lambda/10$ we have:

\begin{align*}
\text{monopole} & \quad 1 \\
\text{dipole} & \quad 0.5 \\
\text{quadrupole} & \quad 0.1.
\end{align*}

### 2.4.3 BUBBLE CLOUD OSCILLATIONS

At low void fractions the frequency spectrum of sound emission from a cloud of bubbles is determined by summation of the contributions of all individual bubbles. Eventually higher modes must be incorporated into the model and at very high void fraction the phenomenon of global motion of the bubble cloud with a low frequency sound emission becomes possible.

The collapse of spherical bubble clouds was investigated by Hansson and Mörch [36]. Their findings were based upon the assumption that an infinitesimally thin shock wave moves across the cloud as a result of pressure increase in the surrounding liquid, but only the compression phase existed since shock velocities
are unattainable during the expansion phase, hence no resultant cloud oscillation. Prosperetti [37] showed that thermal and viscous effects in the liquid may be neglected when gas clouds compress. One of the principal determinants of bubble cloud oscillation is pressure at the cloud/liquid interface; which is itself a function of thermal effects in the gas. A polytropic index is suitable to characterise the cloud behaviour, with isothermal behaviour apparent at low incident frequency changing to adiabatic response at higher frequencies.

The major influence on damping, as with individual bubbles, is the thermal damping component. Mechanical, energy is dissipated by the cloud and is a function of the driving frequency. Omta [38] used a series of averaged equations of motion; continuity and energy to reach an expression for the fundamental oscillation frequency of a bubble cloud.

\[ f_{\text{cloud}} = \sqrt{\frac{\gamma_{\text{eff}} P_0}{\beta \rho_D D_0^2}} \]  

(2.95)

where \( D_0 \) is the cloud diameter, \( \beta \) is the void fraction.

Thus the cloud's natural frequency exhibits the same \( r^{-1} \) relationship as for individual bubbles, but additionally the oscillation frequency is inversely proportional to the square root of the void fraction.

The polytropic effect is even more pronounced for a bubble cloud than for its individual members. At the edge of the cloud damping is strong and pressure changes are slow and compression is isothermal, whereas at the cloud centre changes are rapid and adiabatic compression results.

The acoustic absorption and scatter cross sections of a bubble cloud differ greatly from those of an equivalent single large bubble since the acoustic properties are functions of the degree of dispersion of the gas phase within the fluid.
2.5 SALT AND FRESH WATER BUBBLES

2.5.1 INTRODUCTION

Three principal differences arise with respect to bubble properties in fresh and saline water namely:

(i) Bubble size and distribution
(ii) Bubble lifetime or persistence
(iii) Coalescence

For a given void fraction the mechanical, acoustical, optical and electrical properties may be totally different dependent upon the nature of the fluid. Increased persistence of small bubbles in salty water and reduced incidence of coalescence indicates the existence of some form of bubble stabilisation mechanism. In this chapter a range of stabilisation models are critically examined; bubble persistence data are assessed and changes in damping mechanisms are explored in an attempt to explain the differences observed between bubbly fresh and bubbly salt water responses.

2.5.2 BUBBLE STABILISATION MECHANISMS

Four basic models for the stabilisation of bubbles exist and are discussed in the following sections.

2.5.2.1 SURFACE SKIN MODEL

It is thought that organic materials of monomolecular hydrocarbons and proteins collect on bubble surfaces and inhibit or block out gas diffusion. The molecules attach to the bubble surface in an end-on configuration linking together sideways thus inhibiting molecular diffusion and reducing surface tension. It is believed that concentrations as low as $10^{-6}$ down to $10^{-8}$ would be sufficient to coat bubbles. The surface skin model was proposed originally by Fox & Herzfeld [35] in the 1950's. Yount [40] provided evidence of the elasticity of surface skins and their variable permeability. When bubbles are compressed by an external pressure their skins contract and their permeability decreases. Beyond a critical pressure bubbles dissolve very quickly; indicative of a collapse of the outer shell formed by the compressed skins. Bernd [41] found that bubble dissolution rates reduced by an order of magnitude upon addition of film agents to water whilst Liebermann [42] observed a twofold decrease in dissolution rates with a variety of surfactants.
added to the water.

2.5.2.2 DISSOLVED GAS SATURATION

Outward gas diffusion from a bubble increases the dissolved gas content in the surrounding liquid up to a point where equilibrium is attained. The gas saturation model works only for saturated or supersaturated water and predicts the monodisperse size distribution of bubbles; any other distribution would lead to instability. This model could be used to explain bubble persistence near to a free surface with air entrainment from above providing the requisite supersaturation conditions. In such a turbulent environment as wave breaking or a ship's wake there would be sufficient instability to produce the necessary bubble size distribution, but the model breaks down for quiescent seas or undersaturated liquids.

Franklin et al [43] concluded that the gas saturation model was acceptable if accompanied simultaneously by another mechanism for stabilisation.

2.5.2.3 ION SKIN REPULSION

Akulichev [44] proposed a bubble stabilisation mechanism based upon a collection of hydrophobic ions (eg. Cl⁻, F⁻, K⁺) coating a bubble. Mutual coulombic repulsion would negate surface tension and equalize inner and outer diffusion pressures. In theory it is possible for coulombic repulsion to exceed surface tension and form compressive stressed shells such that gas diffusion ceased, even in solutions which were undersaturated.

Such a model is limited to small sized bubbles since the coulomb force varies as \( r^{-2} \) whilst surface tension varies as \( r^{-1} \). It is not known what size bubbles would have equal coulombic and surface tension effects, but the concentrations of hydrophobic ions in most waters especially seawater are more than adequate to coat bubbles.

2.5.2.4 TRANSIENT BUBBLES

This model proposes the continuous generation and subsequent depletion and dissolution of bubbles; thus providing a constant supply of relatively "new" bubbles. Four mechanisms are identifiable:
a. Breaking waves.
b. underwater biological activity
c. cosmic rays.
d. Fluctuations of water molecule rotation creating voids which then fill with water vapour - otherwise known as homogenous nucleations [45].

These mechanisms are listed in order of priority and c and d may be ignored since the timescales involved for both processes are extremely small $10^{-9}$ to $10^{-12}$ sec.

2.5.3 DISSOLUTION MODELS

From Epstein and Plesset [46] we get

$$\frac{\partial n}{\partial t} = D \left( \frac{\partial^2 n}{\partial r^2} + \frac{2}{r} \frac{\partial n}{\partial r} \right)$$

(2.96)

and at the bubble wall of variable radius $R$

$$\left. \frac{\partial n}{\partial r} \right|_R = - \left( C_S - C_\infty \right) \left[ \frac{1}{R} + \frac{1}{(\pi D t)^{1/2}} \right]$$

(2.97)

where $n$ is the concentration of dissolved gas $D$ is thermal diffusity and $t$ is the time in seconds. $C_S$, $C_\infty$ are saturated dissolved gas concentration and equilibrium saturated gas concentration respectively.

If the dependent term in (2.97) may be neglected an expression for mass outflow may be derived:

$$\frac{dm}{dt} = 4\pi R^2 \rho_g \frac{dr}{dt} = 4\pi R^2 D \frac{dn}{dr} \bigg|_R$$

(2.98)

which leads to

$$\frac{dR}{dt} = -D \frac{C_S - C_\infty}{\rho_g}$$

(2.99)

(2.99) may be re-expressed thus:

$$\frac{d(R^2/R_0^2)}{dt} = -\frac{2D(C_S - C_\infty)}{\rho_g R_0^2}$$

(2.100)
where \( R_0 \) is the equilibrium radius at \( t = 0 \).

Equation (2.100) is the solution for bubble wave dynamics applicable for stationary dissolving bubbles with zero convection.

For a slowly rising bubble Stokes flow is applicable and two solutions result for bubble dissolution dependent on the change in the level of bubble contamination.

For "clean" bubbles the mass outflow is given by

\[
\frac{dm}{dt} = \frac{-4}{3} (C_S - C_\infty) \left( \frac{2gR_0^2}{\nu} \right)^{1/2} R^{5/2}
\]  

(2.101)

where \( \nu \) is the kinematic viscosity the resultant dissolution expression is thus:

\[
\frac{d}{dt} \left( \frac{R^2}{R_0^2} \right) = -2(C_S - C_\infty) - \left( \frac{2gD}{\pi\rho g^2} \right)^{1/2} R^{3/2}
\]  

(2.102)

If the bubble surface is contaminated then the mass outflow is given by:

\[
\frac{dm}{dt} = -8 \ (C_S - C_\infty) \left( \frac{2gD^2}{9\nu} \right)^{1/3} R^2
\]  

(2.103)

with the dissolution rate given by:

\[
\frac{d(R^2/R_0^2)}{dt} = -4(C_S - C_\infty) \left( \frac{2gD}{\pi\rho g^2} \right) \left( \frac{R}{R_0} \right)^{1/3}
\]  

(2.104)

The final situation occurs when both sides of the air/water interface are coated with films. (see Figure 2-3). Since molecular motion of gas molecules offers minimal resistance to mass outflow, the effect of the inner film may be neglected. The resultant mass outflow expression is:

\[
\frac{dm}{dt} = -x \ (C_S - C_\infty) \ A_1
\]  

(2.105)

where \( x \) is a coating factor and \( A_1 \) is the surface area of the interface.
The dissolution is given by:

\[
d\left(\frac{R^2}{R_0^2}\right) \frac{d}{dt} = \frac{-2x (C_S - C_\infty)}{\rho g R_0^2} R
\]  

Equation (2.100) is appropriate for stationary bubbles. Equations (2.102) and (2.104) describe adequately the dissolution of slowly rising bubbles, the former equation to be used when little contamination is present and the latter for most naturally occurring fluids such as seawater. Finally (2.106) expresses bubble dissolution in turbulent flow fields. It is interesting to observe that (2.104) and (2.106) are linear functions of radius.

2.5.4 DIFFUSION RATES

It appears that bubbles dissolve more slowly in seawater than in fresh water because of the higher concentrations of surfactants and ionic material in seawater. Gowing [47] found that the presence of dissolved solids in seawater retarded diffusion by 5 to 7%. It has been common practice to use fresh water values of diffusion rates due to the difficulty in predicting diffusion rates in seawater. Goncharov et al. [48] obtained measurements for diffusion rates in the Black Sea and off the eastern seaboard of the former USSR. The apparatus used comprised a tightly sealed vertical pipe with a glass plate for trapping and photographing bubbles, which were illuminated uniformly from 3 light sources. Bubbles diameter sizes were 50µm to 1mm and depths sampled were 1m to 50m with temperatures 15 to 20°C and falling with increasing depth. The results obtained indicate that the diffusion rate in seawater is 10 times less than for tap water and 50 times less than for distilled water. Miner et al [49] observed a 20% to 33% reduction in dissolution rates between fresh and seawater. Griffiths [50] observed bubbles dissolution rates of between 5 to 10 times less than fresh water values when using 35ppt NaCl simulated seawater.

In general, dissolution rates for bubbles rising in fresh water are in agreement with theoretical predictions of a surface skin model. In seawater (actual or simulated) the dissolution rate is slower than for fresh water. The dissolution rate is not proportional to the local concentration gradient and the most probable cause is the presence of surfactants coating the bubbles. Even traces of contaminants can eliminate internal circulation in bubbles increase drag and reduce mass shear transfer rates even though they exert no detectable effect on bulk fluid properties. Contaminants with the greatest effect are those which are insoluble in both liquid and gas phases.
Contaminants affect terminal velocity and actually cause an increase in the Eötvös number (Eo) \([51]\) where

\[
Eo = \frac{gD\bar{d}^2}{\sigma}
\]  \hspace{1cm} (2.107)

where \(\Delta \rho\) is the density change and \(\bar{d}\) the mean diameter. The percentage increase over Stokes Drag Law Curve as a function of Eötvös number is shown in Figure 2.4. Surface active materials reduce interfacial tension between the phases consequently the fluid becomes less sensitive to variations in concentrations hence mass transfer is reduced. Surfactants reduce interfacial motions also by introducing an effective surface viscosity.

### 2.5.5 BUBBLE PERSISTENCE IN FRESH WATER

Turner \([52]\) detected gas bubbles down to \(\sim15\mu m\) in size. The persistence of microbubbles affects acoustic and mechanical properties of water resulting in increased acoustic attenuation and scattered energy; potential reduction of propagating velocity and greatly reduced tensile strength.

Franklin et al \([43]\) investigated the stability of cavitation microbubbles. It was found that the concentration of small bubbles increased significantly if the liquid had experienced recent agitation. Turbulent motions within the fluid enhance the processes giving rise to nucleation. This explains the fact that transient small bubbles generate and disappear at a rate proportional to the free gas concentration.

The probability of occurrence for a radius less than \(R\) is expressed thus \([43]\):

\[
P_R(\delta) = (1 - 1/\delta^2)
\]  \hspace{1cm} (2.108)

Thus the probability of occurrence for a bubble of radius in excess of 10 \(R_{\text{min}}\) is 0.01 or 1% and the probability of occurrence for a bubble of radius in excess of 100 \(R_{\text{min}}\) is \(10^{-4}\) or 0.01%. Thus it may be possible to produce viable estimates of stable volumetric concentrations of gas microbubbles. The spread in the size spectrum reinforces the requirement for a stabilisation mechanism. Bachhuber and Sanford \([53]\) investigated dissolution mechanisms by observing the rise of small bubbles in distilled water and in contaminated tap water. They concluded that drag regime, thus the dissolution model, was a function of the...
distance travelled by the bubble. Thus close to its point of inception a bubble has minimal coating with contaminants and behaves as a fluid sphere even when the liquid is contaminated. Differences arise however between distilled water bubbles and those in tap water after the bubble has travelled several hundred radii; with bubbles in contaminated liquids resembling solid spheres thus altering their drag properties and subsequent bubble dissolution.

Deformation effects are much less in contaminated systems rather than pure water where surface or shape oscillations are commonplace. In freshwater elongation and flattening of bubbles results in a shape or surface natural frequency which modulates any volume pulsations and increases mass and heat transfer by the factor \((1+\kappa)\frac{1}{2}\) where \(\kappa\) is the maximum to minimum bubble diameter ratio. Typical oscillations are shown in Figure 2.5.

### 2.5.6 BUBBLE SURFACE LIFETIME

Bubble persistence in an open tank was measured by Zheng [54] using an electronic stop watch. A laser optical system with a photodetector was used to measure bubble diameters. Three fluids were investigated and the associated mean bubble lifetimes are given in Table 2.1.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface Lifetimes (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week old tap water</td>
<td>2.24</td>
</tr>
<tr>
<td>Seawater 20m off Delaware Bay</td>
<td>2.98</td>
</tr>
<tr>
<td>Seawater 10m off US Atlantic Coast</td>
<td>3.98</td>
</tr>
</tbody>
</table>

All data were fitted by the approximation:

\[
\bar{\tau} = a_1 \frac{d}{\sigma^2} \exp\left(-\frac{d}{2a_2^2}\right)
\]  

(2.109)

where \(\bar{\tau}\) is the mean surface lifetime and \(a_1\) and \(a_2\) are empirical constants.

Strutwolf and Blanchard [55] measured bubble persistence for distilled water; 3% Na Cl fluid and seawater. Experiments were performed in a rotating water tank with bubbles produced by capillary tips. Bubble sizes were measured using a
laser scattered light system. It was found that the bubble surface lifetime was almost independant of salt used in saline solution (eg Na Cl, K Cl etc) and that 3% NaCl solution had a 30% lower surface lifetime than seawater and distilled water bubbles had surface lifetimes ~ 90% lower than seawater bubble lifetimes.

One of the definitive papers on bubble persistence was written by Scott[56]. He found that bubble persistence increased with salt concentration. Seawater bubbles persisted 50% longer than tap water bubbles. In conditions free from organic contaminations salt concentrations of oceanic proportions are sufficient to affect small bubble numbers and coalescence. Small bubbles rise slowly so their arrival at the surface is delayed thus they arrive in greater numbers at the surface than larger bubbles. The mild surface activity of salt appears to retard bubble coalescence and stabilize surface bubbles. In retarding the coalescence of the many small bubbles formed during wave breaking, the entrained air takes a longer time to reach the surface; extending the time during which bubbles arrive and allowing the formation of a foam layer:

2.5.7 SUMMARY OF DIFFERENCES BETWEEN FRESH AND SALT WATER BUBBLES

All the evidence from preceding sections indicates that bubble stabilizing mechanisms exist. Salt water bubbles tend to be smaller and more numerous than fresh water bubbles; with reduced coalescence and longer surface lifetimes. Evaluation of the evidence indicates that bubbles are coated with contaminants even in "fresh" water, but the contamination is much increased in saline water. Some ambiguity remains with respect to the effects of salinity. There is no doubt that the presence of dissolved salts in a fluid affects bubble properties but other contaminants, possibly organic in origin, have an equal if not greater effect. Simulation of seawater using common salt is adequate but not a true representation of seawater since it may be the additive effects of salt and organic contaminants in seawater which enhance the rate of "skin" production hence altering the size distribution; coalescence properties and lifetime. There is clear evidence [47], [48] and [49] that bubble surface lifetime in salty water increases because the thermal damping coefficient reduces due to the decrease in the thermal diffusion constant; itself a result of the "skin effect". Thus the stabilization process appears to follow a feedback loop, where bubble surface lifetime is the analogue of amplification in an amplifier, as shown in Figure 2.6.
Thermal damping
Radiation damping
Viscous damping
Total damping

Resonant frequency (kHz)

Damping coefficient at resonance (x10^3)

FIGURE 2-1 DAMPING COEFFICIENT AS A FUNCTION OF BUBBLE RESONANT FREQUENCY.

FIGURE 2-2 ACOUSTIC SCATTERING FROM BUBBLE CLOUD.
FIGURE 2-3 FILM COATED BUBBLE (GOWING'S MODEL)

FIGURE 2-4 INCREASE IN BUBBLE DRAG COEFFICIENT AS A FUNCTION OF EOTVOS NUMBER.

FIGURE 2-5 BUBBLE SHAPE OSCILLATIONS. (SUBHARMONIC)

FIGURE 2-6 BUBBLE SURFACE LIFETIME FEEDBACK LOOP.
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CHAPTER 3

PROPAGATION OF PRESSURE WAVES THROUGH BUBBLY FLUIDS

3.1 INTRODUCTION

Unlike gases, liquids show minimal compressibility characteristics thus large pressure variations result in small volumetric changes. Bernoulli's steady flow theorem [1] indicates that negative pressures may become dynamically stable. The propagation of large negative pressures in all but the purest liquids results in cavitation. It is a well established fact that liquids comprising infinitesimal gas void fractions withstand much greater tensions before the onset of cavitation than do liquids with quantifiable gas inclusions. Temperature is also a dominant factor with respect to the propagation of pressure waves in a liquid medium. Briggs [2] showed that the cavitation limit for distilled water diminished by 60 atmospheres for a 40°C rise in temperature from 10°C to 50°C. A decrease in the cavitation limit was also observed as the temperature fell from 5°C to 0°C; hardly a surprising result in view of the anomalous behaviour of water between 0°C and 4°C.

3.2 ACOUSTIC LIMIT

In a compressible fluid the laws of acoustics become applicable at the hydrodynamic limit. The laws of acoustics state that small amplitude pressure waves propagating through a fluid do so at a well defined velocity:

\[ c = \sqrt{\frac{dP}{d\rho}} \]  

(3.1)

As the amplitude of pressure disturbance increases non-uniform propagation results, due to increased harmonic components. Regions of high amplitude travel faster than those of low amplitude and result in steepening of the wave front as shown in Figure 3.1. In theory, an infinitely steep wave front could be obtained; in practice this does not occur due to the dissipative effects of thermal conductivity and viscosity.

3.3 REIMANN'S FINITE AMPLITUDE WAVE THEORY

For small amplitude waves propagating in a homogeneous fluid, the fluid particle acceleration may be determined by the partial time derivative of the velocity only. When considering large amplitude waves the full expression must be applied which in one dimension is:
when propagation is independent of \( y \) and \( z \), (3.2) simplifies to:

\[
\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x}
\]

Likewise the 1D equation of continuity may be expressed thus:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} = 0
\]

Reimann [3] obtained wave propagation equations by introducing a new variable \( \Phi \), with units of velocity for mathematical purposes, such that:

\[
\Phi = \int_{\rho_0}^{\rho} \left( \frac{dP}{d\rho} \right) \frac{d\rho}{\rho}
\]

\( \rho_0 \) is the density in the undisturbed fluid.

Combining (3.5) with (3.1) allows equations (3.3) and (3.4) to be modified thus:

\[
\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} = -\frac{1}{\rho} \frac{dP}{d\rho} \frac{d\Phi}{dx} = -c \frac{\partial \Phi}{\partial x}
\]

\[
\frac{\partial \Phi}{\partial t} + u_x \frac{\partial \Phi}{\partial x} = -\rho \frac{d\Phi}{d\rho} \frac{d\Phi}{dx} = -c \frac{du_x}{dx}
\]

If equations (3.6) and (3.7) are summed we get a propagation equation for a forward travelling wave:

\[
\frac{\partial (\Phi + u_x)}{\partial t} + (c + u_x) \frac{\partial (\Phi + u_x)}{\partial x} = 0
\]

\( \Phi + u_x \) is propagated forward with velocity \( (c+u_x) \). Since the complementary quantity \( \Phi - u_x \) is zero the forward wave is of finite amplitude with \( \Phi \) and \( c \), speed of sound, increasing proportional to the pressure. As infinite steepness is approached energy dissipation must be incorporated into any solution and the Reimann theory collapses.
The Reimann solution may be extended easily to cover spherically spreading waves. Similar solutions will result but the initial pressure disturbance would be of increased magnitude by necessity for a shock front to develop, due to the increased attenuation associated with the inverse square law spreading.

3.4 SHOCK FRONTS

A shock front may be defined as a fluid surface across which pressure and density are discontinuous. To fully characterise shock propagation it is necessary to move on from Reimann and to evoke dissipative mechanisms. The specific rate of energy loss is a function of shock thickness i.e. the rate of pressure increase, both spatial and temporal. For small amplitude waves it is proportional to the cube of the pressure differential. Large pressure differentials require very narrow shock fronts in order to dissipate energy quickly. The specific rate of dissipation of mechanical energy \( \dot{w} \) is given by, Campbell and Pitcher [4]:

\[
\dot{w} = 2\mu \left[ \frac{\partial u}{\partial x} \right] = \frac{2\mu \ c \ \Delta p}{\rho_0 \ \delta} \tag{3.9}
\]

and an estimate of the thickness of a shock front as:

\[
\delta = \frac{2\mu \ c \ \rho_0^3}{k \ \Delta p} \tag{3.10}
\]

where \( \Delta p \) is the resultant density change in kg/m\(^3\) and \( k \) is a constant proportional to the P-V adiabatic gradient. For distilled water the value of \( \delta \) is approximately:

\[
\delta = 2 \times 10^{-2}/\Delta p \tag{3.11}
\]

The value of \( \delta \) will alter when impurities are present in water thus the distilled water shock thickness is not directly comparable with values in tap water, seawater or bubbly fluids. There are two principal reasons for the discrepancies between pure and impure liquids:

i. the rates of dissipation vary due to additional thermal and viscous damping of the fluid.

ii. the shape of P-V curve alters thus the \( k \) value (in 3.10) alters.
3.5 SHOCK WAVE PROPAGATION

Campbell and Pitcher [4] showed that a shock wave is a jump discontinuity where relative motion between gas and liquid phases may be neglected. They observed steepening of finite amplitude compression waves into shocks for upstream to downstream pressure ratios of 1.1 to 6 and void fractions 1% to 40%. The shock propagation velocity was found to be:

\[ v_s = \left( \frac{\rho_d}{\rho_g \beta_u (1 - \beta_u)} \right)^{\frac{1}{2}} \]  (3.12)

where subscripts u and d refer to upstream and downstream respectively. The speed of sound in the bubbly fluid was given by Woods equation [11]:

\[ c_Q = \left( \frac{\rho_u}{\rho_g \beta_u (1 - \beta_u)} \right)^{\frac{1}{2}} \]  (3.13)

with the Mach number of shock propagation:

\[ M_s = \left( \frac{P_d}{P_u} \right)^{\frac{1}{2}} \]  (3.14)

Four propagation regimes were shown to exist and the resultant Mach number expressions are given below.

i. No relative motion between liquid and isothermal gas phases due to the effect of viscosity – thus as above:

\[ M_s = (P_d/P_u)^{\frac{1}{2}} \]

ii. No relative motion between liquid and adiabatic gas phases due to the effect of viscosity:

\[ M_s = \left[ \left( \frac{P_d}{P_u} - 1 \right) / \left[ 1 - \left( \frac{P_u}{P_d} \right)^{\frac{1}{\gamma}} \right] \right]^{\frac{1}{2}} \]  (3.15)

3.4
iii. Viscous forces negligible – relative motion between liquid and isothermal gas phases:

\[ M_s = \left[ \left\{ \frac{P_d}{P_u} - \beta \right\} \frac{1}{1 - \beta} \right]^{\frac{3}{2}} \tag{3.16} \]

iv. Viscous forces negligible – relative motion between liquid and adiabatic gas phases:

\[ M_s = \left[ \left\{ \frac{P_d}{P_u} - 1 \right\} \frac{1}{1 - (P_u/P_d)^{1/\gamma}} \right]^{\frac{3}{2}} \tag{3.17} \]

The isothermal or adiabatic response of the air/water mixture is governed principally by the bubble size spectrum. It is assumed however, that the shock front thickness is of much greater dimensions than the mean or dominant bubble size. There may be some overlap between isothermal and adiabatic responses where a polytropic regime is apposite. This region is mentioned in Section 3.7 but no rigorous mathematical treatment is given.

For very low frequency pressure variations, the Korteweg de Vries [5] equation is applicable, which for a 1D system becomes:

\[ \frac{\partial P}{\partial t} + \frac{\partial \left( \rho \right)}{\partial x} \left( \gamma + 1 \right) \frac{\partial P}{\partial x} + \frac{C_\rho^2}{2 \rho \beta} \frac{\partial^3 P}{\partial x^3} + \frac{\partial^2 P}{\partial x^2} = \frac{\delta}{2 \omega_0^2} \frac{\partial^2 P}{\partial x^2} \tag{3.18} \]

The Korteweg de Vries model is the simplest one which incorporates non-linearity and dispersion, but it breaks down if extended to encompass high amplitude shock profiles with \( P_d/P_u >> 3 \). Thus as a shock deepens it can no longer be characterised satisfactorily by this model.

Whether isothermal or adiabatic laws are observed is determined by the thermal relaxation process. Noordzij [6] proposed a relaxation mechanism where the presence of a pressure differential induces relative motion between the phases and effects a temperature change. The time constant for the relaxation process has components arising from viscosity and thermal diffusion with values [7]:

\[ \tau_{vis} = R_o^2 / 9 \, \nu \ell \] \quad \text{for mean bubble radius } R_o \leq 2 \text{mm} \\
\tau_{th} = R_o^2 / 3 \, \text{Kg} \]

For air bubbles in water at 20°C the thermal component has approximately three
times the magnitude of the viscous component. Large thermal relaxation time constants
- hence slow energy loss - results in isothermal processes, whilst small time constants
with high resultant heat energy loss indicate adiabatic behaviour. Slight modification
of the above expressions might be required when considering bubbles larger than 2mm
radius.

3.6 THE EFFECT OF RELATIVE MOTION BETWEEN LIQUID AND GAS
PHASES

3.6.1 NO RELATIVE MOTION BETWEEN PHASES

If the gas content of individual bubbles obeys isothermal laws then:

\[ \frac{P}{P_0} = \frac{R_0^3}{R^3} \]  \hspace{1cm} (3.19)

where \( P_0 \) and \( R_0 \) represent initial conditions.

If there is no relative motion between the liquid and gas phases then the gas to
liquid mass ratio remains constant:

\[ \frac{P_0 \beta}{P_g (1 - \beta)} = \text{const} \]  \hspace{1cm} (3.20)

The local speed of sound (Wood's Equation (3.13)):

\[ c_g = \left[ \left( \frac{\partial P}{\partial \rho} \right)_s \right]^{\frac{1}{2}} = \left[ \frac{P_0}{\rho_g \beta_0 (1 - \beta_0)} \right]^{\frac{1}{2}} \]  \hspace{1cm} (3.21)

where the subscript \( s \) refers to constant entropy, i.e. Wood's equation.

In the adiabatic limit (3.21) becomes:

\[ c_g = \left[ \frac{\gamma P_0}{\rho_0 \beta_0 (1 - \beta_0)} \right]^{\frac{1}{2}} \]  \hspace{1cm} (3.22)

Now a characteristic gas diffusion length \( \lambda_g \) may be defined thus:

\[ \lambda_g = \left[ \frac{K_g}{\omega} \right]^{\frac{1}{2}} \]  \hspace{1cm} \lambda_g \gg R_0 - \text{isothermal}

\[ \lambda_g \ll R_0 - \text{adiabatic} \]  \hspace{1cm} (3.23)
and a corresponding characteristic length scale may be defined for the liquid phase thus:

\[ \lambda_\text{L} = \left( \frac{\kappa_\text{L}}{\omega} \right)^{\frac{1}{2}} \]  
(3.24)

The specific heat capacity of the liquid within the characteristic length surrounding a bubble of initial radius \( R \) is then given by

\[ Q_\text{L} = \frac{4}{3} \pi \rho_\text{L} \left( \frac{(\lambda_\text{L} + R_0)^3 - R_0^3}{C_\text{pL}} \right) \]  
(3.25)

where \( C_\text{pL} \) is the heat capacity of the liquid at constant pressure. The specific heat capacity of the gas bubble is:

\[ Q_\text{g} = \frac{4}{3} \pi \rho_\text{g} R_0^3 \]  
(3.26)

with \( C_\text{pg} \) the heat capacity of the gas at constant pressure;

The ratio \( Q_\text{g}/Q_\text{L} \) is dependent on bubble size and fluid and determines whether or not adiabatic or isothermal laws are obeyed, when there is no phase separation.

3.6.2 RELATIVE MOTION BETWEEN PHASES

The relative motion depends on drag forces and the size and shape of a bubble are critical when examining drag laws.

The effective mass of a bubble in an incompressible liquid \( (m_\text{e}) \) may be expressed:

\[ m_\text{e} = \frac{2}{3} \pi R_0^3 \rho_\text{L} \]  
(3.27)

where bubble motion is resisted by viscous drag.

Levich [8] defined the drag force on bubbles of radius less than 2mm to be analogous to that for solid spheres:

\[ F_\text{D} = 6\pi R_0 \mu \eta u_\text{rel} \]  
(3.28)

where \( u_\text{rel} \) is the velocity of the bubble relative to the liquid.
The Rybczynsky–Hadamard equation is used when the viscosity of both gas and liquid are significant resulting in the following drag relation:

\[ F_D = 4\pi R_o \mu_L u_{rel} \]  

(3.29)

Bachhuber and Sandford [9] showed that after initial formation when bubbles obey fluid sphere dynamics, they progress to a solid sphere model with drag force given by:

\[ F_D = 12\pi R_o \mu_L u_{rel} \]  

(3.30)

For gas and liquid velocities \( u_g \) and \( u_L \) respectively and bubble volume \( V_B \) we get:

\[ \frac{d}{dt} \left( \rho_g V_B u_g + \frac{1}{2} \rho_L V_B (u_g - u_L) \right) - \rho_L g V_B \]  

(3.31)

thus for \( \rho_L >> \rho_g \) equation (3.31) becomes:

\[ F_D = \frac{\rho_L V_B}{2} \frac{d}{dt} (u_g - 3u_L) \]  

(3.32)

Bubbles which obey equation (3.32) move relative to the liquid at an initial velocity of \( u_g = 3u_L \) due to an incident pressure disturbance. It is assumed that well travelled or coated bubbles will emulate solid sphere behaviour. Conversely those in pure liquids or very close to their generation point will respond as fluid spherics.

A relaxation time, \( \tau_o \), useful for determining the significance of damping parameters which affect isothermal/adiabatic/polytropic response may be defined thus:

\[ \frac{du_{rel}}{dt} = - \frac{u_{rel}}{\tau_o} \]  

(3.33)

where

\[ \tau_o = \frac{2 F_D}{3 \rho_L V_B} \]  

(3.34)

Noordzij [6] derived an expression for the local sound speed when high frequency waves propagate through bubbly fluids with the caveat that the incident wave frequency is still less than bubble resonance frequency:
Thus the value of the local speed of sound is that of an adiabatic system (see equation (3.22)) with an additional term $(1+2\beta_0)^{1/2}$ to account for phase separation due to the passage of a relatively high frequency wave through the bubbly fluid.

### 3.7 INFLUENCE OF MACH NUMBERS

Crespo [10] identified 3 propagation regimes (outlined below) based upon the influence of low and high frequency Mach numbers compared to Campbell and Pitcher's reliance on low-frequency-Mach values alone [4]—which resulted in 4—propagation regimes — isothermal and adiabatic systems with and without phase separation. Isothermal systems with phase separation appear somewhat paradoxical, but the term is used here to indicate that the average macroscopic temperature of the ensemble remains constant even though the temperature fluctuations on the microscopic level, i.e. individual bubbles, are permissible.

#### 3.7.1 PROPAGATION AS A FUNCTION OF MACH NUMBER

i. For low frequency waves, fluid viscosity acts to ensure uniform flow of both liquid and gas. Thermal considerations indicate that liquid and gas will maintain the same temperature thus bubble dynamics will obey the isothermal gas laws. For the case when:

$$1 \ll \frac{v_g}{\omega_r^2} \ll \frac{K_g}{\rho_g C_{pg} \omega_r^2}$$

then Wood's formula for the speed of sound may be applied as given in equation (3.13):

$$c_L = \left[ \frac{\rho_L}{\beta \left(1 - \beta\right)} \right]^{1/2}$$
At intermediate frequency range the effect of viscosity is minimal and bubbles move in response to inertial forces. The frequency however is still sufficiently low for isothermal gas dynamics to be appropriate. In this case:

\[ \frac{v_g}{\omega_r^2} \ll 1 \ll \frac{K_g}{\rho_g C_{pg} \omega_r^2} \]

and in this regime the speed of sound takes the form:

\[ c_q = \left[ \frac{P}{\gamma \rho_q} \frac{1 + 2\beta(1-\beta)/\Gamma}{\beta (1-\beta)} \right]^{\frac{1}{2}} \quad (3.36) \]

where \(\Gamma\) is a function of the void fraction (which is defined in Crespo [12]). For low void fractions \(\Gamma\) is unity; its value decreases with increased void fraction as the bubbly fluid tends to a foam with considerably reduced compressibility.

Although isothermal gas laws are obeyed there is flow separation between gaseous and liquid components.

iii. At the high frequency limit both viscous and thermal effects are negligible. Here:

\[ \frac{v_g}{\omega_r^2} \ll \frac{K_g}{\rho_g C_{pg} \omega_r^2} \ll 1 \]

There is isentropic behaviour in the fluid; bubbles obey the adiabatic gas laws and there is flow separation. The local speed of sound is given by the expression [10]:

\[ c_q = \left[ \frac{\gamma P}{\rho_q} \frac{1 + 2\beta(1-\beta)/\Gamma}{\beta (1-\beta)} \right]^{\frac{1}{2}} \quad (3.37) \]

3.7.2 SHOCK SPECTRA AS A FUNCTION OF MACH NUMBERS

Shock waves comprise contributions from a wideband of frequencies. It is therefore not necessarily true that frequency and amplitude components in both gas and liquid phases are in equilibrium. Volume oscillations of the gas phase accelerate the surrounding liquid. An increase in entropy is a prerequisite for shock production such
that:

\[ M_{Qf} = \left( \frac{P_d}{P_u} \right)^{\frac{1}{2}} = \frac{U_u}{c_{Qf}} \]  

(3.38)

this is identical to equation (3.14) but we identify (3.38) as the low frequency Mach number.

In the intermediate and high frequency ranges the Mach number takes the form [12].

\[ M_{hf} = \left( \frac{P_d}{\gamma P_u} \right)^{\frac{1}{2}} = \left( \frac{U_u^2 \beta_u (1 - \beta_u)}{(1 + 2\beta_u (1 - \beta_u)/\Gamma)} \right)^{\frac{1}{2}} = \frac{U_u}{c_{hf}} \]  

(3.39)

Following Crespo, two discrete regimes may be identified now where shock spectra are functions of both Mach numbers.

### 3.7.2.1 Isothermal and Adiabatic Mach numbers > 1

In this regime thermal and viscous dissipative terms have no effect upon the shock pressure since the limiting parameter is bubble size. The timescales over which viscous and thermal effects occur are very long in comparison with the bubble oscillation period (see 3.7.1 iii) The pressure distribution across a shock takes the form of a fast exponential rise which might be followed by subsequent sinusoidal oscillations resulting from volume expansion and contraction of the gas phase. For a one dimensional system the resultant pressure may be represented thus:

\[ P_s = P_0 \exp^{-k'x} \]  

(3.40)

during the compression phase,

whilst immediately after the pressure maximum has been reached,

\[ P_s = P_0 \exp^{-k'x} \sin k''x \]  

(3.41)

The attenuation term is real while the oscillatory term is imaginary and characterises phase shifts
Crespo [12] has shown that on the upstream side of the shock:
The oscillatory component is lightly damped with a frequency which is equal to the natural resonant frequency of the mean bubble size as expressed in (3.7). During the rapid initial exponential rise \( k^* \) has a positive value, but thereafter \( k^* \) is negative. At the upstream end of the shock front the pressure rise resulting from increased density compresses the bubbles which in turn causes an exponential increase in bubble numbers i.e. more bubbles pushed together in a reduced fluid volume. Conversely at the downstream edge of the shock wave the bubble compression pressure has greater magnitude than subsequent pressure increases in the liquid, this results in bubble oscillation i.e. pressure does not drop once the compression limit is reached because of multiple phase changes.

In order to obtain the pressure-time relationship for true shock waves a limiting condition is set for \( k^* \) by allowing \( r_u \) in (3.42) to assume the value of one millimetre. Thus knowing the magnitude of pressure, effective impact velocity and void fraction in conjunction with the estimated shock width the necessary conditions are fulfilled for determining a value for the rise time in milliseconds.

Conversely it is possible to estimate peak shock pressures using the above criteria and the measured value of the rise time. Crespo also makes the following points. The value of \( \Gamma \) in (3.43) remains close to unity. \( \Gamma \) is a function of void fraction and as void fraction \( \beta_u \) increases the function changes to a power series in \( \beta_u \) thus setting an upper limit to the void fraction which will sustain true shock waves. In theory the higher the void fraction, the lower is the local speed of sound hence the greater the probability for shock wave generation. In practise the altered form of \( \Gamma \) at void fractions in excess of 20% militates against the production of bubbly fluid shock waves, hence true shock wave generation is limited to void fractions of less than 20%. Some calculated pressure-time curves (using above equations) are shown in Figures 3.2 and 3.3.

\[
k^* = \frac{1}{r_u} \left[ \frac{3 \beta_u (1-\beta_u)}{(1 + 2 \beta_u (1-\beta_u)/\Gamma)} \right]^{1/2} \left[ 1 - \frac{1}{M_{hf}^2} \right]^{1/2} \quad (3.42)
\]

Where \( u_{eff}^{-1} \) is the effective impact velocity in m/s.
3.7.2.2 Adiabatic Mach number < 1

In this regime the shock formation process is governed by the dissipative action of thermal and viscous damping. The shock width is greater than that in the previous case; the pressure rise is slower and a function of gas phase compressions. The expressions for determining the coefficient $k'$ in the rising pressure term are obtained by solving Crespo's expression [10] for bubble energy and momentum conservation.

\[
\frac{dP_g}{dx} - A \frac{dP_g}{dx} - B = 0 \quad (3.44)
\]

\[
\frac{dP_g}{dx} - C \frac{dP_g}{dx} - D = 0 \quad (3.45)
\]

where the values of coefficients A to D are given in Appendix B.

Unlike the case described in section (3.7.2.1) above, it can be assumed [12] that pressure amplitudes in liquid and gas phases are equal and a quadratic expression for the rise time is obtained:

\[
a_0 \tau^2 + a_1 \tau + a_2 = 0 \quad (3.46)
\]

Conversely the expression may take the form

\[
b_0 P_s^2 + b_1 P_s + b_2 = 0 \quad (3.47)
\]

The coefficients $a_0$, $a_1$, $a_2$ and $b_0$, $b_1$, $b_2$ are functions of peak pressure, rise time, mean bubble size, effective impact velocity and low frequency Mach number and are given in Appendix B.

Some calculated pressure - time curves and time as a function of velocity, void fraction and mean bubble size (using above equations) are given in Figures 3.4 to 3.8, based on expressions in Appendix B.

It is apparent that given impact velocity, void fraction and mean bubble size data it is possible to determine the rise time value which in turn may be used to ascertain peak pressures.

Rise times are almost independent of explicit pressure dependence, in contrast to exponential shock waves. Nearly all pressure dependence for rise time values is implicit because of the very strong pressure - velocity relationship. It is evident that
peak pressures and rise times are strong functions of mean bubble size with slightly weaker dependence upon void fraction; the smaller the bubble size the greater the probability of transition from compression wave to shock wave (see 3.7.1). For low velocity impacts the rise time increases with void fraction whilst the trend is reversed for peak pressure - void fraction relationships. At the transition region between low and high frequency Mach numbers all impacts rise more quickly than before and those with high air content (i.e. > 10%) rise more steeply at an earlier point in time than those with little air. This divergence results as a consequence of the dispersive nature of the speed of sound in bubbly fluids.

3.8 SHOCK WAVES AT OBLIQUE INCIDENCE

Unlike subsonic pressure waves which radiate isotropically supersonic waves are restricted to propagate within a fixed zone referred to as "the Mach Cone", as shown in Figure 3.9. External to this core is the zone of silence whilst inside the cone there-are abrupt changes of pressure and density thus the region is referred to as the zone of action or the region of influence. Shock waves however are not restricted to normal incidence but may result at angles obliquely incident to the flow. Under these circumstances it becomes necessary to separate the velocity into its normal and tangential components. Shock pressures result from a reduction of the normal downstream component whereas the tangential component remains unaffected resulting in wave deflection. The deflection angle for shock waves is as shown in Figure 3.10 and is expressed thus:

\[
\tan (\psi - \psi_d) = \frac{2 \cot \psi_u \left( M_u^2 \sin^2 \psi_u - 1 \right)}{M_u^2 \left( \gamma + \cos^2 \psi_u \right) + 2}
\]

obviously there is no deflection when \( \psi_u = 90^\circ \) re-normal shock waves.

For a given upstream Mach number equation (3.48) is dual valued with respect to \( \psi_u \) except for a single maximum - hence a cone.

The wave corresponding to the lower value of \( \psi_u \) is observed more often and is known as a weak oblique shock wave. Oblique shock waves may experience deflection at a solid non-absorbing boundary, angles of incidence and deflection are however different in most cases.

Two double shock waves may interact in their downstream regions resulting in the generation of two further waves at the intersection point, with excess energy dissipated as a vortex street, as shown in Figure 3.11.
3.9  EFFECT OF BUBBLE SIZE UPON PROPAGATION OF PRESSURE WAVES

If an air pocket is subjected to a shock pressure then the air pocket or bubble collapses completely or compresses to a minimum radius then oscillates for several cycles. According to the Rayleigh cavity collapse model (see Chapter 2.4.1) bubble life time, hence pressure rise time, is directly proportional to bubble size. Additionally equation (3.49) shows that bubble lifetime is inversely proportional to the square root of the fluid density.

\[ \tau = 0.915 \frac{R_0}{(\rho/\alpha P)^{1/2}} \]  

(3.49)

The higher the air content the greater the probability of partial compression and subsequent bubble oscillation compared to total bubble collapse. Although the Rayleigh model is simplistic it elicits the significant parameters which affect volume contraction/ pressure rise.

The "elastic properties" of the "quasi-permanent" liquid/gas mix accompanied by the inertial effects of the liquid evoke the required conditions for an oscillating system. On contraction of a bubble there is a cushioning or damping effect until the gas pressure increase is of sufficient magnitude to reverse the \( dR/dt \) sign at minimum bubble radius.

Thereafter the bubble expands and a pressure pulse is radiated into the liquid; the cushioning effect diminishes rapidly and the intensity of the outward pressure wave reduces in preparation for the next compression cycle once the maximum radius has been reached. At a distance of tens of bubble diameters from the bubble it is anticipated from spherical spreading, that the pressure differential will be proportional to the second time derivative of the volume, i.e. simple harmonic motion.

As pressure waves propagate their amplitudes diminish whilst their duration increases. For small wave amplitudes the characteristic duration of pressure perturbations is close to the dominant bubble resonance period, the wider the bubble size spectrum the greater time smearing effect. As wave amplitudes increase the duration of single free pulses decreases due to strongly nonlinear bubble action.

Qualitative changes in wave structure arise when very large amplitude waves propagate since solitary waves tend to couple and the coupled waves propagate with reduced attenuation. The attenuation process acts to transform such pressure waves into oscillatory shock waves with the principal dissipation mechanism being thermal damping between gas bubbles and the surrounding liquid.

If a bubbly fluid contains very few large bubbles then propagating waves are shaped by the action of small bubbles alone and oscillation is of small amplitude and high frequency.
As the percentage of large bubbles increases full oscillatory waves form with the large bubbles governing the wave duration ie number of cycles and the small bubbles determining the oscillation frequency.

When the percentage of large bubbles within the void fraction assumes dominance then the wave amplitude decreases significantly due to absorption and scatter and the oscillation frequency is low, with few cycles. Void fraction dominates initial pressure rise and bubble size dominates the oscillatory phase when bubbles are small and uniform. As the percentage of larger bubbles increases the mean bubble size increases rapidly and signal attenuation results.

Liquids with N sized bubbles is a system of N nonlinear oscillators. Nonlinear interaction is the reason for the formation of oscillatory propagating waves at fundamental frequency. Higher order waves of mode (n,m) form when pressure amplitudes are very large (typically greater than 100 kPa). Thus in many circumstances bubble size is even more critical with respect to pressure wave propagation than void fraction. Although large bubbles determine the wave duration it is often small bubbles which determine dissipation levels due to the absorption of energy by thermal damping (see Chapter 3.7.1 and Chapter 2.2.4.1).
FIGURE 3-1 WAVE STEEPENING LEADING TO SHOCK FORMATION.
FIGURE 3-2 THEORETICAL PRESSURE-TIME CURVES FOR SHOCK WAVES.

Impact velocity 100m/s

- 20% 10%
- 30% 5%

Impact velocity 60m/s

- 30% 1%
- 20% 10%
- 10% 5%

RISE TIME (milliseconds)
FIGURE 3-3. THEORETICAL PRESSURE-TIME CURVES FOR SHOCK WAVES WITH 10% VOID FRACTION.
FIGURE 3-4 THEORETICAL PRESSURE-TIME CURVE FOR WATER COMPRESSION WAVE WITH IMPACT VELOCITY 20m/s & MEAN BUBBLE DIAMETER 1mm.
FIGURE 3-5 THEORETICAL PRESSURE-TIME CURVE FOR WATER COMPRESSION WAVE WITH VOID FRACTION 20% & MEAN BUBBLE DIAMETER 1mm.
FIGURE 3-6 THEORETICAL PRESSURE-TIME CURVE FOR WATER COMPRESSION WAVE WITH IMPACT VELOCITY 20m/s & VOID FRACTION 20%.

Mean bubble diameter

20 microns

200 microns

1 mm

4 mm

10 mm

0 100 200 300 400 500 600 700 800 900 1000

RISE TIME (milliseconds)

0 10 20 30 40 50 60 70 80 90 100

PEAK PRESSURE (kPa)
FIGURE 3-7 THEORETICAL CURVE OF WATER COMPRESSION WAVE IMPACT PRESSURE AS A FUNCTION OF VOID FRACTION FOR CONSTANT RISE TIME OF 100 milliseconds & MEAN BUBBLE DIAMETER OF 1 mm.
FIGURE 3-8 THEORETICAL CURVE OF IMPACT RISE TIME AS A FUNCTION OF VOID FRACTION FOR MEAN BUBBLE DIAMETER 1mm.

Impact velocity (m/s)

- 5
- 10
- 15
- 20
- 25
- 30

Rise time (milliseconds)

0 5 10 15 20 25 30 35 40

% Air
FIGURE 3-9 PROGRESSION OF SHOCK WAVE IN MACH CONE.

FIGURE 1-10 DEFLECTED SHOCK WAVES

FIGURE 3-11 VORTEX SHEDDING BEHIND SHOCK FRONT.
REFERENCES - CHAPTER 3.


INTRODUCTION

Laboratory testing falls into 4 principal categories:

i) Aeration measurement using 2 independent techniques in fresh water;

ii) Aeration measurement using 3 discrete techniques in saline water;

iii) Pressure measurement in tap water with acoustic "listening" for unaerated and aerated water;

iv) Pressure measurement for a range of aeration levels and salinities.

4.1 INITIAL AERATION MEASUREMENTS

It was considered of paramount importance to determine accuracy and sensitivity levels of the impedance method of aeration detection in order that future field data trends might be characterised. To this end it was decided that direct comparison between two or three different aeration detection methods should be made. Initially, a direct comparison between acoustic and electrical (impedance) techniques was made in fresh water using the parametric acoustic array sensing technique as described in Technical Report SCSE93-009 [1] and the prototype aeration gauge as shown in Figure 4.1 with the associated electronics as outlined in Figure 4.2. Aeration was provided by a ring of aerator stones and variable flow pump. Void fractions obtained for each technique are listed in Table 4.1 along with the associated air flow rates and consequent void fraction first order approximation using:

\[
\beta \approx \frac{\Delta V_T}{V_g} \times 100\% \tag{4.1}
\]

where \( V_g \) is the approximate volume occupied by the bubble cloud \( \Delta V \) is the volume flow rate of air and \( \tau \) is the time for bubbles to rise to the surface.
TABLE 4.1
VOID FRACTION DATA FROM TWO INDEPENDENT AERATION MEASUREMENT METHODS

<table>
<thead>
<tr>
<th>AIR FLOW FRACTION 1pm</th>
<th>RATE &amp; VOID APPROXIMATION %</th>
<th>ACoustic VOID FRACTION DATA %</th>
<th>ELECTRICAL VOID FRACTION DATA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>3.30</td>
<td>1.53 ± 0.27</td>
<td>8.40 ± 2.90</td>
</tr>
<tr>
<td>0.7</td>
<td>1.10</td>
<td>0.43 ± 0.10</td>
<td>3.40 ± 0.80</td>
</tr>
<tr>
<td>0.2</td>
<td>0.47</td>
<td>0.05 ± 0.02</td>
<td>1.30 ± 1.20</td>
</tr>
</tbody>
</table>

The void fractions obtained from electrical measurements assume a homogeneous mix of air and water, spherical bubbles, large interbubble separations and a parallel plate configuration. It is evident from Table 4.1 that variance between the data sets is considerable. The principal reasons for vast discrepancies are:

a. Instability and oscillation of the impedance gauge electronic circuitry.

b. Adhesion of bubbles to the probe surface; especially to the electrodes at low air flow rate.

c. The absence of an appropriate power amp for the acoustics circuit.

With the exception of b. these problems were addressed and new data sets obtained.

4.2 FURTHER COMPARISON OF AERATION MEASUREMENT TECHNIQUES

The impedance gauge was operated at a lower frequency to avoid severe oscillatory characteristics whilst a new driving electronics circuit was produced in order to facilitate operation in salty water. Thus two transformer boxes were available, one dedicated to freshwater applications the other, with a measurement resistor of 1kΩ cf. 18kΩ for fresh water, enabled experiments to be conducted in saline solutions. The experimental configuration of the second aeration techniques comparison was as shown in Figure 4.3. Three independent measurement methods were applied simultaneously - the impedance gauge; acoustics and the inductively coupled electrodeless Conductivity Depth and Temperature (CDT) probe as described in Technical Report SCSE93-010[2]. Cooking salt was added to tap water in the ratio 17.5 parts per thousand (ppt). For this series of tests different aerators were used, namely 3 x 25cm blocks of sandstone in preference to the ring of aerator which was proving troublesome due to inhomogeneous distribution of air and blockages at the air entry point.
Figures 4.4 to 4.8 show the measured acoustic attenuation for the air flow rates under investigation. The distributions are clearly peaked and thus at variance with distributions detected and/or postulated by Baldy and Bourguel and Medwin as discussed in Technical Report SCSE93–006 [3]. The apparent discrepancy presents no cause for alarm since the bubble generation mechanism used for these laboratory tests is the inverse of breaking waves i.e. what Baldy and Bourguel termed the "generation zone" is located at the base of the tank close to the bubble source – the aerator blocks. Consequently aeration measurements performed well above the "generation zone" are in the "dispersion zone" where the peakedness is anticipated.

An illustration of the generation/dispersion zone" concept is given in Figure 4.9. Table 4.2 lists the aeration values obtained for each of the measurement techniques. Statistical deviations of the three measured sets are also included.

<table>
<thead>
<tr>
<th>AIR FLOW RATE (Gpm) AND APPROXIMATION VOID FRACTION</th>
<th>CDT PROBE VOID FRACTION DATA</th>
<th>ACOUSTIC VOID FRACTION DATA</th>
<th>ELECTRICAL VOID FRACTION DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gpm</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>0.4</td>
<td>1.0</td>
<td>0.7</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>0.7</td>
<td>1.1</td>
<td>1.5</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td>1.0</td>
<td>1.6</td>
<td>1.9</td>
<td>1.7 ± 0.4</td>
</tr>
<tr>
<td>2.1</td>
<td>3.3</td>
<td>2.8</td>
<td>3.0 ± 0.7</td>
</tr>
<tr>
<td>3.85</td>
<td>6.1</td>
<td>5.0</td>
<td>4.1 ± 1.1</td>
</tr>
</tbody>
</table>

Clearly there is high correlation between the three independent aeration measurement techniques except at low air flow rate. Once again the problem of bubble adhesion to the surface of the impedance gauge was in evidence. Two aspects of the bubble problem needed to be addressed:

a. Bubble affinity for the probe due to the presence of surface charges. A problem likely to be exacerbated in field tests due to the abundance of organic contaminants.

b. The effect due to reduced flow rate alone. If so this would result in bubble stagnation around the impedance gauge.
The adhesion effect was observed for fresh water bubbles in approximately equal magnitude as that for saline solution bubbles; a factor which appears to reinforce option b above, since the probability of surface layers should be much greater for a strong electrolyte such as seawater in contrast to an extremely weak electrolyte like fresh water. In order to test this hypothesis the impedance gauge was positioned at the edge of the bubble cloud. Some bubble migration toward the probe was observed—a levitation type effect, but its magnitude was minimal. Thus surface charges on the gauge made a small contribution to the adhesion effect but this component was greatly exceeded by the effects of reduced water and air flow. It was decided therefore that the combined actions of strong wind and water currents anticipated in field trials would nullify this effect, by transporting any small bubbles away from the electrode surface. Bubble adherence would occur only during the calmest of conditions thus bearing no relevance to breaking waves.

Determination of aeration using the impedance technique relied upon satisfaction of Maxwell criteria as described in Technical Report SCSE93-008 [4]. It became obvious that there should be some attempt to specify the electrical field pattern for extreme cases as well as for isotropic conditions. The electrical field pattern was also determined experimentally. An artificial "bubble" of rectangular cross section with volume 2.8cm was made from packaging material. The magnitude of impedance change was recorded for different spatial orientations of the "bubble" as shown in Figure 4.10. The field pattern approximated a 3-D Gaussian distribution which could be simplified quite legitimately to a cube of dimensions $\sigma^3$ for mean integrated response. Both theoretical predictions and experimental results were in good agreement.

4.3 INITIAL IMPACT PRESSURE TESTS

Once confidence was established with respect to aeration measurement techniques, then impact pressure investigations in the laboratory were undertaken. A steel swinging drop arm arrangement was fabricated as shown in Plate 4.1. An attachment was made so that two different types of pressure sensor could be fixed to the arm—a 2.5cm diameter rubber faced Kulite pressure transducer and a 2.5cm diameter Maywood Instruments sensor as shown in Plates 4.2 and 4.3 respectively. Both sensors comprised piezoelectric elements which produced an output voltage proportional to the applied pressure with measurement sensitivities of 15kPa/V and 17.3kPa/V for Kulite and Maywood respectively. Drop tests were performed by attaching a pressure transducer to the arm which was
then released from a known height. The resultant impact as the sensor struck the water surface at a small angle was measured.

Three drop heights were used and the normal drop velocity obtained from the relationship:

\[ U_\perp = \sqrt{2gh} \quad (4.2) \]

Measurements were made with fresh still water (no aeration) and in the presence of an aerated water column (approximately 14% aeration) produced using 4 x 25cm long aerator blocks such as used in the previous experiment and as shown in Plate 4.4. A maximum air flow rate of 8.15Lpm was used from a combination of two air pumps each supplying two blocks.

The acoustic technique (see SCSE93–009) was used to determine the air content.

The receiving hydrophone for the acoustics system acted as a "passive listener" for any shock waves introduced by the impact of the swinging arm on the water surface. Table 4.3 lists the relative delay introduced by the addition of the bubble column.

Intensity variations for both pressure transducers show reproducibility.

Approximations for the speed of sound in the bubbly region may be obtained from the measured time delay data between clear and bubbly regimes and these are also included in Table 4.3. The approximate speed of sound values obtained from Kulite transducer data appear acceptable. There does appear to be some detectable impact velocity dependence when compared with calculated speed of sound values for known void fractions. The same calculations based upon Maywood data appear to be an order of magnitude too great thus indicating the presence of spurious sound transport mechanisms, once again undermining confidence in the Maywood transducer's suitability for these investigations.

Owing to the absence of definite trends it was decided that "passive listening" would not provide any useful additional data although confidence in the attenuation mechanism due to the presence of bubbles was enhanced.
### TABLE 4.3
HYDROPHONE RESPONSE: AMPLITUDE AND PHASE

<table>
<thead>
<tr>
<th>VELOCITY</th>
<th>TIME LAG (µs)</th>
<th>EFFECTIVE VELOCITY OF SOUND (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ul (m/s)</td>
<td>NO AIR</td>
<td>14% AIR</td>
</tr>
<tr>
<td>A 1.25</td>
<td>1664 ± 394</td>
<td>400 ± .50</td>
</tr>
<tr>
<td>1.53</td>
<td>2757 ± 356</td>
<td>645 ± 116</td>
</tr>
<tr>
<td>1.77</td>
<td>2800 ± 329</td>
<td>994 ± 227</td>
</tr>
<tr>
<td>B 1.25</td>
<td>2861 ± 424</td>
<td>7154 ± 109</td>
</tr>
<tr>
<td>1.53</td>
<td>2970 ± 258</td>
<td>809 ± 271</td>
</tr>
<tr>
<td>1.77</td>
<td>3201 ± 317</td>
<td>1090 ± 276</td>
</tr>
</tbody>
</table>

A = Kulite, B = Maywood

Measured impact pressure and pressure rise times are listed in Tables 4.4 and 4.5. Three calculated variables U₁, ϕ and K/D are included, the first two expressions are used in Taylor's jet impact theory [5] whilst K/D is an expression from Bagnold's air piston model [6]. Both models are described in Chapter 1 Sections 1.1 and 1.3 respectively.

Taylor investigated the impact of a narrow angle (ϕ) jet of water upon a moving surface and obtained the following expressions for impact pressure and resultant tangential velocity:

\[
P_s = \frac{1}{2} \rho g \left( v + \frac{U_1}{\sin \phi} \right)^2
\]

(4.3)

where \( U_1 \) is the velocity of impact normal to the surface and \( v \) is the velocity of the jet of water.

\[
U_1 = \frac{U_L}{\tan (\phi/2)}
\]

(4.4)

There is an analogy with wave breaking upon a vertical structure where \( U_1 \) and \( \phi \) adopt the same meaning as above while \( v \) now becomes the velocity of the water in the wave crest relative to the rest of the wave.

For laboratory swinging arm tests \( v \) assumes the value zero; thus with \( \rho g \) and \( U_1 \) known and using measured data for \( P_s \) it becomes possible to determine values for
### Table 4.4: Maywood Transducer, Measured Impact Pressure and Rise Time Data; Calculated Contact Angles; Effective Velocities; Exponent (Taylor & KID (Bagno1d)).

<table>
<thead>
<tr>
<th>Drop Velocity (m/s)</th>
<th>Peak Pressure (kPa)</th>
<th>Rise Time (μs)</th>
<th>Contact Angle (deg)</th>
<th>Effective Normal Velocity (m/s)</th>
<th>Effective Tangential Velocity (m/s)</th>
<th>Exponent (&quot;m&quot;)</th>
<th>Bagno1d (KID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AIR ADDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>17.4</td>
<td>1235</td>
<td>12.2</td>
<td>5.0</td>
<td>11.7</td>
<td>-0.33</td>
<td>4.11</td>
</tr>
<tr>
<td>1.53</td>
<td>20.4</td>
<td>1185</td>
<td>12.2</td>
<td>7.3</td>
<td>14.4</td>
<td>-0.35</td>
<td>4.18</td>
</tr>
<tr>
<td>1.77</td>
<td>40.3</td>
<td>1038</td>
<td>11.4</td>
<td>10.1</td>
<td>17.8</td>
<td>-0.38</td>
<td>4.76</td>
</tr>
<tr>
<td>14% AIR ADDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>12.0</td>
<td>1388</td>
<td>13.4</td>
<td>5.4</td>
<td>10.7</td>
<td>-0.33</td>
<td>3.40</td>
</tr>
<tr>
<td>1.53</td>
<td>20.2</td>
<td>1242</td>
<td>12.0</td>
<td>8.9</td>
<td>13.5</td>
<td>-0.35</td>
<td>3.7</td>
</tr>
<tr>
<td>1.77</td>
<td>30.7</td>
<td>1103</td>
<td>12.1</td>
<td>8.8</td>
<td>18.7</td>
<td>-0.38</td>
<td>4.22</td>
</tr>
</tbody>
</table>

### Table 4.5: Maywood Transducer, Measured Impact Pressure and Rise Time Data; Calculated Contact Angles; Effective Velocities; Exponent (Taylor & KID (Bagno1d)).

<table>
<thead>
<tr>
<th>Drop Velocity (m/s)</th>
<th>Peak Pressure (kPa)</th>
<th>Rise Time (μs)</th>
<th>Contact Angle (deg)</th>
<th>Effective Normal Velocity (m/s)</th>
<th>Effective Tangential Velocity (m/s)</th>
<th>Exponent (&quot;m&quot;)</th>
<th>Bagno1d (KID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AIR ADDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>23.6</td>
<td>642</td>
<td>10.6</td>
<td>8.9</td>
<td>13.9</td>
<td>-0.33</td>
<td>5.66</td>
</tr>
<tr>
<td>1.53</td>
<td>35.4</td>
<td>532</td>
<td>10.5</td>
<td>8.4</td>
<td>16.7</td>
<td>-0.34</td>
<td>5.57</td>
</tr>
<tr>
<td>1.77</td>
<td>48.6</td>
<td>454</td>
<td>10.6</td>
<td>9.7</td>
<td>16.1</td>
<td>-0.35</td>
<td>5.6</td>
</tr>
<tr>
<td>14% AIR ADDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>19.1</td>
<td>694</td>
<td>10.8</td>
<td>8.7</td>
<td>13.2</td>
<td>-0.33</td>
<td>5.24</td>
</tr>
<tr>
<td>1.53</td>
<td>23.5</td>
<td>620</td>
<td>12.0</td>
<td>7.4</td>
<td>14.6</td>
<td>-0.27</td>
<td>4.31</td>
</tr>
<tr>
<td>1.77</td>
<td>26.0</td>
<td>639</td>
<td>13.2</td>
<td>7.8</td>
<td>15.4</td>
<td>-0.28</td>
<td>3.57</td>
</tr>
</tbody>
</table>
It appeared logical to determine whether the jet impact model was more appropriate for drop testing than that of Bagnold whose experimental data on the impact of model waves results in an empirical relationship (see Equation 4.5 below) between impact pressure and \( \frac{K}{D} \) where \( K \) is the "active length" of the cylinder of fluid involved in the pressure surge and \( D \) is the length of an air pocket at the front of the "active length" of fluid which acts as a piston.

\[
P_s = 2.7 \rho U_{\parallel}^2 \left( \frac{K}{D} \right)
\]

(4.5)

Using Bagnold's compressional model an approximate relationship between \( K, D \) and \( \tau \) was obtained from the form:

\[
\tau = \left[ \frac{A_0}{A_1} \right]^{\frac{1}{2}} D \left\{ 1 + 4.67 \left[ \frac{D}{A_1} \right] + 52.1 \left[ \frac{D}{A_1} \right]^2 + 148.4 \left[ \frac{D}{A_1} \right]^3 \right\} + 144.6 \left[ \frac{D}{A_1} \right]^4
\]

(4.6)

where \( A_0 = 6.57 \times 10^{-2} K (1 - \alpha_1 (D) - \alpha_2 (\beta)) \)

\[
A_1 = A_0 U^2 + 7D
\]

(4.7)

where \( \alpha_1 \) and \( \alpha_2 \) are functions of \( D \), the air pocket length and \( \beta \), the void fraction respectively.

Equation (4.6) is an extension of Bagnold's own approximate integral equation for rise time [6].

By comparing and contrasting these results, in Tables 4.4 and 4.5, obtained using both Taylor and Bagnold models a direct comparison is possible between an incompressible model and a compressive model.

The effects of aeration can be seen in Figures 4.11 to 4.14 which show the variation of impact pressure and rise time as functions of velocity.

A decrease in impact pressure results for both transducers when aerated water is present. For the Kulile sensor the decrement is \( \sim 25\% \) whilst variations detected with the Maywood sensor were greater but less consistent. Conversely the measured rise times increased in magnitude when aerated water was present; this trend may be exaggerated by the Maywood sensor due to its lack of temperature compensation as
observed by Graham [7]. This temperature anomaly may have affected subsequent estimates of aerated water. What is apparent, however, is the consistent relationship between rise time, \( \tau \), and \( U_\perp \) for the Kulite transducer as illustrated by Figure 4.15 and which assumes the form:

\[
\left( \frac{U_\perp}{\sin \phi} \right) \propto \tau^{-m} \tag{4.8}
\]

where \( U_\perp \) is in m/s and \( \tau \) in seconds.

The rise time \( \tau \), is defined as the period from the start of the impulse to the point of maximum pressure. The value of the exponent \( m \) in equation (4.8) obtained empirically from laboratory tests assumes an approximate value of 1/3. The left side of (4.8) is the effective jet impact velocity derived by Taylor (see Chapter 1.3) thus if subsequent experiments were to reinforce these findings then it might be possible to exploit the velocity/rise time relationship in field tests by measuring both parameters, to assist in determining the form of impact, i.e. whether shock or compression water waves or air pocket collapse.

The relationship expressed in (4.8) may appear contrived since it is based upon the angle \( \phi \) being variable but it results empirically in a functional dependence upon approach velocity and air content. From geometrical considerations the contact angles with the water surface were 11.3° and 8.9° for Kulite and Maywood respectively, the discrepancy arising due to configurational and dimensional differences.

It is evident that bubbles at the air/water interface may cause the contact angle to vary but the magnitude of the variation is difficult to predict.

Therefore a different approach was adopted and \( \phi \) values were fixed at 12° for Kulite and 9° for Maywood with the exponent \( m \) also fixed at a value of 1/3. The figure of 1/3 for \( m \) is in agreement with theoretical considerations of a narrowing shock cone by Longuet-Higgins [8]. It was postulated by Longuet-Higgins that jet motion resulting from the collapse of bubbles approaching an interface may be characterised by an ellipsoid hyperbolic function. The limits of cone shaped water particle velocity contours tend to infinity with the response \( V \propto t^{-1/3} \) as time \( t \) tends to zero.

From (4.8) with \( m = 1/3 \):

\[
\left( \frac{U_\perp}{\sin \phi} \right) \propto \tau^{-0.333} \quad \text{or} \quad \tau \propto \left( \frac{U_\perp}{\sin \phi} \right)^{-3}
\]
this was rearranged in terms of a parameter $\psi$ such that:

$$\psi = \frac{1}{\tau} \left( \frac{U_1}{\sin \phi} \right)^{-3}$$  \hspace{1cm} (4.9)

Although no clear trend emerged from Maywood data a trend began to appear from Kulite data showing a functional power dependence of $\psi$ upon $U_1$. This trend is explored further in section 4.4.

### 4.4 IMPACT PRESSURE DROP TESTS OVER A RANGE OF AERATION AND SALINITY VALUES

The final series of laboratory tests, using the same swinging arm arrangement, comprised impact pressure measurements with both Kulite and Maywood transducers over a range of aeration and salinity levels. The salinity levels varied between 0g/l and 35g/l (simulated seawater). Measured values of impact pressure and rise times are listed in Tables 4.6 and 4.7 for Kulite and Maywood sensors respectively.

Aeration levels were varied from 0.5% to 13.9%. Four aerator blocks were used to produce a column of bubbles. Two variable flow rate air pumps were attached to the stones as described in 4.3. Flow rates over the range 0.14lpm to 8.15lpm were applied to the stones. Void fractions were determined using the parametric acoustic array [1].

The relationship between pressure and rise time is considered below.

The velocity - time relationship from Equation (4.8) of

$$u \propto \tau^{-1/3}$$

implies a pressure - time relationship of

$$P_s \propto \tau^{-2/3}$$

(since $P \propto u^2$)

Hattori et al [9] performed laboratory experiments to investigate the pressure - time relationships of model scale breaking waves. The wave breaking was achieved by using a 1/20 sloping beach. From their results, a limiting peak pressure - time relationship was derived, as shown in Figure 4.16, of the form

$$P_s = 40\tau^{-3/4}$$  \hspace{1cm} (4.10)

with $\tau$ in milliseconds and $P_s$ in kPa.
Most of Hattori’s data points occurred below the curve given by equation 4.9. The curve demonstrates the upper limit of the pressure – time response for shock type model scale breaking waves obtained from Hattori’s results.

By applying a similar principle to the data from tables 4.6 and 4.7, the following peak pressure – time relationship for the drop arm tests resulted

\[ P_s = 90r^{-2.3} \]

Equation (4.11)

A scatterplot of the measured data points along with the limiting curve of Equation (4.11) is shown in Figure 4.17.

It is highly probable that the difference in the exponent values of Equations (4.10) and (4.11) arises due to the difference in impact angle of the two laboratory regimes. Hattori used actual waves which might not have acquired the fully breaking state when impacting on the transducers. Hattori’s results indicate a gentler pressure – time slope than those obtained from the drop arm tests. The trends are similar however ie high peak pressures with short impact durations and vice versa.

Typical bubble size distributions for each air-flow rate and using tap water are shown in Figures 4.18 to 4.23. It is apparent that geometrical scattering is the major component of the total extinction cross section for larger size bubbles with absorption affecting only smaller bubbles in their resonance regimes.

Figures 4.24 to 4.29 show acoustic attenuation as a function of drive frequency for each air flow rate in tap water. Figures 4.30 to 4.35 show attenuation as a function of drive frequency along with variations of acoustic extinction for different void fractions, scattering and dipole cross sections for each void fraction case. Figure 4.36 shows the variation of mean damping coefficient with drive frequency for the 6.9% void fraction.

The effects of aeration and salinity can be seen in the graphical representations of impact pressure and rise time as functions of air content and tangential velocity as a function of rise time as shown for each transducer in Figures 4.37 to 4.40. It is evident from these figures that impact pressure is a function of both air content and velocity. As expected from Bernoulli’s equation [10], measured values of peak impact pressures increase as the drop arm velocity increases. Peak pressures have the strongest functional dependence on velocity whereas rise time values are inversely proportional to impact velocities ie high pressure – low rise time and vice versa.

Salinity dependence is, however, somewhat obscure since Kulite data indicate that higher salinities produce greater impacts whereas Maywood data present a reversed trend.

One potential reason for this anomaly is temperature sensitivity fluctuations associated with the Maywood sensor. As salinity increases, density also increases – typically
tapwater at 4°C has a density of 1000Kg/m³ whilst that of seawater at the same temperature is approximately 2.5% greater. Thus on density considerations alone the results obtained with the Kulite sensor appear logical.

The reverse characteristics observed from Maywood data may be indicative of the variation of bubble size spectra (hence polytropic index) with salinity. Enhanced bubble persistence and the preponderance of smaller bubbles for high salinity fluids may lead to a thermal differential between gas and liquid components and serve to exaggerate thermal characteristics of the Maywood transducer. It must be stated that random errors of drop velocity due to the variability of positioning the arm, at the required height were approximately 2% thus may have equal weighting to any potential temperature anomalies. Positioning errors arose since the arm was raised manually. This error source could be eliminated by using an automatic mechanism.

The dependence of rise time upon aeration is less obvious than that of impact pressure. What is apparent however, is the general trend for increased rise time in the presence of aeration. It is less obviously a function of void fraction or even density, rather a stochastic process highly dependent upon positioning and size of gas bubbles/pockets (see Chapter 3).

Figures 4.37 to 4.40 confirm the correspondence between laboratory drop impact tests and Taylor's incompressible jet impact model. Equation (4.3) is reinforced overwhelmingly by the rise time/equivalent impact velocity dependence. The value of the exponent m in (4.8) is approximately 0.35 from measured rise times and subsequent calculation of $\Phi$.

Figure 4.41 shows the effective impact velocity versus rise time for both transducers.

Clearly the analogy with tangential velocity of jet impact is not perfect since there is a preferred direction of motion for jets impinging on a vertical wall determined by their constantly changing frame of reference as the jet/wave breaks upon the wall. Whereas drop arm tests results in near isotropic motion over $2\pi$, with the arm impacting upon the water in the same region each time.

Values for the parameter $\psi$ obtained using (4.9) are also listed in Table 4.6 and 4.7 and the mean values of $\psi$ for each void fraction are given in Table 4.8. $\psi$ decreases with increasing impact velocity and from Kulite data the following relationship may be established:

$$\psi \propto U_1^{-2.5}$$  \hspace{1cm} (4.12)
## TABLE 4.6

**IMPACT PRESSURE AND RISE TIME DATA FOR THE KULITE TRANSDUCER OVER A RANGE OF AERATION AND SALINITY LEVELS**

<table>
<thead>
<tr>
<th>DROP VELm/s</th>
<th>SALINITY g/l</th>
<th>% AIR</th>
<th>IMPACT PRESSURE kN/m</th>
<th>RISE TIME microsecond</th>
<th>APPROACH ANGLE deg</th>
<th>TANGENTIAL VELm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.170</td>
<td>0</td>
<td>0</td>
<td>69.7</td>
<td>1415</td>
<td>10.6</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>48.0</td>
<td>1480</td>
<td>12.7</td>
<td>19.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>49.1</td>
<td>1521</td>
<td>12.5</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.9</td>
<td>39.0</td>
<td>2042</td>
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### TABLE 4.7

**IMPACT PRESSURE AND RISE TIME DATA FOR THE MAYWOOD INSTRUMENTS TRANSDUCER OVER A RANGE OF AERATION AND SALINITY LEVELS**

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The constant of proportionality, obtained empirically, has an approximate value of 4.85. If the series of impact velocities were considered to have a range of values rather than being unitary, then the proportionality constant of 4.85 would correspond to a centre impact velocity of 1.88 m/s. The dependence of $\psi$ upon void fraction was less evident except that $\psi$ values for the larger void fractions ($> .69\%$) were reduced proportional to the fluid density change, but equation (4.12) was valid for all void fractions.

Maywood data showed a general increase in $\psi$ with decrease in impact velocity and a decrease with increasing void fraction. The general trend, however, was too obscure to elicit, thus no attempt at a pressure – time relationship was attempted for the Maywood data.

**TABLE 4.8**

$\psi$ AS A FUNCTION OF VELOCITY AND VOID FRACTION

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A = Kulite  
B = Maywood

**4.5 CONCLUSION**

Laboratory based pressure impact tests were performed for clear and aerated water using a swinging arm. The results obtained were analysed using two models - Bagnold's compressible piston model and Taylors incompressible jet model.

Some of the data obtained using the Maywood sensor were suspect due to temperature sensitivity of the device affecting the pressure readings. Kulite data however were reliable and showed clear trends with respect to the rise times and aeration. Although aerated water is clearly a compressible fluid, there was still excellent agreement between the test results and those from the incompressible impact model.
There is some doubt as to the optimum expression of the velocity/time relationship i.e. whether to use a variable contact angle or whether to use a fixed angle and to vary other parameters. What is apparent however is that a relationship of the form in equation (4.8) exists even for bubbly fluids thus some form of quasi (in)compressible model appears relevant.

The velocity - time relationship is best characterised in the form of a power law as given in Equation (4.8). The value of the exponent m, obtained from the drop arm tests, is approximately 1/3 which is in good agreement with the exponent in the theoretical power law relationship derived by Longuet-Higgins [8].

There is also good agreement between the drop arm tests and those obtained by Hattori although Hattori's exponent is slightly higher resulting in a gentler pressure - time response curve.

Results show conclusively that the presence of aeration does affect the spread in the pressure - time curves. The presence of artificially generated bubbles reduces the peak pressures of impacts whilst increasing the impact rise time or duration.

The observed trend due to aeration is not a simple function of void fraction but is also dependent on bubble size. As the void fraction increases so does the mean bubble size thus affecting the probability of a shock wave occurring. The relationship between impact type (shock or compression), void fraction and mean bubble size is discussed fully in Chapter 7.

The effective contact angle calculated using Taylor's model is consistently larger for aerated water than clear water. The validity of this parameter may appear suspect for drop tests as conducted with a swinging arm, but it does have relevance when considering the impact of waves on vertical coastal structures.
PLATE 4-1. DROP ARM FOR LABORATORY PRESSURE TESTS.

PLATE 4-2. KULITE PRESSURE TRANSDUCER & ELECTRONICS.
PLATE 4-3. MAYWOOD PRESSURE TRANSDUCER.

PLATE 4-4. PROTOTYPE AERATION GAUGE.
FIGURE 4-1 PROTOTYPE AERATION GAUGE

FIGURE 4-2 AERATION GAUGE ELECTRONICS.
FIGURE 4-3 THREE AERATION MEASUREMENT TECHNIQUES DEPLOYED SIMULTANEOUSLY.
FIGURE 4-4. ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY. (17.5g/l salt; 4.1% void fraction)

FIGURE 4-5. ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY. (17.5g/l salt; 3.0% void fraction)

FIGURE 4-6. ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY. (17.5 g/l salt; 1.7% void fraction)
**FIGURE 4-7. ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY. (17.5 g/l salt ; 1.2% void fraction)**

**FIGURE 4-8. ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY. (17.5 g/l salt ; 0.4% void fraction)**
FIGURE 4-9 BUBBLE GENERATION & DISPERSION ZONES
FIGURE 4-10 ELECTRIC FIELD DISTRIBUTION AROUND BOLTHEAD ELECTRODE.
The closer the lines the more intense the field. The values of field intensity when integrated over each sector are equal, i.e. the field achieves maximum intensity (hence sensitivity) close to the bolthead.
FIGURE 4-11. IMPACT PRESSURE AS A FUNCTION OF DROP VELOCITY - KULITE TRANSDUCER.

FIGURE 4-12. IMPACT RISE TIME AS A FUNCTION OF DROP VELOCITY - KULITE TRANSDUCER.
FIGURE 4-13. IMPACT PRESSURE AS A FUNCTION OF DROP VELOCITY - MAYWOOD TRANSDUCER.

FIGURE 4-14. IMPACT RISE TIME AS A FUNCTION OF DROP VELOCITY - MAYWOOD TRANSDUCER.
FIGURE 4-15. POWER LAW RELATIONSHIP BETWEEN IMPACT RISE TIME AND EFFECTIVE IMPACT VELOCITY.
FIGURE 4-16 LIMITING PRESSURE-TIME CURVE POSTULATED BY HATTORI.
FIGURE 4-17 LIMITING PRESSURE-TIME CURVE (AFTER HATTORI) FOR DATA OBTAINED USING KULITE SENSOR.
FIGURE 4.18 BUBBLE SIZE PROBABILITY DISTRIBUTION

(~ 13.9% AIR)
(TAP WATER)

FIGURE 4.19 BUBBLE SIZE PROBABILITY DISTRIBUTION

(~ 12.1% AIR)
(TAP WATER)

FIGURE 4.20 BUBBLE SIZE PROBABILITY DISTRIBUTION

(~ 6.9% AIR)
(TAP WATER)
FIGURE 4-21 BUBBLE SIZE PROBABILITY DISTRIBUTION

C- (~ 4.9% AIR) (TAP WATER)

FIGURE 4-22 BUBBLE SIZE PROBABILITY DISTRIBUTION

C- (~ 1.1% AIR) (TAP WATER)

FIGURE 4-23 BUBBLE SIZE PROBABILITY DISTRIBUTION

C- (~ 0.5% AIR) (TAP WATER)
FIGURE 4-24
ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY.

(~ 13.9% AIR)
(~ TAP WATER)

FIGURE 4-26
ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY.

(~ 6.9% AIR)
(~ TAP WATER)

FIGURE 4-25
ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY.

(~ 12.1% AIR)
(~ TAP WATER)

FIGURE 4-27
ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY.

(~ 4.9% AIR)
(~ TAP WATER)
Figure 4-28
Attenuation as a function of drive frequency.

Figure 4-29
Attenuation as a function of drive frequency.

(≈ 1.1% Air)
(≈ 0.5% Tap Water)
Figure 4-30(a) Acoustic attenuation as a function of drive frequency

Figure 4-30(b) Extinction cross section as a function of drive frequency

Figure 4-30(c) Scattering cross section as a function of drive frequency

Figure 4-30(d) Dipole cross section as a function of drive frequency

(~ 13.9% air, 35 g/l salt)
FIGURE 4-31(a) ACOUSTIC ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY

(\sim 12.1\% \text{ AIR, } 35 \text{ g/l SALT})

FIGURE 4-31(b) EXTINCTION CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-31(c) SCATTERING CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-31(d) DIPOLE CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY
FIGURE 4-32(a) ACOUSTIC ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY

(≈ 0.9% AIR, 35 g/l SALT)

FIGURE 4-32(b) SCATTERING CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-32(c) EXTINCTION CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-32(d) DIPOLE CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY
Figure 4.33(a) Acoustic Attenuation as a Function of Drive Frequency

Figure 4.33(b) Scattering Cross Section as a Function of Drive Frequency

~ 4.9% Air, 35 g/l Salt

Figure 4.33(c) Extinction Cross Section as a Function of Drive Frequency

Figure 4.33(d) Dipole Cross Section as a Function of Drive Frequency
FIGURE 4-34(a) ACOUSTIC ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY

(~ 1.1% AIR, 35 g/l SALT)

FIGURE 4-34(c) SCATTERING CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-34(b) EXTINCTION CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-34(d) DIPOLE CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY
FIGURE 4-33(a) ACOUSTIC ATTENUATION AS A FUNCTION OF DRIVE FREQUENCY

(~ 0.5% AIR, 35 g/l SALT)

FIGURE 4-33(b) EXTINCTION CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-33(c) SCATTERING CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY

FIGURE 4-33(d) DIPOLE CROSS SECTION AS A FUNCTION OF DRIVE FREQUENCY
Figure 4-36 Typical Variation of Mean Damping Coefficient as a Function of Drive Frequency

(~ 6.9% Air, 35 g/l Salt)
FIGURE 4.37(a). IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY 2.17 m/s; KULITE TRANSDUCER.

FIGURE 4.37(b). IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY 1.96 m/s; KULITE TRANSDUCER.

FIGURE 4.37(c). IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY 1.77 m/s; KULITE PRESSURE SENSOR.
FIGURE 4.39(a) IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY
2.17m/s - MAYWOOD TRANSDUCER.

FIGURE 4.39(b) IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY
1.98m/s - MAYWOOD TRANSDUCER.

FIGURE 4.39(c) IMPACT PRESSURE AS A FUNCTION OF % AIR FOR DROP VELOCITY
1.77m/s - MAYWOOD TRANSDUCER.
FIGURE 4-40(a) IMPACT RISE TIME AS A FUNCTION OF % AIR FOR DROP VELOCITY 2.17m/s
MAYWOOD TRANSDUCER.

FIGURE 4-40(b) IMPACT RISE TIME AS A FUNCTION OF % AIR FOR DROP VELOCITY 1.98m/s
MAYWOOD TRANSDUCER.

FIGURE 4-40(c) IMPACT RISE TIME AS A FUNCTION OF % AIR FOR DROP VELOCITY 1.77m/s
MAYWOOD TRANSDUCER.

4-51
FIGURE 4-41 IMPACT RISE TIME vs. EFFECTIVE IMPACT VELOCITY EXPRESSED AS A POWER LAW.
REFERENCES - CHAPTER 4.


CHAPTER 5

INITIAL FIELD MEASUREMENTS

Introduction

This chapter is devoted to a range of full scale pressure and aeration measurements performed over the period October 1990 to March 1992. The measurement sequence falls into 4 main categories:

i) Initial testing of the instrumentation at sea;
ii) Environmental testing at the proposed site for dual pressure and aeration measurements;
iii) Initial field measurements with a pressure transducer and "listening" hydrophone;
iv) Field tests on a sea wall using the dual pressure/aeration measurement device.

Throughout the period of field tests visual records of sea conditions were obtained using photography initially and later video recordings.

5.1 INITIAL TESTING OF PROTOTYPE AERATION GAUGE AND PRESSURE SENSOR AT SEA

The prototype aeration/pressure gauge as used is shown at Plate 4.4 in Chapter 4. Sea trials were conducted on 9th and 30th October 1990 in Plymouth Sound from the boat "Pandora" as shown in Plate 5.1. It was not possible to conduct simultaneous aeration and pressure measurements but this was not the primary objective. The principal aim of these sea trials was to determine the efficacy of the impedance aeration gauge in a relatively hostile environment. Pressure measurements were obtained using the rubber faced Kulite transducer (see Chapter 4) which was attached to a long pole to facilitate dropping the transducer over the side of the vessel. The transducer was dropped from a height of approximately 30cm resulting in a normal velocity component of the order of 2.4m/s. Aeration measurements were performed using the prototype aeration gauge which was also attached to a pole and held in the bubble wake at fixed locations around the boat.

Tables 5.1 and 5.2 list the recorded aeration and pressure data respectively for sea trials on 9th October. Between the two sea trials it became apparent that the value of the transformer resistor in the aeration gauge should be reduced since different transformers were required for fresh and salt water applications. The raw aeration
data was in the form of a voltage level. In order to convert voltage to void fraction certain assumptions were made:

a. that the Maxwell criteria were satisfied i.e homogeneous mix of small bubbles with interbubble separation much greater than bubble diameter (see 4.2),

b. that the sample volume remained constant.

If the above criteria are met then the void fraction in percent may be obtained from the expression:

\[ \beta = 2 \frac{(R_m - R_w)}{(2R_m - R_w)} \times 100\% \]  \hspace{1cm} (5.1)

where, \( R_m \) is the resistance of the bubbly mix and \( R_w \) is the resistance of still water.

Resistance is related to measured voltage thus:

\[ R_m = \frac{V_m}{i} - r_p \]  \hspace{1cm} (5.2)

where \( V_m \) is the measured voltage in and \( i \) and \( r_p \) are the driving current and probe resistance respectively which for the gauge at this time assumed the values 1.33 mA and 0.8Ω.

### TABLE 5.1
AERATION DATA FOR SEA TRIAL (9 OCTOBER 1990)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>% AIR</th>
<th>NO. SAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stern Wake - Port</td>
<td>1.3 ± 1.3</td>
<td>7</td>
</tr>
<tr>
<td>Stern Wake - Starboard</td>
<td>1.9 ± 1.1</td>
<td>29</td>
</tr>
<tr>
<td>Stern Wake - Midships</td>
<td>6.7 ± 2.3</td>
<td>19</td>
</tr>
<tr>
<td>Still Water</td>
<td>0.7 ± 0.4</td>
<td>17</td>
</tr>
<tr>
<td>Boat Circling</td>
<td>9.7 ± 9.8</td>
<td>12</td>
</tr>
</tbody>
</table>
TABLE 5.2
PRESSURE AND RISE TIME DATA FOR SEA TRIAL (9 OCTOBER 1990)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>PRESSURE (kN/m²)</th>
<th>( \tau ) (ms)</th>
<th>( \phi ) (deg)</th>
<th>( u_\parallel ) (m/s)</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.7</td>
<td>5.5</td>
<td>26.6</td>
<td>10.2</td>
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<td></td>
</tr>
<tr>
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<td>10.6</td>
<td>-0.32</td>
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</tr>
<tr>
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<td>31.9</td>
<td>8.4</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>16.8</td>
<td>4.2</td>
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<td>-0.36</td>
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<td>21.8</td>
<td>12.5</td>
<td>-0.33</td>
<td></td>
</tr>
</tbody>
</table>

\( u_\parallel = 2.4 \) m/s.

As in Chapter 4, values for \( \phi \) and \( u_\parallel \) from Taylor's jet impact theorem were calculated from measured pressure and aeration data and frequency distributions for
the two variables are given in Figures 5.1 and 5.2. Figure 5.3 shows calculated velocity values as a function of rise time. There is a clear trend which obeys a relationship of the form:

$$U_\perp \propto \tau^{-m}$$

(5.3)

The exponent $m$ varies in the range .3 to .35.

The above relationship between rise time and velocity is in excellent agreement with that obtained during laboratory investigations with a swinging arm drop mechanism (Chapter 4.3) where the pressure-time curve is shown in Figure 4.16 and those of Hattori et al [1] as shown in Figure 4.15. As with the laboratory tests there is isotropic spreading of energy (tangential velocity) over $2\pi$ radians unlike the case of a perfect breaking wave on a vertical structure when most of the wave energy is directed vertically upwards and there is minimal wave-reflection from the structure.

High variability and uncertainty was present during the field trials with respect to the water surface around the various wakes of the boat and drop parameters (height, velocity, position etc). Thus it is highly probable that variation of contact angle occurred between transducer and water surface.

Modified aeration electronics were used for the second sea trial which meant enhanced sensitivity since the drive current was increased. The measurement process was the same as for the first trial and the aeration and pressure data acquired are given in Tables 5.3 and 5.4. Figures 5.4 and 5.5 are frequency distributions for calculation jet impact parameters $\phi$ and $u_\parallel$. Figure 5.6 shows the velocity as a function of rise time. The relationship between effective impact velocity and rise time obeys an equation of the form of (5.3) with the exponent $m$ in the range 0.28 to 0.38.

| TABLE 5.3 |
| AERATION DATA FOR SEA TRIAL (30 OCTOBER 1990) |

<table>
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<tr>
<th>LOCATION</th>
<th>% AIR</th>
<th>NO. SAMPLES</th>
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<tr>
<td>Stern</td>
<td>5.4 ± 4.1</td>
<td>6</td>
</tr>
<tr>
<td>Slow circling</td>
<td>12.5 ± 12.5</td>
<td>12</td>
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<tr>
<td>Fast circling</td>
<td>16.0 ± 11.2</td>
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TABLE 5.4
PRESSURE AND RISE TIME DATA FOR SEA TRIAL (30 OCTOBER 1990)

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<tr>
<th>LOCATION</th>
<th>PRESSURE (kN/m²)</th>
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<th>Φ(deg)</th>
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<td>8.0</td>
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<tr>
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<td>9.6</td>
<td>6.4</td>
<td>33.5</td>
<td>8.0</td>
<td>-.30</td>
</tr>
</tbody>
</table>

Some of the pressure - time traces obtained were of an oscillatory nature. On first
examination this behaviour may appear to result from the oscillation of trapped air pockets. Subsequent investigation indicated that these oscillatory pressures did not occur when the impact pressure was of small magnitude and the rise time of longer duration. Many of the calculated values for the normal and tangential velocity were of similar magnitude to speed of sound values in bubble mixtures. It would be possible, therefore, for shock waves to be generated under such conditions especially if the wake were behaving as a sound channel.

If the acoustic Mach number exceeds unity there are two generation mechanisms for the propagation of shock waves. If the system obeys adiabatic gas laws then shock formation is controlled by thermal and viscous dissipative mechanisms. Shock pressure spectra assume a gas law curve with the rise time showing some dependence upon the mean bubble radius which in general may be quite large. Such a regime has a low frequency Mach number in excess of unity but a high frequency Mach number less than unity as explained in Chapter 3.

When both Mach numbers exceed unit then thermal and viscous damping are irrelevant during initial shock formation and bubble size becomes the critical parameter. Oscillatory pressure waves may form with the period of oscillation in general proportional to the mean bubble diameter. Thus some impact pressure recordings from sea trials are indicative of oscillatory shock waves but with dominant bubble sizes in the range 1 to 6cm. Shock oscillations due to very small bubbles were rare. These mean bubble sizes may appear large but it must be remembered that experiments were conducted in the propeller wake of a boat where entrainment rates are high due to the generation of turbulence layers at the air/water interface. An alternative explanation for these relatively long period oscillations is collective oscillation of the bubble cloud arising from air entrainment as discussed in Chapter 2 Section 4.3.

Sea trials proved that the aeration gauge operated well under hostile conditions and that impact pressure and rise times such as observed in the laboratory are possible in full scale measurements although the scenario was by no means representative of the ultimate goal—measurements of breaking waves on a sea wall.

5.2 TESTING OF CHOSEN FIELD SITE FOR ENVIRONMENTAL CONDITIONS

As a precursor to investigation into aeration of breaking waves it became evident that some indication of temperature fluctuation measurement was requisite before finally deploying the dual pressure/aeration gauge. The HDW-Elektronik CDT probe was deployed at various positions around the chosen site for field tests—Bovisand sea wall see Figure 5.7.
The equivalent circuit for the HDW-Elektronik CDT probe is shown in Figure 5.8. The conductivity sensor comprises an inductively coupled electrodeless device. Changes in conductivity are detected using a bridge facility; the sensing element being one arm of the bridge. Two toroids are coupled by the medium under test; the degree of coupling being a function of conductivity. The resultant magnetic field induced by a current flowing round a toroid is given by:

\[ B_T = \frac{\mu_0 N I}{2\pi r} \]  

(5.4)

where \( N \) is the number of turns, \( I \) is the electric current (amp), \( \mu_0 \) is the permeability of free space (4 x 10E-7 H/m) and \( r \) the toroid radius (m).

Components of magnetic induction due to \( B \) exist outside the toroid and it is this property which is exploited in the sensing element. Figure 5.9 shows a toroid with magnetic-field and-current vectors. If a conductive loop is present at a distance greater than the toroid radius then the medium under test may be treated as a single current loop and an electric field will arise due to induced currents such that:

\[ J_i = \frac{2 B_T}{\mu_0 r} \]  

(5.5)

\[ E_i = \frac{2 B_T}{\mu_0 \sigma_m r} \]  

(5.6)

where \( J_i \) and \( E_i \) are induced current density (amp/m) and electric field V/m) respectively and \( \sigma_m \) is the conductivity of the medium (S/m). \( r \) is the radius of the current loop.

As the conductivity varies the bridge must re-establish balance conditions. The CDT probe was deployed at positions outlined in Figure 5.7.

5.2.1 RESULTS AND DISCUSSIONS

Values of conductivity, depth and temperature obtained at the various locations are expressed in Table 5.5 along with equivalent salinity values.
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>D (m)</th>
<th>T (deg C)</th>
<th>Conductivity (mS/cm)</th>
<th>Salinity (g/l)</th>
<th>Integration time (sec)</th>
<th>number of samples</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>6.08</td>
<td>32.6</td>
<td>32.8</td>
<td>1</td>
<td>22</td>
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<tr>
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<td></td>
<td>±0.02</td>
<td>±0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.01</td>
<td>±0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td>6.78</td>
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<td>34.8</td>
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<td>19</td>
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<tr>
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<td>0.1</td>
<td>±0.00</td>
<td>±0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>6.18</td>
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<td>33.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>±0.01</td>
<td>±0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.8</td>
<td>6.39</td>
<td>34.1</td>
<td>34.1</td>
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<td>19</td>
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<td>±0.05</td>
<td>±0.2</td>
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<td>1</td>
<td>15</td>
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<tr>
<td></td>
<td>(swinging)</td>
<td>±0.01</td>
<td>±0.0</td>
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</tbody>
</table>

Temperature values increased with depth and proved to be greater inside the sea wall than at the same depth outside.

Conductivity increased accordingly with depth and temperature, the pressure dependence of conductivity being a weak function of depth whereas conductivity is a strong function of temperature. It is usual for temperature to decrease slightly with increasing depth over the first 10m, however the results obtained are not erroneous since the air temperature on the day the measurements were performed was 2°C maximum, thus heat was being lost from the upper layers of the sea to the atmosphere.

In all cases the variation in conductivity values (given in Table 5.5) was greater than expected due to errors in depth and temperature evaluation. The potential explanations for these errors are now given.

a. Salinity variations due to the presence of biological matter e.g. seaweed, sewage etc;
b. Bubbles;
c. Flowing water causing a magneto-hydrodynamic effect;
d. Electrical and electronic noise in the probe;
e. Quantisation errors.
a. Excessive Salinity Variations

Maximum salinity variation occurs between 200m and 500m depth in the sea with much less variation occurring in the first 10m [2]. In the vicinity of sewage outfalls or river estuaries however, the presence of biological matter, heavy metals and undissolved salts results in salinity fluctuations. The degree of fluctuation is a function of the chemical composition of the foreign matter, its concentration and mass density as well as external factors such as temperature, tide level and general topography. From Table 5.5 it is apparent that salinity inside the wall is about 1% greater than outside and that the relative increase is a weak function of depth. These findings appear acceptable since measurements were performed close to the time of high water thus the flow rate inside the wall would be much less than that outside. The depth dependence arises because any biological matter or undissolved salts would be more abundant at greater depths, whilst close to the surface wave action, turbulence and currents would cause enhanced fluctuation.

b. Bubbles

The presence of bubbles would cause a reduction in conductivity. Bubbles could emanate from two sources:

i. wave breaking
ii. biological matter.

If bubbles were generated via i. there would be a depth distribution with maximum concentration at the surface and probably an exponential decrease with depth. On the day of the measurements the sea state was slight and capillary wave action occurred only at the sea wall. The intensity of the wave action was certainly not sufficient magnitude to produce bubbles to a depth of 40cm let alone 4m thus source i above, may be discarded in this case.

If bubbles originated from source ii. they would be found at much greater depths than from source i., but the mean size would be less than 100 micron radius and the effect of low concentrations of small bubbles upon conductivity measurements is negligible. Thus bubble action may be discounted in this case.

c. Magnetohydrodynamics

If a moving conductor is placed in a magnetic field an excess electric field will result given by:
\[ E_x = V \wedge B \]  

(11.7)

where \( V \) is the conductor velocity (m/s).

For the case of water flowing through the conductivity sensing head we have:

\[ E_x = V \wedge B_T \]  

(11.8)

and taking maximum value we have:

\[ 1E_x |_{\text{MAX}} = 2 B_T V_{\text{MAX}} \]  

(11.9)

now substituting from (11.6) we get:

\[ 1E_x |_{\text{MAX}} / 1E_i \cdot 1 = \mu_0 \sigma_m r V_{\text{MAX}} \]  

(11.10)

if \( r = 10 \text{cm} \) and \( V_{\text{MAX}} = 10 \text{m/s} \) (excessive) and \( \sigma_m = 3 \text{ S/m} \).

\[ \frac{1E_x |_{\text{MAX}}}{1E_i} \sim 4 \times 10^{-6} \]

Thus magnetohydrodynamics effects may be neglected.

d. Electronic Noise

Errors occur at the measurement stage due to temperature effects in the various resistors and nonlinearities in the amplification stage. Error contributions from various electronic sources are listed in the instrument data sheets. The values quoted are of the order of some of the measured errors but much less than others. Thus electronic noise is a component of the measurement errors but in some cases only a minor factor.

e. Quantisation Error

The instrument comprises a 12 bit A to D. Quantisation error of +/- half of the analogue value of the least significant bit is significant for some of the results as in part d) above but affords only a small component of the total error for other results.
5.2.2 CONCLUSION

Measurements of temperature and conductivity at several locations around Bovisand sea wall afforded useful predictions with respect to the contributions of temperature and salinity fluctuation upon aeration measurement. Fluctuations were greatest at least depth and diminished with increasing depth. Temperature and conductivity values were greater inside the sea wall as was the salinity. The magnetohydrodynamics effect may be neglected since it is at least an order of magnitude down on other error sources.

The main contributors to the fluctuations at depths in excess of 3m are electronic component noise and quantisation errors in the instrument itself. Nearer to the surface the principal contribution to signal fluctuation results from local salinity and temperature fluctuations due to increased water circulation.

Data obtained from CDT measurements indicated that in principle the existence of local temperature and salinity variations could be problematic with respect to the accuracy of future aeration measurements at the site. It was evident however that measurements obtained using the CDT probe were probably of far greater accuracy than could be achieved with the aeration gauge. This fact coupled with the laboratory and sea trial data, in Chapter 4 and Section 5 of this Chapter respectively, indicated that there was no simple relationship between impact pressure or rise time and aeration levels, afforded some confidence in the choice of location with respect to non geographic environmental factors.

If enhanced confidence in future measurements were required if would be possible to deploy the CDT probe inside the sea wall whilst pressure and aeration measurements were conducted at the wall's seaward face. Thus information would be available about tide level and temperature fluctuation. Results obtained from deployment of the CDT inside the jetty would not offer an accurate representation of conditions outside the wall, but to a first order might elicit any evolutionary trends.
5.3 INITIAL FIELD MEASUREMENTS OF IMPACT PRESSURE AT BOVISAND

5.3.1 EXPERIMENTAL ARRANGEMENT AND THEORY

Initial pressure measurements were made using the rubber faced Kulite pressure sensor positioned at locations as shown in Figure 5.10 during May and June 1991. Site 1 was at the base of some steps inside the jetty where conditions were similar to those in a model wave tank. Experiments were conducted in calm conditions and typically wave heights were of the order of approximately 10 cm. Owing to the steep incline at the steps there was almost continuous breaking of these small waves. No attempt was made to quantify aeration levels or velocity at this time since the logic for these tests was to determine if similar impact pressures and rise times would be observed as those obtained in model tests. Typically peak pressures in excess of 20 kPa and rise times of less than 20 ms were recorded.

Impact pressure and rise time data are listed in Table 5.6, also noted is the presence of any oscillatory behaviour and its associated period. Wave celerity was observed visually, using a video recorder, and found to be approximately 1.8 m/s. It was possible to determine the maximum and minimum bubble radius (Chapter 2 (2.7)) since the period of oscillation was known. In most cases there was not complete bubble collapse but several periods of pressure oscillation were detectable thus indicating that the bubble oscillated between a maximum and minimum size each cycle. Bubble extrema may be established using a simplified form of the Rayleigh's equation of bubble motion (Chapter 2 (2.90)).

\[
\begin{align*}
\frac{3}{2} \mu R + \frac{4}{2} \frac{\dot{R}^2}{\rho g R} + \frac{2\alpha}{\rho g R} &= P_b (R, t) - P_0 \\
\end{align*}
\]

(5.11)

terms 3 and 4 on the left hand side may be neglected when bubble diameter is not small and approximations may be made for terms 1 and 2 thus:

\[
\begin{align*}
\dot{R} &= - \frac{U_1}{\tau} \\
\ddot{R} &= U_1
\end{align*}
\]

(5.12)

Assuming zero initial phase angle, equation (5.11) now may be rewritten thus:

\[
\begin{align*}
\frac{3}{2} \frac{U_1}{\tau} - \frac{U_1^2}{\tau} &= P_{MAX} \\
\end{align*}
\]

(5.13)
where $P_{\text{MAX}}$ is the maximum bubble pressure above atmospheric in units of kN/m$^2$.

$R$ is the mean initial bubble radius

$R_{\text{MIN}}$ is the minimum bubble radius which tends to zero upon bubble collapse

$U_\perp$ is the velocity normal to the bubble

$\tau$ is the initial pressure rise time.

Equation (5.13) was used to determine the maximum and minimum bubble radius values listed in Table 5.6, assuming symmetrical oscillation about $R$.

The second site for measurements was the seaward facing wall of the western boundary of the jetty. In this region the still water level was deep compared to site 1 and water wave celerity was estimated to be 1.4m/s from visual observation. Table 5.7 lists the measured peak pressures, pressure rise times and calculated bubble dimensions from (5.13).

5.3.2 DISCUSSION OF RESULTS

The observed pressure spectra resulted from entrapment of bubbles or air pockets at or in close proximity to the face of the transducer. The mean of the bubble sizes was typically 10mm radius at location 1 and 6mm radius at location 2 with size variation at location 1 exceeding that at location 2 by a factor of 3. The relative size differences between the two locations correspond to the square of the relative wave celerities and is thus in agreement with equation (5.13). The term wave is somewhat inappropriate for location 2 in view of the depth of water and quiescent sea state. The observed pressure spectra at site 2 originate from the gentle collapse of small Airy waves [3] at or near to the transducer. There is little variation in waveheight thus the size of a trapped bubble or air pocket is a function of wave collapse position only, thus bubble size variance is minimal. Conversely the waves at site 1 are shallow water waves thus detected pressure spectra are a function of water depth and waveheight in addition to spatial variation effects.

One outstanding feature of pressure spectra measured in these tests is the number of bubble oscillation cycles before collapse - in some cases as great as 20 cycles. There are two principal reasons for such features:


b. Environmental factors e.g. small waveheights and quiescent sea state (little wind) thus inhibiting immediate bubble collapse;
Finally it must be stated that although the pressures involved have relatively small magnitude, they occur in the absence of any hydrostatic regime. It will be shown in later sections that as waveheight and water velocity increase, bubble pressures may still greatly exceed hydrostatic pressure fluctuations.
TABLE 5.6

BUBBLE PRESSURE AND TIME DATA FROM SITE 1 BOVISAND

| Impact Pressure P(kN/m²) | Rise Time τ(ms) | Rise Oscillation Δτ(ms) | No. of Oscillation c/s n | Bubble Sizes | |
|-------------------------|----------------|-------------------------|-------------------------|--------------|
|                         |                |                         |                         | R(µm)        |
|                         |                |                         |                         | RMAX(µm)     |
|                         |                |                         |                         | RMIN(µm)     |
| 2.85                    | 1.0            | 4.0                     | 20                      | 13.00        |
|                         |                |                         |                         | 14.12        |
|                         |                |                         |                         | 11.88        |
| 2.70                    | 1.0            | 4.0                     | 20                      | 13.00        |
|                         |                |                         |                         | 14.20        |
|                         |                |                         |                         | 11.80        |
| 0.62                    | 2.4            | 6.8                     | 3                       | 22.10        |
|                         |                |                         |                         | 27.75        |
|                         |                |                         |                         | 16.45        |
| 1.17                    | 2.0            | 4.8                     | 13                      | 15.60        |
|                         |                |                         |                         | 19.70        |
|                         |                |                         |                         | 11.50        |
| 0.92                    | 3.0            | 8.0                     | 6                       | 26.00        |
|                         |                |                         |                         | 32.57        |
|                         |                |                         |                         | 19.43        |
| 3.09                    | 0.4            | 1.6                     | 5                       | 5.20         |
|                         |                |                         |                         | 5.59         |
|                         |                |                         |                         | 4.81         |
| 2.31                    | 0.5            | 6.0                     | 11                      | 19.50        |
|                         |                |                         |                         | 20.21        |
|                         |                |                         |                         | 18.79        |
| 3.51                    | 1.6            | 3.6                     | 4                       | 11.70        |
|                         |                |                         |                         | 12.90        |
|                         |                |                         |                         | 10.50        |
| 3.15                    | 0.5            | 1.2                     | 6                       | 3.90         |
|                         |                |                         |                         | 4.38         |
|                         |                |                         |                         | 3.43         |
| 2.70                    | 0.3            | 0.8                     | 7                       | 2.60         |
|                         |                |                         |                         | 2.96         |
|                         |                |                         |                         | 2.24         |
| 1.68                    | 0.2            | 0.8                     | 6                       | 2.60         |
|                         |                |                         |                         | 2.95         |
|                         |                |                         |                         | 2.25         |
| 5.76                    | 0.6            | 1.6                     | 14                      | 5.20         |
|                         |                |                         |                         | 5.12         |
|                         |                |                         |                         | 5.28         |
| 2.85                    | 1.2            | 3.6                     | 20                      | 11.70        |
|                         |                |                         |                         | 13.04        |
|                         |                |                         |                         | 10.36        |
| 5.55                    | 1.2            | 3.6                     | 22                      | 11.70        |
|                         |                |                         |                         | 11.97        |
|                         |                |                         |                         | 11.43        |
| 2.79                    | 0.5            | 1.0                     | 9                       | 3.25         |
|                         |                |                         |                         | 3.83         |
|                         |                |                         |                         | 2.68         |
| 5.85                    | 0.75           | 1.7                     | 11                      | 5.53         |
|                         |                |                         |                         | 5.58         |
|                         |                |                         |                         | 5.48         |
| 2.37                    | 1.2            | 3.0                     | 8                       | 9.75         |
|                         |                |                         |                         | 11.41        |
|                         |                |                         |                         | 8.09         |
| 4.14                    | 0.2            | 0.6                     | 8                       | 1.95         |
|                         |                |                         |                         | 2.03         |
|                         |                |                         |                         | 1.87         |
| 4.65                    | 0.3            | 1.6                     | 8                       | 5.20         |
|                         |                |                         |                         | 5.23         |
|                         |                |                         |                         | 5.17         |
**TABLE 5.7**  
**BUBBLE PRESSURE AND TIME DATA FROM SITE 2 BOVISAND**

<table>
<thead>
<tr>
<th>Impact Pressure (kN/m²)</th>
<th>Rise Time (τ) (ms)</th>
<th>Period of Oscillation (Δt) (ms)</th>
<th>No. of Oscillation (n)</th>
<th>Bubble Sizes</th>
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</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$\bar{R}$ (mm)</td>
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<td>3.25</td>
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<td>2.2</td>
<td>6</td>
<td>7.15</td>
</tr>
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<td>2.4</td>
<td>12</td>
<td>7.80</td>
</tr>
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<td>2.6</td>
<td>10</td>
<td>8.45</td>
</tr>
<tr>
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<td>2.2</td>
<td>6</td>
<td>7.15</td>
</tr>
<tr>
<td>1.05</td>
<td>0.15</td>
<td>1.0</td>
<td>8</td>
<td>3.25</td>
</tr>
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<td>1.8</td>
<td>13</td>
<td>5.85</td>
</tr>
<tr>
<td>2.25</td>
<td>0.7</td>
<td>1.8</td>
<td>16</td>
<td>5.85</td>
</tr>
<tr>
<td>1.29</td>
<td>0.15</td>
<td>1.4</td>
<td>5</td>
<td>4.55</td>
</tr>
<tr>
<td>1.29</td>
<td>0.55</td>
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<td>0.5</td>
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<td>3.25</td>
</tr>
</tbody>
</table>

5.16
PLATE 5-1. UNIVERSITY BOAT "PANDORA".

(a) front view

(b) side view
FIGURE 5-1 FREQUENCY DISTRIBUTION FOR CALCULATED IMPACT ANGLE FROM SEA TRIAL 9/10/90.

FIGURE 5-2 FREQUENCY DISTRIBUTION FOR EFFECTIVE JET IMPACT VELOCITY FROM SEA TRIAL 9/10/90.

FIGURE 5-3 IMPACT RISE TIME AS A FUNCTION OF EFFECTIVE VELOCITY FOR SEA TRIAL 9/10/90.
FIGURE 5-4 FREQUENCY DISTRIBUTION FOR CALCULATED JET IMPACT ANGLE FROM SEA TRIAL 30/10/90.

FIGURE 5-5 FREQUENCY DISTRIBUTION FOR EFFECTIVE JET IMPACT VELOCITY FROM SEA TRIAL 30/10/90.

FIGURE 5-6 IMPACT RISE TIME AS A FUNCTION OF EFFECTIVE VELOCITY FOR SEA TRIAL 30/10/90.
FIGURE 5-7 CDT DEPLOYMENT AT FORT BOVISAND

FIGURE 5-8 EQUIVALENT CIRCUIT FOR HDW-ELECTRONIK CONDUCTIVITY SENSOR.

FIGURE 5-9 MAGNETIC INDUCTION COMPONENTS

FIGURE 5-10 KULITE DEPLOYMENT AT FORT BOVISAND
REFERENCES - CHAPTER 5.


CHAPTER 6

DUAL PRESSURE/AERATION SENSOR FOR FIELD TESTS

Introduction

It was finally decided that the optimum technique for determining aeration levels at sea was to use an invasive impedance probe. This chapter is devoted to logistics i.e. to describing the design; fabrication; testing and positioning of the dual sensor; prior to actuation.

6.1 DESIGN

The choice of pressure sensor was quite straightforward since it was possible to purchase pressure sensors commercially which met requirements. The selected pressure gauge was produced by Kulite Instruments. It comprised a 2.7cm diameter metal diaphragm with a layer of oil between diaphragm and piezoelectric sensing element. The gauge read absolute pressure to a maximum level of 2 atmospheres and a schematic of the sensor is given in Figure 6.1. The cushioning oil layer acted not only as dissipation mechanism for overpressures but in addition the sensor was shielded from temperature fluctuations - a problem which beset the Maywood Instruments sensor used in laboratory tests.

The choice of aeration gauge was not so straightforward due to the dearth of commercially available instrumentation thus necessitating "in house" design and fabrication. The final choice of aeration sensor was an invasive impedance/admittance gauge the principal measurement variable being fluid conductivity. Owing to the temperature dependence of conductivity, as shown in Figure 6.2, it was necessary to compensate any measurements because of the strong temperature dependence of conductivity. Preliminary investigations at Bovisand with the CDT (Chapter 5) indicated that temperature fluctuations were not a problem in relatively still water but that situation might change significantly in the presence of breaking waves. There was also a definite requirement for a baseline datum for aeration measurements with respect to unaerated water. Thus it was decided to locate a dummy gauge and temperature sensor inside of the pressure/aeration system housing and to include some mechanism in the design whereby unaerated water may enter into the portion containing the control sensors. At the design stage there were alternative suggestions to this arrangement including:
i) Use of two sets of external electrodes operated at different AC amplification levels then passed through a differential amplifier resulting in a large AC with no DC bias. Such an arrangement would mean that the actual fluctuation levels could be recorded directly onto the RACAL tape recorder without the presence of a DC bias. The dummy gauge aspect would be dropped in favour of laboratory calibration with seawater thus requiring the presence of some form of temperature sensor alone.

ii) Use of two dual gauges located as indicated in Figure 6.3. Such a configuration would afford a baseline for the aeration measurements since the lower gauge would be located in water that was as unaerated as is possible in seawater, yet at almost the same temperature. The second advantage of this arrangement is the additional pressure information it affords. The arrangement was considered untenable however, due to the extra time and cost involved in producing two systems.

6.2 FABRICATION

The housing for the dual gauge system was made from fibre glass and produced by the Advanced Composites Group of the School of Manufacturing Studies.

There were two sections – a deep front section and a flat backing plate as shown in Figure 6.4 with the two sections connectible via twenty two 9mm stainless steel nuts and bolts, located at the housing periphery. The front section of the housing comprised four chambers – three of which were interconnected as shown in Figure 6.5. The first section was the water inlet section which was to contain some artefact to de-aerate the water. The bubble free water then passed in to the second chamber which contained the two dummy bolthead electrodes and a separate bolthead as temperature sensor located on the chamber roof. The third chamber in this sequence provided the overflow mechanism. The fourth section of the housing was to hold the electronics. This chamber was to be accessible when the housing was opened for internal electronics calibrations and checks but it was essential that the section be watertight when deployed for measurements. The original configuration to make the chamber watertight consisted of a fibreglass cover and gasket fixed to the chamber edge with a series of 12 screws.

It was decided to use a housing which could be opened rather than having a sealed unit, in order that the electronics could be modified or improved as time progressed and that supplementary circuitry could be added as or when required. The reason for locating the bulk of the circuitry in the housing itself was to minimise signal noise.
and distortion resulting from the passage of electrical signals along lengthy cables—in our case 20 metres of 8 way underwater cable, with the cable fed into the housing as shown in Figure 6.6.

6.3 TESTING

The testing regime in the laboratory was designed to check for:

a. the absence of water leaks;
b. the absence of air bubbles in the dummy gauge section;
c. correct operation of pressure and aeration gauges.

a. Water leakage

Testing for water leakage was accomplished by weighting down the fastened housing in a tank of water and leaving for 24 hours. Initial leak tests were a failure due to inadequate gasket material. Later tests proved much more successful once the gasket material had been changed. The new gasket material was closed cell foam material used for divers' dry suits which, during laboratory testing and for initial sea deployment, proved an excellent leak deterrent.

b. Bubble checks in the dummy gauge section

Entrance and exit of water was effected as shown in Figure 6.5. The device chosen for inhibiting bubbles in the dummy gauge section was a series of sponge pieces. There was some doubt concerning the ability of sponge to absorb not only gases but also salts and organic material thus providing spurious dummy gauge data. Observation of the operation of the dummy gauge was achieved visually using a video camera. The rear section of the fibreglass housing was replaced by perspex thus allowing passage of water through the dummy gauge to be filmed.

The housing was placed under a hydraulic jump with water impacting on the top of the housing in an attempt to simulate breaking wave action. Originally the entire water input channel was filled with sponge pieces but this arrangement was unacceptable due to the protracted time for the water to fill the middle chamber and cover the dummy electrodes. The amount of sponge was reduced leaving only a few small pieces of sponge at the base of the entry chamber which improved the timescale of water passage. Some bubbles were created due to flow separation at the base of the water entry section due to the presence of sharp corners and a series of
holes which were not a feature of the original design. There was also evidence of bubble occurrence at the electrode edges and on the perspex backing. One potential reason for the bubbles was an affinity for the perspex and it was considered that the problem would not persist once the fibreglass back plate was in place.

c. Operation of pressure and aeration gauges

Correct operation of the pressure gauge was verified by placing the housing at various depths of water and noting the static pressure reading. The dynamic response of the transducer was tested by projecting a sharp object at high speed onto the face of the transducer and noting the response. The fastest impact velocities resulted in pressure rise times of \( \sim 100\mu s \) — at least an order of magnitude less than that expected in field trials. The transducer responded in its fundamental vibration mode in most impact tests but there was some evidence of higher order vibration when the transducer was excited by an impact at a glancing angle. Harmonic oscillation was thought unlikely to occur in field trials but it was essential to be aware of its existence.

The aeration gauge was tested by measuring its response in air and in salty water of concentration 17.5ppt at 15°C and 35ppt at 10°C, 15°C and 20°C. Air was then added to the water at void fractions determined by the acoustic technique; the resultant response is shown in Figure 6.7 along with some curves extrapolated to different salinities or temperatures using the data from a recognised Oceanographic textbook — Chemical Oceanography volume 3.

6.4 SITE DEPLOYMENT

The dual pressure/aeration gauge was deployed on the seaward south facing wall of the jetty at Fort Bovisand 9km south east of Plymouth. The housing was attached 4 metres down from the top of the sea wall by a series of twelve 12mm bolts which were drilled into the wall as shown in Plate 6.1. Originally the electrical cable was held taut by 3mm stainless steel cable fixed vertically up the wall. This arrangement proved unsatisfactory in bad weather when the cable was struck by laterally moving waves which resulted in the electrical cable loosening and flapping around and finally shearing away from the housing with subsequent flooding of the housing.

It was then decided that boat mooring chain might be more appropriate in the prevailing weather conditions. The final cable anchoring arrangement was thus 2 metres of 6mm steel chain fixed to bolts at the top of the wall with 3 retaining nuts. At the base of the chain there were two 30cm lengths of chain links connected to the top retaining bolts for the housing. The cable was tightened at the top of the
wall by the use of a 20cm turn buckle, thus it was possible to hold the electrical
cable taut during storms and retrieval of the transducer housing was facilitated by
loosening the turn buckle. Owing to the severity of the weather conditions and the
protracted deployment times there was leakage into the housing and at one stage the
veroboard in the electronics compartment began to corrode. Leakage occurred for a
variety of reasons so finally some alternative measures were taken to ensure that
measurements were no longer interrupted due to flooding, these included:

a. replacing the closed cell foam material with commercial gasket material;

b. replacing the intermediate electronic circuitry laid out on veroboard with PCB's
and then sealing the top of the electronics compartment with araldite;

c. sealing the edge of the housing where the front and back sections met with
silicone sealant.

As a result of these modifications the housing was able to withstand some violent
storms without leaking and simultaneous pressure and aerations measurements were
achieved.
PLATE 6-1. DUAL PRESSURE/AERATION GAUGE IN SITU.
FIGURE 6-1 EXPLODED VIEW OF PRESSURE SENSOR. 
(not to scale)

FIGURE 6-2 TEMPERATURE VARIATION OF CONDUCTIVITY
FIGURE 6-3 PROPOSED DUAL-GAUGE DEPLOYMENT

FIGURE 6-4 PRESSURE/AERATION GAUGE

FIGURE 6-5 INSIDE OF PRESSURE/AERATION SENSOR

FIGURE 6-6 ELECTRICAL CABLE ATTACHMENT
FIGURE 6-7. AERATION GAUGE OUTPUT VOLTAGE AS A FUNCTION OF % AIR.
CHAPTER 7

FIELD RESULTS AND DISCUSSION

INTRODUCTION

Laboratory investigations into impact pressure spectra were conducted using a swinging arm with pressure transducer located at the base as described in Chapter 4. These pressure measurements were made for a range of aeration levels and fluid salinities.

Initial field trials data was collected as described in Chapter 5.

Field data were collected at various intervals during the months November 1991 to April 1992 using the dual pressure/aeration gauge (see Chapter 6). Despite the exigent array of mechanical difficulties encountered with respect to gauge deployment as outlined in Chapter 6, in excess of 120 hours of wave action was recorded.

7.1 FIELD RESULTS

7.1.1 DATA COLLECTION

The instrumentation for data collection was housed in the Panel Room on the jetty at Fort Bovisand (Plate 7.1) where mains power was readily available. The 24V supply for the gauge electronics was provided by two 12V car batteries in order to eliminate the possibility of mains interference. Both pressure and aeration outputs were input to a Store 7D Racal Recorder whilst being monitored simultaneously via a Philips DSO as shown in the block diagram - Figure 7.1. Since the pressure gauge afforded absolute pressure, it was necessary to remove the 5V DC offset resulting from atmospheric pressure in order to optimise data storage on tape, thus a DC offset was introduced on the pressure channel.

7.1.2 Data Abstraction

Tapes with stored pressure and aeration data were played back in the laboratory into the Philips DSO. Although in excess of 120 hours of data were obtained, many were either insignificant or hydrostatic variations alone, thus the DSO was adjusted to trigger at significant pressure levels. These captured waveforms were then transferred to an Opus PC V microcomputer using MASK software from Philips to facilitate data
analysis. For most signals two waveforms were captured - pressure and aeration and amplitude and time figures evaluated for each.

7.1.3 Evaluation

Weather and tide conditions for each day field trials were operational are given in Appendix E

As stated earlier many of the stored signals were discarded due to the absence of interesting features. All significant data which were obtained are listed in Tables 7.1 to 7.8. The format of the tables is such that each wave has an identification code and a classification, the relevance of which is explained in Section 7.2. Peak pressure amplitudes and pressure rise times (duration of impulse from start to peak pressure) as measured are listed along with the period of pressure or volume oscillation if applicable. Horizontal and vertical water velocity components are listed for some waves, these were obtained from video measurements and performing frame extractions using an Image Analyser (Cambridge Instruments Image Analysis System, Biological Sciences Dept., University of Plymouth).

Clearly it was impossible to acquire video data for all waves since many measurements were conducted during darkness hours, but all identifiable waves were captured on video. Estimates of the angles of wave approach were made by substituting the measured velocity components into the Taylor jet impact expression (Chapter 1.3), thus enabling jet impact pressures to be evaluated in the appropriate cases. The normal velocity component was assumed to have the same value as the wave celerity and the tangential velocity component was obtained from the rate of travel of the water jet up the sea wall.

There is also a column in the tables for equivalent diameter of air pocket or bubble which produce impacts or pressure surges as a result of collapse at or near to the transducer.

When air pockets collapse or oscillate there is an accompanying pressure fluctuation and for impacts of this form it is possible to estimate to first order the size of the air pocket by using Rayleigh's continuity equation for a bubble (Chapter 2 Equation 2.90) or by using Minnaert's equation for bubble resonance (Chapter 2 Equation 2.7). The term equivalent diameter is used in preference to diameter since the values given are for spheres of equivalent diameter and in actuality air pockets may assume highly non-spheroidal configurations.

Two columns are devoted to void fraction data, one lists the percentage air calculated
from aeration gauge output assuming that the Maxwell criteria are valid [1] (ie. small bubbles, large inter-bubble separation and homogenous solution). The second aeration column lists values obtained by feeding peak pressure and rise time information into the program outlined in Appendix B – which cover the responses for subsonic and supersonic propagation of pressure waves resulting from jet impact in a bubbly fluid.

A sample of pressure and aeration spectra, obtained in the field, are given in Figures 7.2 to 7.27.

7.2 DISCUSSION OF RESULTS

7.2.1 SUMMARY

Analysis of the results in Tables 7.1 to 7.8 combined with general acoustics theory indicates the existence of 3 discrete wave impact-effects:

a. Class I. Variation of still water level i.e. non-breaking waves resulting in hydrostatic pressure fluctuations;

b. Class II. Pressure changes arising from wave breaking events and the motion of water waves/jets.

c. Class III. Pressure variations resulting from the collapse or oscillation of bubbles or air pockets alone.

Although the above phenomena are ostensibly independent only a. and b. are mutually exclusive since combinations of a. and c. or b. and c. are often in evidence. Each type of event is discussed subsequently in greater detail.

7.2.2 Class I – Hydrostatic variation of non-breaking waves

Such events may not be classified as "impacts" due to their long timescale, typically seconds, and as such are of limited relevance in a study of wave impacts. Inclusion of this category is justified because of the large number of non-breaking waves observed during field trials and although of long duration compared to breaking wave impacts, hydrostatic pressure fluctuations may occur on timescales comparable with the resonance periods of sea defence armour units.

Within this wave category three distinct groupings are identifiable:
a. Class I(a) - pressure variations at or above still water level e.g. Figure 7.28

b. Class I(b) - pressure variations well below the still water level e.g. Figure 7.29

c. Class I(c) - pressure variations for waves at tangential or oblique incidence e.g. Figure 7.30

Typical aeration data obtained were indicative usually of little air present or the absence of air in the wave; two exceptional circumstances with much air entrained being:

i. wave broken on approach at the rocks some distance in front of the gauge e.g. Plate 7.2

ii. wave approaching the sensor housing tangential to the wall under windy conditions e.g. Plate 7.3

7.2.3 Class II - Impacts Due to Breaking Waves

Pressure changes occur due to the action of waves breaking fully or partially on a structure accompanied by a rapid uprush of water. Observed timescales for such events are in the range milliseconds to hundreds of milliseconds although rise times of microseconds are theoretically valid although difficult to measure due to the relatively low resonant frequency of many pressure transducers which are well below 100kHz [2].

The exact shape of the curve and the final rise time is strongly dependent upon the location of breaking, the bubble content of the wave and/or the high and low frequency acoustic Mach numbers (more correctly referred to as adiabatic, isentropic and isothermal Mach numbers respectively). The final and perhaps most important factor is the type of wave, its generation mode and breaking criterion; this will be discussed subsequently in more detail. In this regime it is possible to use experimental values for peak pressure and rise time to estimate the air content in the wave. As shown in the Tables many of these estimates are in good agreement with void fraction data obtained from the aeration gauge. Clearly this process does not always give single valued results rather indicating an acceptable range of aeration values over which such impulses would be allowed. The void fractions calculated using aeration gauge data are generally slightly larger than the theoretical values from Appendix B and are thus indicative of an upper limit for the air content of the wave and should be treated as such rather than as absolute values.
7.2.3.1 Bubble oscillation periods > pressure rise time

When bubbles of relatively large dimensions are present in a fluid they offer a source for the scattering and attenuation of pressure waves as discussed in Chapter 1. Irrespective of the origin of the pressure waves — radiative or due to impact pressures, if the maximum frequency component exceeds the resonance frequency of entrained bubbles then it is highly improbable that dispersive effects will be observed. Pressure wave attenuation in this case results principally due to geometric scattering and there is no velocity dependence upon air content; the speed of sound in water remains at 1500 m/s. Attenuation levels in these circumstances are proportional to bubble area and to void fraction to the exponent 2/3, assuming that the bubble size spectrum is relatively narrow [3].

\[ A (\text{dB}) = 4.343 \cdot \ell \sum_{n} \sigma_n n_n \]  \hspace{1cm} (7.1)

where \( \ell \) is the path length; \( \sigma_n \) is the extinction cross section of the \( n \)th bubble and \( n_n \) the \( n \)th bubble density in units of m\(^{-3} \).

Clearly this regime is no longer valid as pressure wave frequencies approach the resonance values of entrained bubbles. Under such circumstances linear attenuation at the fundamental frequency is very strong; typically two orders of magnitude greater than geometric scatter and it is expected that any pressure impulse propagation would contain little of the fundamental component and any detected signal would comprise harmonic components propagated non-linearly. If the pressure impulse could be approximated by a sawtooth wave then the harmonics would be present in the ratios of their Fourier coefficients \( 1/n \pi \) where \( n \) is order of the harmonic. Thus second and third harmonics would be propagated with approximately equal magnitudes after bubble attenuation has been calculated.

7.2.3.2 Adiabatic Mach Number < 1

When the frequency components of propagating pressure waves are much lower than the resonance frequency of entrained bubbles, then dispersive effects occur as discussed in Chapter 3. The characteristics of impulses such as peak magnitude and rise time now become some function of the void fraction and mean bubble size but the exact relationship is determined by the initial velocity of propagation and the local speed of sound. As discussed in Chapter 3, when the entrained bubbles are large enough for thermal and viscous effects to be small with respect to bubble size, then phase separation occurs and gas and liquid phases move with different velocities. In this
regime the local speed of sound obeys adiabatic gas laws and is determined by the equation:

\[ C = \sqrt{\frac{P_0}{\rho_0 \beta (1-\beta)}} \]  \hspace{1cm} (7.2)

Pressure gradients are gentle in this regime. Rise times are determined by such factors as the ratio of specific heats of gas and liquid and hence Prandtl number, maximum allowable peak pressure and mean bubble size.

In this regime, provided that the adiabatic acoustic Mach number is not exceeded, the only difference between subsonic and supersonic (with respect to the isothermal Mach number) pressure wave propagation is a factor corresponding to the inverse of the isothermal Mach number which appears in some of the expressions shown in Appendix B. The shape of the impulse is that of a characteristic adiabatic curve with no oscillatory behaviour present since the shape of the "shock" front is governed by the limiting effects of viscous, or more probably, thermal dissipation. A point is reached for subsonic propagation where the pressure rise time approaches the times observed in hydrostatic pressure fluctuations, (the compressible limit is reached) and the model is no longer valid, but the intervening region encompasses the partial breaking wave situation. The model's upper limit is the acoustic or incompressible limit.

7.2.3.3 Both Adiabatic and Isothermal Mach Numbers > 1

In this regime true shock wave propagation is observed. Very fast exponential pressure rises are observed and bubble effects are the limiting factor in shock front generation thus pressure rises are often accompanied by oscillatory behaviour (see Chapter 3). The period of oscillation is typically directly proportional to the mean bubble size. There is no phase separation between gas and liquid which move at the same velocity. Dominant factors in determining initial rise time are the heat transfer between bubble and bulk fluid; viscous drag and most important bubble size. Any void fraction dependence appears to be implicit i.e. imbedded in Wood's [4] velocity of sound equation and has no influence on the final impulse characteristics. This assumption breaks down if there is a broad bubble size spectrum when the ratio of large to small bubble size void fractions is crucial in determining the initial rise time. Thus although the mean bubble size may be small there may be sufficient larger bubbles to dominate the size dependence relationship thus increasing the rise time. In the shock wave regime there is a direct proportionality between mean bubble size and
rise time whereas in 7.2.3.2 the rise time is generally much greater than the mean bubble oscillation period.

It is possible to observe oscillatory shock wave behaviour in bubble free water where the primary mechanism is not dominant bubble resonances but rather the reflection of shock waves at an interface causing pressure oscillations. This effect is most improbable at sea, in the breaking wave zone, due to finite aeration levels and more importantly due to the pressure of a large free surface. Occurrences of this nature are usually restricted to rigid vessels such as pipes and shock tubes, or in the deep ocean far from the air/water interface.

In addition to pressure/volume oscillations at the mean resonant diameter and reflective pressure oscillations in bubble free water, there is one more category of pressure oscillations which approximates a composite response of adiabatic and isothermal behaviour. At a certain impact velocity the resultant vertically moving jet adopts wavy or oscillatory flow behaviour hence the hybrid pressure response. In contrast to pressure waves emanating from the volume oscillation of trapped bubbles or air pockets, the surface pressure waves as described by Sene’s wavy flow model [5], are generated by the passage of a surface wave in a direction normal to the pressure sensor ie vertical motion of an entrapped air pocket or eddy. Pressure impulses may exhibit oscillatory behaviour on the rising edge as well as on the rarefaction part of the cycle, dependent upon the location of the sensor due to modulation of the pressure waves by the surface roughness of the wall. There is some doubt as to the critical velocity for initiation of wavy flow but it has been decided to include it in this section due to its oscillatory properties and the likelihood of supersonic flow, but caution must be exercised as to which regime this falls into.

7.2.4 CLASS III - Pressure variations due to the collapse or oscillation of trapped bubbles or air pockets

The collapse or oscillation of bubbles has been discussed previously in Chapter 2. Typical timescales for these events are milliseconds or less. The occurrence of such phenomena is independent of whether or not wave breaking takes place. Collapsing air pockets/bubbles may be detectable at considerable distances from the transducer as shown by wave code 13A86 where bubble collapse occurs at 5 metres from the pressure transducer. This collapse was observed and recorded on video tape. Clearly any pressure impacts may be sensed by the transducer provided that there is a medium through which the pressure waves may travel ie. water. Consequently remote pressure impacts had a higher incidence of detection at high tide when the pressure sensor was submerged in at least one metre of water.

7-7
This type of pressure variation is discrete from that described in section 7.2.2 and may occur at any time. If pressure surges result from bubble collapse before wave breaking then such an event may affect the resultant breaking wave spectrum since a large amount of energy is dissipated during bubble collapse and the resultant breaking wave pressure impulse may be severely attenuated. Also the impact velocity of the encroaching fluid is considerably reduced. Such phenomena have been observed during field trials, an example being that of impulse code, Number 11F1093, Table 7.5. Although pressures and rise times of collapsing bubbles are almost independent of void fraction, the probability of occurrence of such an event is directly proportional to the void fraction. Events of this nature are therefore more probable at sea than in the laboratory. The enhanced probability of trapping bubbles or air pockets is enhanced due to increased void fraction and three dimensional shape instabilities.

Subsequent effects on breaking wave pressure spectra reinforce the stereotype that pressure emanating from wave action at sea are (scaled to waveheight) proportionally less than those achieved in the laboratory.
7.3 COMPARISON OF LABORATORY, SEA TRIAL AND FIELD DATA

It has been shown in Chapters 4 and 5 that laboratory results from the swinging arm tests initial sea trial data are coincident with the principle of Taylor's jet impact theory [6]. The presence of aeration in the water may have caused an increase in the effective contact angle at the air/water interface, a logical assumption since highly aerated water is presents a turbulent boundary layer at contact with the pressure sensor. Alternatively, assuming a fixed contact angle, a constant or proportionality between effective impact velocity and pressure the time is required which is a strong function of velocity and weaker function of compressibility.

Laboratory data indicated that increasing the salinity had little effect except it may have enhanced bubble surface lifetime, thus increasing the probability of a larger contact angle or reduced proportionality constant between impact velocity and rise time with consequently slower rise time and reduced amplitudes. Since the mean bubble diameters were quite small (~100 μm) the dispersion formulae would apply and the potential for shock wave propagation would exist. The mean bubble size in salty water is less than that in fresh or tap water, thus if oscillatory behaviour were detectable the oscillation period in tap water would exceed that in salty water. The bubble size distribution was not necessarily the same in the acoustic measurement region as at the surface and indeed there was ample photographic evidence of coalescence at the surface and a correspondingly larger mean bubble size at that point.

Direct comparison between laboratory data and sea trial results from Pandora, as given in Chapter 4.4 and Chapter 5.1 respectively show good agreement and that the same impact mechanism may occur in either case. One major discrepancy arises due to the difference in mean bubble size in the two regimes with the sea trial data showing bubble sizes at least an order of magnitude greater (see Chapter 5.1). Such results appear to be erroneous on first inspection since it would be expected that the mean bubble size in seawater should be less than that in freshwater. For a given bubble generation mechanism the previous statement is true, but bubbles considered in this comparison resulted from different generation mechanisms and extremely large bubbles were present during the sea trial since measurements were undertaken at the surface of the boat's propeller wake, since this was effectively the turbulent boundary layer.

Despite minor anomalies from the laboratory and the sea trials was well matched to the Taylor jet impact theory i.e. relatively incompressible flow even in the presence of void fractions of ~10% and both laboratory and field data sets appear to conform to Class II impacts. The final pressure spectrum is a function of bubble size.
spectrum, but principally a function of impact angle and distance of the transducer from the impact site.

It is clear from the tables in Chapter 4 that many of the exponent values, m, are much greater than 1/3 and the reasons for this are twofold:

i. most of the breaking wave impacts are of the form which obey an adiabatic or isentropic shock pressure law, consequently the rise time is a function of void fraction;

ii. many of the impacts recorded did not occur at the transducer but the resultant propagated pressure waves are detected. As these travel through the fluid, the pressure amplitude is attenuated while the signal expands in time.

Such effects do not nullify the viability of a quasi-incompressible model, rather they identify spatially displaced pressure waves.

A stark contrast is evident between laboratory test data and field pressure measurements at Bovisand (June 1991) as given in Tables 5.6 and 5.7 which are clearly indicative of Class III "impacts" when bubbles or air pockets are trapped at or near the transducer. Measured pressures fit well with the model for forced bubble motion and all energy is concentrated near to the transducer and dissipated during bubble volume oscillations. Such behaviour has been well characterised in varying degrees by Rayleigh [7], Noltingk and Neppiras [8], Herring [9] and others and it formed the basis of the compressible impact pressure model first postulated by Bagnold [10].

Field data, of full scale breaking waves, collected between November 1991 and April 1992 fall into all three classes of impact - hydrostatic, jet impact and bubble collapse/oscillation.

The statistical breakdown of impacts ignoring hydrostatic events; which were the most common type (with peak pressures at 10kPa and rise times of the order 1 second), is of the form:

Class II (Jet Impact) TOTAL 46%

With components:

a. subsonic. Mean bubble resonance frequency < maximum impact frequency component 3%
b. subsonic or supersonic. Adiabatic Mach No. < 1. Mean bubble resonance frequency >> maximum impact frequency component (see Fig 7.11).

36%

c. supersonic. Both Adiabatic and Isothermal Mach numbers at the site of impact thought to be > 1. Mean bubble resonance frequency >> maximum impact frequency component (see Fig 7.25)

7%

Class III (trapped bubble/air pocket) TOTAL

54%

With components:

a. oscillation (see Fig 7.20).

24%

b. direct collapse (see Fig 7.26).

30%

From the above statistics it is possible to devise a hierarchy of influencing factors with respect to wave breaking and impact spectra thus:

1 location - where the wave impacts the structure and distance from the pressure sensor.

2 angle of approach of wave and its shape on approach to the transducer.

3 water particle velocity in the impact zone which will have equal or greater magnitude than the wave celerity in the breaking region.

3 aeration a function of the above parameters whose argument varies with regime thus:

a) mean size and void fraction dependence (Class II (a) and Class II (b))

b) main void fraction dependence (Class II (c))

c) mainly size dependence (Class III) for peak pressure and rise time, but void fraction dependent for the frequency of events

4 tidal cycle: Class II (c) and Class III (b) restricted to near HW, Class III (a) occur nearer LW and Class II (b) relatively independent of cycle.
salinity/contaminants which in turn affects mean bubble size.

miscellaneous – temperature; multipole bubble oscillations; non-linear propagation etc.

Using the program as outlined in Appendix B, with measured pressure, time and horizontal and vertical velocity components it is possible to determine the allowed range of mean bubble sizes and void fractions for which the quasi-(in)compressible jet model is valid.

Examples of Class II (b) compression curves, as calculated, are given in Figures 7.31 to 7.40, these show the allowed values of aeration versus mean bubble diameter for experimental values of peak pressure and rise time.

The echelon of influencing factors given earlier explains the apparent incongruity between model tests and field data:

1. Location: In model tests wave breaking may be effectuated within a narrow spatial region, thus most impacts will be due to wave breaking and statistical spread will be relatively narrow. Many of the impact spectra recorded at sea arise from waves breaking some distance from the transducer which are attenuated in consequence.

2. The angle of approach of a wave and its shape when breaking are determined by the following criteria [11]:

   a. waves break when:

      \[
      \frac{H}{\lambda} > \frac{1}{12}
      \]

      or

      \[
      \frac{H}{d} > 0.8
      \]

      where \(H\) is the waveheight; \(\lambda\) the wavelength and \(d\) the still water depth.

Most wind generated waves at sea break as a result of (i) above, since the wavelength is comparatively short on say a tidal scale. Waves of this type tend to be spilling breakers consequently they present a large contact angle with a seawall and are also
highly aerated. These waves usually fall into Class II (a) or (b).

Conversely swell generated waves tend to break as a result of the second condition since these wavelengths are much greater than those of wind waves. Swell waves tend to result in plunging breakers and these present a very small contact angle with a seawall and may enclose a large air pocket. These waves are more consistent with Class II (c) type spectra or Class III impacts which involve direct collapse of a bubble or air pocket. Shock Class II (c) responses were only in evidence at high water when the gauge was submerged, hence remote from a free surface. Five Class II (c) impact responses as functions of allowed aeration values are shown in Figures 7.41 to 7.45, most show excellent agreement between the upper allowed aeration limit and that obtained from the aeration gauge.

Many model scale waves also break as a result of the wave height to water depth criteria, but still present small contact angles. Thus the combined effects of the small contact angle and the two dimensional effect of the channel-walls-of-the-wave-flume, tends to produce high impact pressures. In order to achieve an accurate comparison between laboratory generated waves and those breakers which occur most often at sea, spilling breakers, it would be necessary to use systems such as those devised by Cipriano and Blanchard [12]. Monahan and Zeitlow [13] also simulated spilling breakers by causing two oppositely inclined waves to collide.

7.4 COMPARISON WITH OTHER IMPACT PRESSURE DATA AND DISCUSSION OF BOVISAND RESULTS

Several investigations, both laboratory and full scale, have been conducted into various aspects of the properties of impact pressures. Laboratory investigations have been undertaken as part of the MAST G6 Coastal Structures programme [14 to 18] encompassing prototype and large scale laboratory measurements. Field data have also been collected by Hydraulics Research [14] in their capacity as eminent member of the Single Layer Armour Research Club (SLAC).

7.4.1 Oumeraci and Partenscky

Analysis of both prototype and full scale results at the Franzius Institute, University of Hannover lead Oumeraci and Partenscky to identify four breaking wave regimes (see Figure 1.5) which in order of impact magnitude are:
1. plunging breaker with very small air pocket
2. well developed plunging breaker
3. upward deflected breaker
4. turbulent bore.

Cases 1 and 2 involve the collapse of trapped air pockets and correspond to Class III type impacts described earlier, whilst Case 3 corresponds to Class II type impacts. This hierarchy is at variance with the results listed in Tables 7.1 to 7.8 which indicate that Class II and Class III impacts may be of similar magnitudes. Oumeraci and Partenscky observed oscillatory behaviour in their Case 2 impacts which they ascribed to collapse of an air pocket followed by the impact of the water wave, the oscillations may have arisen however due to the effect of shock wave propagation in a bubbly fluid, with the bubbles resulting from air entrainment following the collapse of the large air pocket.

Their additional postulation that multiple oscillations of a very large air pocket may also cause the observed oscillations appears improbable though perhaps not impossible due to the constraining effects of the wave tank. There can be no doubt that when plunging breakers collapse there is an audible signal, but since this is a transient and it is expected to be impulsive in nature with contributions from all frequencies. Multiple oscillations of such large pockets (typically ~ 60cm effective diameter according to their data) are unlikely due to surface tension and velocity considerations. Air pockets or bubbles of 10cm diameter or greater are inherently unstable resulting from growth of Rayleigh-Taylor instabilities initiated by low surface tension values due to the 1/r dependence of surface tension. In addition, if the velocity of the impacting water jet/wave is of sufficient magnitude to overcome inertia then collapse will ensue. More probable explanations for the observed oscillatory phenomena for such large air pockets are:

(i) as first suggested by Oumeraci and Partenscky - collapse of an air pocket of dimensions much less than 60cm, (class III), followed by water impact i.e. water uprush as in their cases 3 and 4 (our class III);

(ii) Initial collapse of the air pocket resulting in the entrainment of many smaller air bubbles into the wave; with subsequent peaks resulting from shock wave propagation in the bubbly fluid resulting in collective oscillation of the entrained air cloud with oscillation frequency expressed thus:

\[ f_{\text{cloud}} = \left( \frac{\gamma_{\text{eff}} P_0}{\beta \rho_0 D_0^2} \right)^{\frac{1}{2}} \]  

(7.3)
(iii) measurement of the pressure wave variation across the air pocket rather than its total volume oscillation.

(iv) the onset of wavy flow with limiting surface wavelength and trapped air as given by the expression [20]:

\[ \lambda = 2\pi D \left( \frac{u_r}{u_i} \right)^2 F_r^2 \]  

(7.4)

where \( D \) is the jet width, \( u_i \) the impact velocity, \( u_r \) the recirculation velocity and \( F_r \) the Froude number;

(v) oscillations of smaller air pockets resulting from partial collapse due to Rayleigh–Taylor instabilities [21]

Figure 7.49 shows a Class II (c) response from Oumeraci's data using 1m waves, a result remarkably similar to full-scale wave Number 14A173 (see Figure 7.24).

7.4.2 Jongeling

Oscillatory motion was also observed by Jongeling [17] during the 1/40th scale testing for storm surge barriers in Eastern Scheldt. He proposed a non-linear isothermal compression model for large magnitude shocks; not a dissimilar model from the bubbly shock model. The effects of wave impacts on scale models of the gates, caissons, beams and piers which comprise the storm surge barrier of the Eastern Scheldt were studied in 0.9m and 2.0m deep wave channels. Many of the resultant impact spectra show the sharp exponential rise of a shock wave followed by oscillatory phase changes. Since the oscillation frequencies observed were generally much higher than those due to the natural resonance frequency of the structure, it is most probable that the oscillations were due to oscillation of air entrapped in the fluid once the shock wave had travelled through the medium and reached a free surface.

7.4.3 Witte

A series of laboratory investigations performed at the University of Braunschweig[18] were directed toward simulating the presence of air pockets by enclosing air cushions in a steel grid, the depth and location of which could be adjusted and modified. The intrusive nature of the experimental arrangement made interpretation of the results extremely difficult.

The data set obtained without the air simulator is given in Table 7.9 and values for effective horizontal and vertical velocities and approach angle as specified by the
Taylor jet impact model have been calculated. Using these values the exponent $m$ was calculated (as in Chapter 4) and similar values to those obtained during the swinging arm drop tests ensue, namely $m = 0.39 \pm 0.06$ which is consistent with the transition from shock wave to compressive gas laws. This figure is slightly higher than the $-1/3$ relationship as verified by Longuet-Higgins [22]. Some of the higher values are due to displacement effects as described in Section 7.3. Clearly for situations where the air content does not exceed $\sim 15\%$ then there is good agreement between the incompressible flow model (Taylor), and the model for the propagation of shock waves through a bubbly medium. Some cases exist in Witte's data set with exponent values less than $1/3$. The most plausible explanation for these values is that the impact is due to the collapse of an air pocket and not due to the impact of a water wave.

7.4.4 Hydraulics Research

Examination of the field data obtained by Hydraulics Research at La Collette Breakwater, Jersey, indicates maximum peak impact pressures at 60 kPa measured on the cob units (Figure 7.46). Expanded traces of impact pressures indicated that rise times were of the order 200ms and the trace shapes were consistent with the gas law relationship of Class II (b) waves i.e. compression waves. Some of the peak pressure values measured were comparable to the author's laboratory test results, but their measured rise times were one to two orders of magnitude greater. This indicates that most of their waves must have been spilling breakers.

7.4.5 Graham

Figures 7.47 to 7.50 show responses calculated using compressible flow theory for four model test data sets. Figure 7.47 shows a typical Class II (b) response with little air present obtained during laboratory trials by D. Graham*, clearly this impact is similar to those shown in Figures 7.31 to 7.40, but shifted down in time and void fraction. There is a stark contrast between this response and that achieved by Witte Figure 7.48, whose waveheights were only 2.5 time those of Graham, but with peak pressures 50 times in excess. Such discrepancy arises from the nature of the breaking waves, Graham's model waves were possibly surging breakers whereas Witte used a gentler beach slope (1 in 6 compared to Graham's 1 in 4.5), thus it is likely that the breaking was fully achieved in Witte's case and the waves obtained were plunging breakers, whereas Graham's waves were more comparable with spilling breakers.

*Civil and Structural Engineering, University of Plymouth

7-16
7.4.6 Shih

For completeness Figure 7.50 shows a shock type response for near vertical impacts on a plate observed by Shih and Anastasiou [23]. In their experiment, water jets struck a horizontal surface (representing an oil platform) directly above the still water surface. The angle of approach of the jet at the pressure sensor was by design very small although the actual value was unstated in their discussion. Consequently Taylor’s impact theory is applicable, hence the generation of shock type pressure impacts which reinforces the principle that the resultant impact is a function of the shape of the jet/wave at the pressure sensor.

7.4.7 Bovisand data

Figures 7.51 to 7.54 show a range of Bovisand data as functions of bubble size, impact velocity—and void fraction. Shock wave—pressure—time—impact—curves are shown as functions of varying air content, whilst Figure 7.54 shows compression wave rise time as a function of estimated mean bubble size for a range of aeration values. Figures 7.55 to 7.62 show measured data from Bovisand as functions of aeration, pressure and velocity respectively. It is apparent from Figure 7.62 that most of the shock wave events occur at high impact velocities, thus reinforcing Taylor’s model. However it has been shown in Chapter 3 that shock waves are generated in bubbly fluids. The laboratory test results as well as field trial data indicate that the compressible Taylor model and the bubbly shock wave model are compatible (see Tables 4.4 and 4.5 to Tables 5.1 and 5.2 and Tables 7.2, 7.5, 7.6 and 7.8 where theoretical values of peak pressure obtained using Taylor’s impact model are listed for comparison with measured values).

It is necessary for a small amount of air to be present when shock waves are generated as a result of wave breaking at a free surface in order that water particle velocity exceeds the local speed of sound. Theoretical curves obtained using measured pressure and rise times indicate that the rise times decrease as the void fraction increases (see Figures 7.51 to 7.53). Although such a response is valid for shock waves, it is unlikely that a jet/plunging breaker would contain 30 to 40% entrained air on impact in the form of dispersed bubbles. Thus the theoretical curves are indicative of the probability of exceeding the local speed of sound i.e. the local speed of sound is less for a wave with 30% void fraction than for one with 1% void fraction.

Figures 7.63 to 7.65 show probability distributions for peak pressures, rise times and void fractions for all the Bovisand data. The lower peaks in the distribution of Figure 7.65 corresponds to the most probable void fraction for Class II (c) shock waves,
whilst the second peak corresponds to the most probable void fraction for Class II (b) compression waves.

Figures 7.66 to 7.74 give a statistical breakdown of the types of events while Figure 7.75 is a scatterplot of all the significant measurements performed on impact pressure and the times.

It is apparent from statistical breakdown of the data that water wave (Class II) and bubble/air pocket (Class III) impacts occur with approximately equal probability. Class II (b) wave impacts are the most numerous and may occur at any point on the tidal cycle. Class III (a) bubble impacts, which involve oscillation of bubble or air pockets tend to occur well before or after high water with perhaps a slight bias to ebb tides coincident with the turbidity maximum, but more measurements would be required to confirm the latter hypothesis. Class III (b) bubble collapse impacts and Class II (c) wave shock impacts occur at high water.

There is an apparent cut-off between shock and compression type impacts obtained from the data on the scatterplot Figure 7.75 which occurs for

$$\frac{dP_s}{dt} = 800 \text{ kPa/s}$$ \hspace{1cm} (7.5)

where $P_s$ is the shock pressure

Above this value water wave impacts tend to be exponential shock pressures whilst for lower pressure gradient values compression waves ensue with longer rise times. Clearly impacts resulting from bubble collapse or oscillation have steep pressure - time gradients. These Class III bubble impacts may be resolved from Class II shock bubbly water wave impacts by analysis of the pressure - time curves. It was shown in Chapters 4 and 5 that water wave impacts have a pressure - time relationship characterised thus:

$$P_s \propto \tau^{-2/3}$$ \hspace{1cm} (7.6)

Class III type impacts are characterised by the Rayleigh collapse model (see Chapter 2 Equation 2.90 and Chapter 5 Equations 5.11 to 5.13) or by Minnaert's bubble oscillation equation (Chapter 2 Equation 2.7).

Although empirical in nature equation (7.5) indicates that there is both a minimum water particle velocity and a minimum water particle acceleration for the generation of shock waves and below these values the resultant water wave impacts will always be the compression types. Thus assuming a one dimensional system at the point of impact the water particle velocity is $u_{eff}$ and the pressure gradient may be expressed:
\[
\frac{dP}{dt} = \frac{d}{dt} \left[ \frac{\rho_f u_{eff}^2}{2} \right] - \rho_f u_{eff} \left[ \frac{d u_{eff}}{dt} \right] \quad (7.7)
\]

As the air content increases \( u_{eff} \) decreases (up to 33% void fraction) and \( \rho_f \), the fluid density, also decreases. Thus the minimum acceleration value for high void fractions is greater than for low void fractions. The variation of minimum water particle acceleration as a function of void fraction is shown in Figure 7.76.

Although it is more probable for water particle speeds to exceed the local sound speed in highly aerated water, the acceleration condition as outlined above is more difficult to achieve, hence shock wave generation is more likely for waves/jets with small void fractions (typically less than 15%).

In the shock regime pressure and rise time are not independent, whereas they may be decoupled for compression waves with pressure a function of velocity and rise time a function of void fraction and mean bubble size, but an indirect function of velocity. Shock pressures and rise times may be scaled up or down directly e.g Rouville's result of 550 kPa in 18ms. When scaled down by 1/10th this pressure would have a rise time of 8.7ms.[24]

When scaling compression waves, a reduction in pressure would not affect the rise time directly, but a different value for the velocity would need to be used in order to scale down the rise time correspondingly. Scaling is possible, however, using rise time as the dependent variable.
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**KEY FOR TABLES**

A=ID CODE
B=AERATION (%)  
C=IMPACT PRESSURE(kPa)
D=RISE TIME(milliseconds)
E=OSCILLATION PERIOD(milliseconds)
F=NUMBER OF OSCILLATION CYCLES
G=NORMAL WAVE VELOCITY(m/s) (FROM VIDEO DATA)
H=TANGENTIAL WATER VELOCITY(m/s) (FROM VIDEO DATA)
I=AERATION CALCULATED USING TAYLOR OR BERNOULLI EQUATION
J=IMPACT PRESSURE(kPa) CALCULATED AS I ABOVE
K=EQUIVALENT BUBBLE DIAMETER(mm)
L=WAVE CLASSIFICATION

- possible missed compression
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Possible second jet at lower velocity

Missed compression

Small jets after initial impact
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PLATE 7-1. THE JETTY AT FORT BOVISAND WITH VIEWS OF THE PANEL ROOM AND PLYMOUTH SOUND.

FIGURE 7-1. FIELD DATA COLLECTION INSTRUMENTATION.
PLATE 7-2  WAVE BREAKING ON ROCKS AT BOVISAND BEFORE REACHING SENSOR

PLATE 7-3  BROKEN WAVE TRAVELLING ALONG BOVISAND SEA WALL & STRIKING GAUGE TANGENTIALLY.
FIGURE 7-2.

ID CODE 8E1060
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500ms/div
wave class III(b)

FIGURE 7-3

ID CODE 8E1065
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500ms/div
wave class III(b)
FIGURE 7-4

ID CODE 8E1067
pressure scale 5 kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b)

FIGURE 7-5

ID CODE 8E1329
pressure scale 5 kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(c)
FIGURE 7-6

ID CODE 8E1351
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(c)

FIGURE 7-7

ID CODE 11F372
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(a) & II(b)
ID CODE 11F399
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(b) & II(b)

FIGURE 7-8

ID CODE 11F708
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b) & II(c)

FIGURE 7-9
ID CODE 11F773
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b) & II (b)

FIGURE 7-10

ID CODE 11F1094
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(b)

FIGURE 7-11
ID CODE 11F1152
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(b)

FIGURE 7-12

ID CODE 12F18
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b)

FIGURE 7-13
ID CODE 12F619
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(c)

FIGURE 7-14

ID CODE 12F666
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(b)

FIGURE 7-15
ID CODE 12F897
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(b)

FIGURE 7-16

ID CODE 12F1064
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes II(a) & II(b)

FIGURE 7-17
FIGURE 7-18

FIGURE 7-19
ID CODE 14A91
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(b) & II(b)

FIGURE 7-20

ID CODE 14A123
pressure scale 5kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(b) & II(b)

FIGURE 7-21
ID CODE 14A138
pressure scale 20kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b)

FIGURE 7-22

ID CODE 14A166
pressure scale 20kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class III(b)

FIGURE 7-23
FIGURE 7-24

ID CODE 14A173
pressure scale 20kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(b) & II(c)

FIGURE 7-25

ID CODE 14A667
pressure scale 10kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave class II(c)
ID CODE 14A779
pressure scale 20kPa/div (A)
% air scale 80%/div (B)
time scale 100 ms/div
wave class III(b)

FIGURE 7-26

ID CODE 14A838
pressure scale 20kPa/div (A)
% air scale 80%/div (B)
time scale 500 ms/div
wave classes III(b) & II(b)

FIGURE 7-27
FIGURE 7-28 HYDROSTATIC PRESSURE VARIATION AT SWL.

< 15 kPa  < 1.5 m

FIGURE 7-29 HYDROSTATIC PRESSURE VARIATION WELL BELOW SWL.

> 15 kPa  > 1.5 m

FIGURE 7-30 HYDROSTATIC PRESSURE VARIATION FOR WAVES IMPACTING OBLIQUELY.

2 seconds  0.5 seconds
FIGURE 7-31 ALLOWED VALUES OF WAIR/MEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 12F621

FIGURE 7-32 ALLOWED VALUES OF WAIR/MEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 11F708

FIGURE 7-33 ALLOWED VALUES OF WAIR/MEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 11F96

FIGURE 7-34 ALLOWED VALUES OF WAIR/MEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 12F397
FIGURE 7-39 ALLOWS VALUES OF HADMEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 14A602

FIGURE 7-40 ALLOWS VALUES OF HADMEAN BUBBLE SIZE FOR CLASS II(b) IMPACT 14A668

FIGURE 7-41 ALLOWS VALUES OF HAD/JET CONTACT ANGLE FOR CLASS II(c) IMPACT 8E1331

FIGURE 7-42 ALLOWS VALUES OF HAD/JET CONTACT ANGLE FOR

CLASS II(c) IMPACT 8E1969

peak pressure 24 kPa
rise time 10 ms
wave velocity 3 m/s
wave height 1 m
depth below SWL 2 m
no measured session

peak pressure 22 kPa
rise time 30 ms
wave velocity 3 m/s
wave height 1 m
depth below SWL 1 m
no measured session
FIGURE 7-43 ALLOWED VALUES OF %AW/ JET CONTACT ANGLE FOR
CLASS II(c) IMPACTS 9E8876(a) & 9E9174(b)

- peak pressure 35 kPa (a)
- rise time 140 ms
- measured sensation 7%
- peak pressure 20 kPa (b)
- rise time 160 ms
- measured sensation 4%
- waveheight 1m
- depth below SWL 1.5m

FIGURE 7-44 ALLOWED VALUES OF %AW/ JET CONTACT ANGLE FOR
CLASS II(c) IMPACT 14A173

- peak pressure 42 kPa
- rise time 17.3 ms
- wave velocity 3.6 m/s
- waveheight 2m
- depth below SWL 2m
- measured sensation 7%

FIGURE 7-45 ALLOWED VALUES OF %AW/ JET CONTACT ANGLE FOR
CLASS II(c) IMPACT 14A667

- peak pressure 16 kPa (a)
- rise time 2.3 ms
- peak pressure 24 kPa (b)
- wave velocity 3.6 m/s
- waveheight 2m
- depth below SWL 2m
- measured sensation 4%
FIGURE 7-46 EXAMPLES OF ARMOUR UNITS USED IN SEA DEFENCES.
FIGURE 7-47 ALLOWED VALUES OF %AIR vs. MEAN BUBBLE DIAMETER FOR DATA SET OBTAINED BY D.GRAHAM*. CLASS II(b) COMPRESSION MODEL WAVE IMPACT.

PEAK PRESSURE 2.8kPa
RISE TIME 5ms
WAVE CELERITY 2m/s
WAVEHEIGHT 10cm

* formerly School of Civil & Structural Engineering
University of Plymouth

FIGURE 7-48 ALLOWED VALUES OF % AIR vs. WATER WAVE IMPACT ANGLE FOR DATA SETS OBTAINED BY WITTE*. CLASS II(c) MODEL SCALE SHOCK WAVES.

peak pressure 149kPa
rise time 0.98ms
no aeration device

peak pressure 70kPa
rise time 1.39ms
aeration device present

peak pressure 70kPa
rise time 1.39ms
aeration device present

wave celerity 3.4m/s
waveheight 25cm

* Universitat Braunsweig
FIGURE 7-49 ALLOWED VALUES OF % AIR vs. WATER WAVE IMPACT ANGLE FOR DATA SETS OBTAINED BY OUMERACI. et al*. CLASS II(c) SHOCK WAVES.

![Graph 1](image1)

- Celerity 1 m/s
- Celerity 2 m/s
- Celerity 5 m/s

- Peak pressure 43 kPa
- Rise time 16 ms
- Waveheight 1 m

* Universität Hannover

FIGURE 7-50 ALLOWED VALUES OF % AIR vs. WATER WAVE IMPACT ANGLE FOR DATA SETS OBTAINED BY SHIH & ANATASIOU*. CLASS II(c) MODEL SHOCK WAVES.

![Graph 2](image2)

- Celerity 1 m/s
- Celerity 2 m/s
- Celerity 5 m/s

- Peak pressure 19.5 kPa
- Rise time 4.4 ms
- Waveheight 40 cm

* Imperial College London.
FIGURE 7-51(a) IMPACT RISE TIME AS A FUNCTION OF % AIR FOR CLASS II(c) IMPACT 8E1351.

FIGURE 7-51(b) PEAK PRESSURE vs. RISE TIME FOR IMPACT 8E1351

aeration key

(a) 1% (b) 5% (c) 10% (d) 25%
FIGURE 7-55 PEAK IMPACT PRESSURE vs. RISE TIME FOR ALL CLASS II WAVE EVENTS (SHOCK & COMPRESSION) AT BOVISAND FEBRUARY-APRIL 1992.
FIGURE 7-56 MEASURED AERATION vs. RISE TIME FOR CLASS II WAVE EVENTS (SHOCK & COMPRESSION) AT BOVISAND FEBRUARY-APRIL 1992.
FIGURE 7-57 SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR NORMAL WAVE Celerities 2 to 4 m/s.

FIGURE 7-58 SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR WAVE Celerities 4 to 6 m/s.

FIGURE 7-59 SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR WAVE Celerities 6 to 8 m/s.
FIGURE 7-60. SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR WAVE CERELITIES 8 TO 10 m/s.

FIGURE 7-61. SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR WAVE CERELITIES 10 TO 12 m/s.

FIGURE 7-62. SCATTERPLOT OF PEAK PRESSURE & % AIR AGAINST IMPACT RISE TIME FOR WAVE CERELITIES > 12 m/s.
FIGURE 7-63 PROBABILITY OF IMPACT AS A FUNCTION OF PRESSURE.

- Mainly class II(b) water wave compression impacts
- Class III(b) bubble oscillation impacts
- Mainly class II(c) water wave shock impacts
- Mainly class III(b) bubble collapse impacts
FIGURE 7-64 PROBABILITY OF IMPACT AS A FUNCTION OF RISE TIME.
FIGURE 7-65 PROBABILITY OF IMPACT AS A FUNCTION OF %AIR.

- mainly class II(c) shock impacts & class III(b) bubble collapse impacts
- mainly class II(b) compression impacts
- mainly class III(a) bubble oscillation impacts
FIGURE 7-66(a) STATISTICAL BREAKDOWN OF CLASS II EVENTS BY AERATION LEVEL.

- 15 TO 20% AIR (17%)
- 20 TO 25% AIR (9%)
- 25 TO 30% AIR (11%)
- 30 TO 40% AIR (4%)
- 40 TO 50% AIR (36%)

FIGURE 7-66(b) STATISTICAL BREAKDOWN OF CLASS II EVENTS BY IMPACT PRESSURE.

- 0 TO 5kPa (8%)
- 5 TO 10kPa (29%)
- 10 TO 15kPa (24%)
- 15 TO 20kPa (15%)
- 20 TO 25kPa (11%)
- >25kPa
FIGURE 7-66(c) STATISTICAL BREAKDOWN OF CLASS II EVENTS BY WAVE Celerity.

- 4m/s to 6m/s (28%)
- 6m/s to 8m/s (28%)
- 8m/s to 10m/s (11%)
- 2m/s to 4m/s (10%)
- >12m/s (10%)
- 10m/s to 12m/s (10%)


- Class III(a) (81%)
- Class II(b) (19%)
FIGURE 7-68 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 9th FEBRUARY 1992.

- class II(b) (35%)
- class II(c) (12%)
- class III(a) (18%)
- class III(b) (35%)

FIGURE 7-69 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 10th FEBRUARY 1992.

- class II(b) (25%)
- class III(a) (63%)
- class III(b) (12%)
FIGURE 7-70 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 11th FEBRUARY 1992.

Class II(b) (59%)
Class II(a) (5%)
Class III(a) (7%)
Class II(b) (29%)

FIGURE 7-71 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 12th FEBRUARY 1992.

Class II(b) (57%)
Class II(a) (2%)
Class III(b) (26%)
Class III(c) (2%)
Class III(a) (13%)
7-69
FIGURE 7-72 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 13th APRIL 1992.

- class III(a) (44%)
- class II(c) (11%)
- class III(b) (45%)

FIGURE 7-73 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR 14th APRIL 1992.

- class II(b) (44%)
- class II(c) (8%)
- class III(a) (6%)
- class III(b) (42%)
FIGURE 7-74 STATISTICAL BREAKDOWN OF IMPACT EVENTS FOR ALL OBSERVATION DATES.

- class II(b) (45%)
- class II(c) (4%)
- class III(a) (21%)
- class III(b) (28%)
- class III(a) (2%)
FIGURE 7-75. IMPACT PRESSURE - RISE TIME SCATTERPLOT
LABORATORY & FIELD DATA.
FIGURE 7-76 MINIMUM WATER PARTICLE ACCELERATION REQUIRED FOR THE GENERATION OF SHOCK WAVES IN BUBBLY WATER AS A FUNCTION OF %AIR.
REFERENCES - CHAPTER 7.


CHAPTER 8

CONCLUSION AND SUGGESTIONS FOR FUTURE INVESTIGATIONS

8.1 CONCLUSION

8.1.1 Overview

The principal aim of this investigation was to determine whether aeration had an effect upon wave impact pressures and if it did to attempt to quantify its contribution, within the scheme of relevant parameters.

In order to ascertain the relative contribution of aeration it became necessary to meet the first objective of quantifying air content in the laboratory. A wide range of aeration measurement techniques were surveyed and tested. Optimal techniques were found in acoustic transmission loss measurement using a parametric array and electrical impedance measurement arrangements and it was the latter technique which was considered sufficiently robust to carry forward as the field trial aeration measurement method.

It was evident from the resultant pressure spectra that the presence of aeration affected the peak pressure and rise time. Impacts were closely modelled by Taylor's jet impact theory [1] for incompressible flow with some modification, for the compressible nature of the fluid and the presence of surface bubbles served to effectively increase the approach angle and decrease the effective normal velocity component. The jet impact model was also appropriate for describing the responses observed during initial sea trials when the pressure sensor was dropped on to the water surface in the bubbly propeller wake of a boat. In both laboratory tests and sea trials the effect of salinity was masked by the fact that the bubble generation mechanism was other than natural air entrainment (ie. aerator stones) which results in smaller long lived bubbles being more prevalent in seawater than freshwater. Likewise in the initial sea trials on Pandora many data were obtained from measurements in the propeller and hull wakes and therefore not necessarily representative of natural wind/wave air entrainment processes.

Initial field trials in calm conditions illustrated the effects of bubble entrapment near to the air/water surface most vividly and owing to the dearth of wave action, trapped bubble vibration was detectable over many oscillation cycles.
Many pressure records were discarded due to an absence of interesting features but all records of interest are tabulated in Tables 7.1 to 7.8 and were recorded on video.

8.1.2 How aeration affects wave impacts.

It is an unequivocal fact that aeration does affect wave impact spectra but the exact relationship between aeration and peak pressure and rise time is extremely complex in nature. Three discrete wave classifications were identifiable namely;

- **Class I**  Hydrostatic variations
- **Class II**  Jet impacts with vertical runup
- **Class III**  Trapped bubble collapse or oscillation

Aeration levels were of little consequence for hydrostatic variations but assumed importance for the other two wave classes. For a Class III pressure wave the peak pressure was clearly a function of bubble dimensions whilst the probability of occurrence for Class III impacts increased monotonically with void fraction. The most interesting and indeed the most subtle aeration dependence arose for Class II waves where either the mean bubble size or the void fraction were crucial factors in determining ultimate pressure spectra.

If the maximum fundamental frequency component of the pressure wave is greater than the resonant frequency of the bubbles then shock waves cannot form since the speed of sound in the fluid would remain at ~1500 m/s. The pressure wave will be attenuated by its passage through the bubbly fluid and its shape will alter due to non-uniform attenuation of the harmonic components. If however the bubbles in the fluid have resonant frequencies well in excess of the frequency components in the propagating pressure wave then dispersion will occur and the conditions requisite for shock wave generation will be achieved.

If the mean bubble size is sufficiently large for viscous and thermal effects to be the limiting factors for "shock" generation then adiabatic gas laws will be obeyed and phase separation between gas and liquid would result. Under these conditions the resultant pressure spectrum will assume an adiabatic compression curve irrespective of whether the flow is subsonic or supersonic with respect to the isothermal Mach number, provided that the adiabatic Mach number is less than unity. The pressure rise
time for such a regime is a complicated function of specific heats ratio; Prandtl and Reynolds's numbers and mean bubble diameter and there is a very strong void fraction dependence.

Conversely if the mean bubble size is small then the effects of thermal and viscous damping are large and the limiting factor becomes bubble size; there is no phase separation. Isothermal gas laws are appropriate under such circumstances as is Wood's curve for the speed of sound [2].

Resultant pressure spectra may display an oscillatory component, the period of which is directly proportional to the mean bubble diameter.

Pressure rise times have an implicit void fraction dependence arising from the dispersion curve but exhibit a much stronger dependence upon mean bubble size. Consequently all else being equal it is expected that oscillatory shock waves will be more common in seawater than freshwater due to the bias toward smaller bubbles.

From the foregoing discussion a hierarchy of influences upon impact pressure spectra has emerged thus:

1. location - where the wave impacts the structure and distance from the pressure sensor
2. angle of approach of wave and its shape at the transducer ie wind wave (mainly spilling breaker) or swell wave (mainly plunging breaker)
3. wave particle velocity in the impact zone
4. aeration - the exact effect which aeration has upon impact pressure and rise time varies with the flow regime

Class II (a) mean size and void fraction dependence. Bubble sizes are large and pressure wave attenuation is a function of geometric scattering ie. bubble area. Assuming a narrow bubble size distribution there is also a functional relationship between attenuation and void fraction of the form $\beta^2$ see 7.2.3.1

Class II (b) - compression waves - mean bubble size and void fraction dependence. Rise time increases in direct proportion to the mean or dominant bubble size whilst peak pressures are reduced. Likewise the rise time increases as the void fraction increases and follows the shape of the compressibility curve for changing speed of sound in bubbly water, the peak pressure is
reduced as the void fraction increases. The relationships between peak pressure, rise time, void fraction and mean bubble size may be calculated by using the equations in Chapter 3 and Appendix B.

Class II (c) - shock waves - mainly void fraction dependence during the compression phase, with an experimental relationship between peak pressure and rise time. In theory, peak pressure increases and rise time decreases as the void fraction increases. However this phenomenon is indicative of the change in the local speed of sound as the void fraction increases and does not occur in practice. The higher the void fraction, the lower the local speed of sound hence the higher the theoretical possibility of generating shock waves.

Class III events are a strong function of bubble size with respect to pressure and time. The possibility of Class III events increases as a function of void fraction.

Tidal cycle: Class II (c) and Class III (b) events restricted to near HW
Class III (a) events occur nearer to LW
Class II (b) events relatively independent of tidal cycle

Salinity/contaminants which in turn affects mean bubble size

miscellaneous - temperature; multipole bubble oscillations; non-linear propagations etc.

Clearly aeration affects impact pressure impulses but it acts in concert with an array of other factors. Aeration alone is not the most important reason for the discrepancies arising when scaling up from model test results to full scale data.

When scaling from model to full scale tests it is common to use gravitational scaling parameters and scale to waveheight using the Froude number. Scaling with this parameter in general overestimates peak pressure since the three dimensional nature of the wave structure in the field promotes the trapping of air pockets and the creation of multiple jets thus diminishing the probability of large wave impacts. In contrast the two dimensional nature of wave tanks discourages the production of multiple jets and promotes the production of clean single jets. In addition model scale waves tend to break on perfectly flat walls, whilst at sea coastal structures have some degree of surface roughness.

Likewise the small angle of approach observed in model tests due to the breaking conditions, is much less common for full scale wind generated waves, consequently time scaling tends to be too restrictive. The relative effects of all these parameters are represented graphically and pictorially in Figures 8.1 and 8.2. Figure 8.1 shows
the effects of altering various parameters when scaling from model waves of 10cm to full scale waves of 1m for peak pressure, whilst Figure 8.2 concentrates on the parametric contributions to rise time when scaling up.

In Chapter 1 it was stated that two schools of thought exist with respect to the mechanism of impact pressure generation which could be separated crudely into compressible and incompressible models. This investigation implies that both mechanisms can and do exist. The compressible model is appropriate for trapped bubbles or air pockets whilst a quasi-incompressible model based upon the Taylor impact theorem is applicable for many breaking waves of the plunging type. Jet impacts at small angle are the more common impact method in model tests whilst either is just as probable in full scale tests. For completeness it must be stated that the absence of very high peak pressures approaching water hammer is not unexpected at whatever scale of testing due to the presence of a free surface at the air/water interface and that true water hammer pressures are probably only achievable in pipes and shock tubes or in the deep ocean.

Shock type pressure impact were observed in the laboratory and during field trials but only at high water when there was considerable distance (> 1 metre) to a free surface.

It is therefore a specious argument to claim that high impact pressures and fast rise times do not occur for full scale waves due to the presence of additional aeration alone. Although wave data statistics from the Fort Bovisand site are somewhat limited, impact pressures of ~50kPa have been recorded with 17.5ms rise times and these figures are comparable with those achieved in well controlled laboratory experiments conducted by Oumeraci et al [3] with 1m or larger breaking waves resulting in peak pressure of 43 kPa with rise time ~16ms.

8.1.3 Implications of this study upon the designs of Coastal Structures

If sufficient pressure sensors could be deployed at the remote location then it is feasible to expect considerably higher pressures and shorter rise times than those recorded. Indeed the presence of aeration, whilst attenuating some of the more excessive water wave type pressures, may actually promote Class III type bubble/air pocket collapse pressures. Class III type pressures can achieve comparable magnitude to water wave pressures and may often present a more serious threat to coastal structures with respect to erosion due to both large positive and negative pressures occurring within a short period of time.
Cavitation damage caused to ship's propellors has been well documented since 1873 [4]. Similar erosive effects may occur, however, on coastal structures due to entrapment of air bubbles by the action of breaking waves. Esche [5] measured cavitation thresholds and concluded that high frequency pressure fluctuations ( > 1MHz) were of little consequence with respect to cavitation initiation in laboratory experiments. Siroiyuk [6] suggested that in full scale situations cavitation nuclei are responsive to a much wider frequency spectrum. Laminar separation and the move to turbulent flow strongly influences cavitation inception due to the increased probability of large pressure fluctuations. Even for turbulence induced cavitation the pressure minimum must last longer than the characteristic timescale of the nucleation material (e.g., longer than the bubble period). Thus the probability of cavitation increases when moving from model to full scale situations even though the very high frequency components will affect the threshold pressure.

It is far easier to initiate shock waves in air than in water and results indicate that Class II and Class III events occur with approximately equal probability, whereas laboratory-generated impacts are principally Class II water wave events.

Coastal and weather conditions determine whether a stretch of coastline will experience impacts due to swell or wind waves or indeed both. Wind waves or spilling breakers impacting on coastal structures tend to result in Class II(b) compression type impacts. Although the peak pressures achieved by compression impacts are less than those from shock waves, the period of impact is much greater, typically one to three orders of magnitude greater (see time results in Tables 7.1 to 7.8). Owing to the prolonged time of impact for compression waves, resonance effects may be initiated in coastal structure components with resonance frequencies in the range 2 to 20 Hz.

It is unlikely that Class II(c) shock waves would generate resonance effects in structures due to their short durations (typically < 20mS). However the damage resulting from shock waves would be of the form of cracks developing in structures with attendant structural weakening or of the form of a direct lifting force upon such members as armour units (see Figure 7.46) similar to that experienced at Plymouth Breakwater in January 1990 [7].

The extremely high tangential velocities associated with shock waves (see Chapter 1.3 Taylor's jet impact model) would also result in frequent overtopping of coastal structures.

Damage resulting from Class III type impacts would be similar to that effected by Class II(b) shock waves. It is unlikely, except when large air pockets in excess of 30cm diameter are trapped, that resonance would occur in structures. Rather the structure would be eroded and thus weakened by rapid pressure fluctuations similar to cavitation damage. Alternatively for very rapid bubble collapse, lifting forces may be generated in the structural members.

For all types of impact on coastal structures, some energy is absorbed by the
structure, some is dissipated in bubble production and heat generation whilst the rest is reflected back into the sea.

Concrete coastal structures present an acoustic mismatch to the encroaching wave and any absorbed energy travels faster in the structure with potentially damaging consequences. If the impulse is of sufficient velocity it may generate stress waves in the structure which may cause instability and eventual collapse.

Sea defences on the Dutch Island of Goeree-Overflakkee are comprised of sand asphalt bases and bitumen coated sea walls [7]. This type of structure is more acoustically matched to seawater than concrete, consequently more energy is absorbed by the structure. The speed of sound in the bitumen coated structure is less than that for a solid concrete i.e., ground wave propagation is slower and less deleterious to the structure as a whole.

If coastal structures were coated with such a polymer or natural vegetation with similar acoustic properties (speed of sound and density) to sea water then some of the effects to structures caused by wave impacts as characterised in 8.1.2 might be minimised.

Many of Britain's coastal defences were designed and constructed in the last century. Even as far back as 1941 promenade designs were questioned such as that at Scarborough [9]. British coastal defence planning was revised after the 1953 flooding with considerable success in the light of storm surges of 1978 which were of greater magnitude than those of 1953. Storm surges of recent years have, however, caused considerable damage such as at Towyn [10], Porthleven [11] and other locations [12–15].

Many coastal engineering soft defence solutions now involve extensive use of vegetation since it is both salt water tolerant and capable of absorbing wave energy and studies have been undertaken [16–19] but no evidence is available to indicate whether or not the acoustic properties of vegetation have been examined.

8.2 FUTURE INVESTIGATIONS

8.2.1 EXPERIMENTAL ARRANGEMENTS

The aeration levels obtained from the impedance gauge are typically upper limits and are heavily dependent upon the Maxwell criteria being met. Future aeration measurements might be based upon acoustic or optical methods which not only provide void fraction information but also afford valuable information about the size of bubbles in the fluid which can be of equal if not greater importance to the void fraction data itself. Acoustic techniques proved useful in the laboratory. Thus if the existing acoustic parametric arrangement could be adapted for hostile conditions by the
use of a more robust and perhaps lower centre frequency transducer along with adequate filtering, then a bubble size profile could be established.

The use of an acoustic listening device would confirm whether or not collapsing plunging breakers do oscillate whilst collapsing or if some other mechanism is causing the oscillation as discussed in Section 7.4. Farmer et al [20] considered it essential to be able to measure bubble size and near surface circulation patterns and consequently developed appropriate instrumentation. Their experimental arrangement for deployment at sea comprised active sonar transducers for bubble size measurement coupled with positive hydrophones for detection of wave breaking events. Future acoustic investigations at sea could be modelled upon such an arrangement.

A small optical probe was made to investigate sizing by light scatter in the laboratory. It was only an exploratory investigation thus no detailed results are included in the text. A laser light scatter technique was also looked at briefly as a means of measuring tangential velocity and the technique was videoed—A measure of normal and tangential velocities in the vicinity of the pressure sensor is essential in order to confirm that the Taylor's model is appropriate, so some form of light scatter arrangement would be apposite for confirmatory measurements.

The final modification should be the addition of extra pressure sensors so that a spatial profile might result rather than the spot pressures measured by the device deployed in this investigation, thus affording more representative peak pressure data.

A proposed suite of instruments for measuring pressure, aeration, void fraction and bubble size and water velocity is shown in Figure 8.3

8.2.2 SITE DEPLOYMENT

The principal advantages of using the sea wall at Fort Bovisand for measurements were its proximity to Plymouth, access to mains power and shelter for the data logging equipment. The location was not perfect from an impact viewpoint due to the abundance of rocks in front of the wall acting as a diffraction grating. It is advisable to diversify locations for future measurements and deploy the chosen measuring system on a breakwater perhaps on cob or shed units in a manner similar to that of Hydraulics Research at La Colletle Breakwater [21]. Potential deployment sites in the UK are given in Appendix F, covering both sea and freshwater locations and with respect to coastal defences both nominally hard and soft sites, along with some of the current coastal zone management procedures.

It has been suggested [22] that the areas most vulnerable to erosion resulting from sea level rise and the attendant increase in storm surges around the U K are
(i) S W Peninsula
(ii) West coast of Scotland and Western Isles
(iii) Northern extremities of Northern Ireland
(iv) S W Eire
(v) South and East coasts of England from Hampshire to South Norfolk

Clearly there is scope for investigations such as described in this thesis to be conducted at various locations around the U K coastline. This is imperative when it is considered that many computer models for damage resulting from storm surges assume that coastal engineering structures remain intact [23].

The final aspect of future work which should be addressed is the possibility of measuring wave impacts on seagoing vessels and offshore structures (here impact pressures could have been limited by growth of vegetation around the structure [24]). Many vessels, especially flat sided bulk carriers, have been lost in stormy seas due to structural weaknesses. One potential reason for the losses is wave impacts or air pocket oscillation and collapse resulting from resonance vibration of a plate at its fundamental frequency or a harmonic. Such an investigation would open up entirely new possibilities since nearly all waves in question would be of the deep water variety.
FIGURE 8-1(a) SCALING FROM 10cm MODEL WAVE TO 1m FULL SCALE SHOCK WAVE; IMPACT ANGLE 1°.
FIGURE 8-1(b) SCALING FROM 10cm MODEL WAVE TO 1m FULL SCALE SHOCK WAVE; IMPACT ANGLE 2°.
FIGURE 8-1(c) SCALING FROM 10cm MODEL WAVE TO 1m FULL SCALE SHOCK WAVE; IMPACT ANGLE 3°.
FIGURE 8-2. RELATIVE influences of all scaling parameters when scaling from model to full scale water wave impact.
FIGURE 8.3 PROPOSED SUITE OF INSTRUMENTS FOR CHARACTERISING WAVE IMPACTS FULLY.
REFERENCES - CHAPTER 3.


APPENDIX A. FLOW CHART FOR PROGRAM TO DETERMINE THE ATTENUATION & SCATTERING OF SOUND DUE TO THE PRESENCE OF BOTH RESONANT & NON-RESONANT AIR BUBBLES & TO DETERMINE THE MEAN VOID FRACTION.

USER ENTERS INITIALISATION PARAMETERS - TEMPERATURE; MEAN WIDTH OF BUBBLE CLOUD; SALINITY; MEASUREMENT DEPTH.

CALCULATE AMBIENT VALUES OF: SURFACE TENSION; PRESSURE; VISCOSITY; FLUID DENSITY; THERMAL DIFFUSIVITY.

READ IN BUBBLE SIZE PROBABILITY DENSITY DISTRIBUTION DATA

READ IN ATTENUATION DATA DUE TO THE PRESENCE OF BUBBLE CLOUD

CALCULATE THERMAL DAMPING EFFECTS BASED ON CALCULATIONS BY CLAY & MEDWIN & BY NISHI

CALCULATE THE NATURAL BUBBLE RESONANCE FREQUENCY BASED ON MINNAERT

CORRECT RESONANCE FREQUENCY VALUES FOR THERMAL PHASING

CALCULATE THERMAL DAMPING FACTOR FOR BOTH RESONANT & NON-RESONANT BUBBLES
CALCULATE VISCous DAMPING FACTOR FOR BOTH RESONANT & NON-RESONANT BUBBLES

CALCULATE RADIATIVE DAMPING FACTOR

SUM ALL DAMPING COMPONENTS TO GIVE TOTAL DAMPING FACTOR

EVALUATE DIPOLE SCATTERING CONTRIBUTION TO TOTAL EXTINCTION CROSS SECTION

EVALUATE TOTAL EXTINCTION CROSS SECTION SUMMING MONOPOLE SCATTERING & ABSORPTION & DIPOLE SCATTERING CONTRIBUTIONS

CALCULATE BUBBLE NUMBER DENSITY

CALCULATE TOTAL VOLUME OCCUPIED BY GAS

MULTIPLY BUBBLE NUMBER DENSITY BY TOTAL VOLUME TO GIVE MEAN VOID FRACTION

OUTPUT DATA: MEAN VOID FRACTION; SCATTERING & EXTINCTION CROSS SECTIONS & MEAN DAMPING FACTOR
APPENDIX B. FLOW CHART FOR PROGRAM TO DETERMINE WATER WAVE IMPACT CLASSIFICATION (SHOCK OR COMPRESSION)

THE MODEL ASSUMED IS INCOMPRESSIBLE WITH RESPECT TO PEAK PRESSURE BUT WAVE PROPAGATION THROUGH THE BUBBLY FLUID IS ASSUMED TO FOLLOW AN ADIABATIC OR ISOTHERMAL COMPRESSION LAW

USER ENTERS EMPIRICAL VALUES OF NORMAL WAVE CELERITY & PEAK IMPACT PRESSURE THEN Chooses AN INITIAL VALUE FOR THE IMPACT ANGLE AS THE WAVE STRIKES THE GAUGE/STRUCTURE

USER DECIDES WHETHER OR NOT THE BUBBLES PRESENT IN THE FLUID ARE 'SUFFICIENTLY SMALL' FOR ISOTHERMAL COMPRESSION

USER SELECTS THE RANGE OF BUBBLE SIZES; VOID FRACTION & IMPACT ANGLES OVER WHICH THE PROGRAM WILL BE STEPPED

ACOUSTIC MACH NUMBER CALCULATED

IF ACOUSTIC MACH NUMBER > 1 FOR CHOSEN SPECIFIC HEATS RATIO (ISOTHERMAL OR ADIABATIC) THEN SHOCK WAVE ROUTINE SELECTED

AS ABOVE WITH ACOUSTIC MACH NUMBER < 1

COMPRESSION WAVE ROUTINE SELECTED

UPSTREAM & DOWNSTREAM DENSITY/PRESSURE RATIOS CALCULATED
I

THERMAL & VISCOUS DAMPING CONTRIBUTIONS CALCULATED

LIQUID/GAS DENSITY RATIO CALCULATED

IMPACT RISE TIME CALCULATED FROM QUADRATIC EQUATION INVOLVING PRESSURE & DENSITY RATIOS AND REYNOLD'S & PRANDTL NUMBERS

SHOCK WAVE ROUTINE SELECTED

SHOCK WIDTH CALCULATED

EXPONENT EVALUATED IN EXPONENTIAL PRESSURE - TIME CURVE

LIMITING VALUE OF IMPACT RISE TIME OBTAINED AS RATIO OF SHOCK WIDTH / SHOCK VELOCITY

COMPARE CALCULATED IMPACT RISE TIME WITH MEASURED VALUES TO OBTAIN ALLOWED VALUES OF MEAN BUBBLE SIZE & OR VOID FRACTION FOR THE WATER COMPRESSION / SHOCK WAVE IMPACT
Listed below are the components for characterising shock/compression water waves with non-zero void fractions as discussed in Chapter 3.

Conservation of momentum & energy results in the need to solve the following:

\[
\frac{dP_g}{dx} - A \frac{dP_g}{dx} - B = 0
\]

\[
\frac{dP_i}{dx} - C \frac{dP_g}{dx} - D = 0
\]

The limiting shock wave case is given in equation (3-43). The coefficients for the compression wave case as listed in equations (3-44) to (3-47) are:

\[A = \gamma \frac{P_g}{\rho_g}\]

\[B = (\gamma - 1) \frac{Q_1}{(V_b u_u)}\]

\[C = 500 \ u_u^2 \ (1 + 1/2 \ \rho_i \ u_u^2 \ (\beta/P_s + [1 - \beta]/(2P_s - P_o)))\]

\[D = 3 \ \rho_i \ u_u^2 \ Q_2 \ (\bar{R} \ (1+1/2 \ \rho_i \ u_u^2 \ (\beta/P_s + [1 - \beta]/(2P_s - P_o)))\]

where \(Q_1 \propto \) Prandtl number \(\times\) Reynolds number (thermal effects) and

\[Q_2 \propto 1/\text{Reynolds number} \ (\text{viscous effects})\]
\[ a_0 = 7.42 \times 10^{-17} \frac{P_{\text{max}}}{R c_i^2} \]

\[ a_1 = 1.85 \times 10^{-3} \left( 1 + 357.14 \frac{c_i^2}{R} \right) \left( \frac{R}{c_i} \right) + 891301 \left( \frac{P_{\text{max}} + 101325}{c_i} \right) - 0.35714 \left( 1 + 357.14 \frac{c_i^2}{R} \right) \left( \frac{R}{c_i} \right) - 0.031 \frac{u_{\text{eff}}^2}{c_i} \]

\[ a_2 = 4666842 \left( 1 + 1/2\beta/\{1-\beta\} \right) \left( 1 - \{u_{\text{eff}}/c_i\}^2 \right)/c_i^2 \]

\[ b_0 = 7.42 \times 10^{-17} c_i^2 \tau^2 / R \]

\[ b_1 = (1.85 \times 10^{-3} \left\{ 1 + 357.14 \frac{c_i^2}{R} \right\} / R - 0.031 \frac{u_{\text{eff}}^2}{c_i} \tau + 7.52 \times 10^{-12} c_i^2 \tau^2 / R + 4666842 \left( 1 + 1/2\beta/\{1-\beta\} \right) \left( 1 - \{u_{\text{eff}}/c_i\}^2 \right)/c_i^2 \]

\[ b_2 = 1.8745 \left\{ 1 + 357.14 \frac{c_i^2}{R} \right\} / R - 3141 \frac{u_{\text{eff}}^2}{c_i} \tau + 4666842 \left( 1 + 1/2\beta/\{1-\beta\} \right) \left( 1 - \{u_{\text{eff}}/c_i\}^2 \right)/c_i^2 + 8.913 \times 10^5 / c_i - 0.4036 c_i / R \]
The mathematical description of an electrical field or temperature field in two dimensions is identical. Using this fact a representative field containing two poles was set up and analysed using a FEM with two dimensional thermal elements. For a full description of this program see the relevant PAFEC manual.

This two dimensional study could also be taken as representative of what happens in a plane normal to the one analysed thus giving an indication of the actual three dimensional field.

The nodes were taken as points whereas the actual nodes are bolt heads. What effect this will have on the distribution is not clear but is not thought to be significant.
## APPENDIX E. TIDAL DATA FOR BOVISAND FIELD TRIALS.

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APPENDIX F. UK SITES SUITABLE FOR IMPACT PRESSURE/AERATION MEASUREMENTS.
Concrete blockwork at Aberdeen, UK

Smooth concrete slope with wave return wall at Lowestoft, UK

Construction of stepped concrete wall at Burnham-on-Sea, UK
Rock armour at Aith, Shetland Islands, UK

Installation of grout mattresses at Portsmouth, UK

Shed armour at Bangor, Northern Ireland

Seawall at mid-tide, Skegness, UK

Vertical masonry wall at Ventnor, UK