MEASUREMENT OF PARAMETERS AFFECTING SLAMMING
FINAL REPORT
Supported by the Department of Energy through the Offshore Energy Technology Board

Report No. 440
February, 1980
MEASUREMENT OF PARAMETERS AFFECTING SLAMMING

Supported by the Department of Energy through the Offshore Energy Technology Board

Wolfson Unit for Marine Technology Report No. 440
Technology Reports Centre No. OT-R-8042

Prepared by
I.M.C. Campbell
P.A. Weynberg

© Crown Copyright 1980
Reproduction of Crown Copyright material is permitted provided that the source is acknowledged. Further copies may be obtained from the Wolfson Unit for Marine Technology, Southampton University.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>SECTION</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDEX OF FIGURES AND TABLES</td>
<td>2</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>4</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>5</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>6</td>
</tr>
<tr>
<td>BACKGROUND TO THE PROBLEM</td>
<td>8</td>
</tr>
<tr>
<td>Experimental approach</td>
<td>8</td>
</tr>
<tr>
<td>Theoretical approach</td>
<td>8</td>
</tr>
<tr>
<td>DESCRIPTION OF TEST RIG AND INSTRUMENTATION</td>
<td>10</td>
</tr>
<tr>
<td>DESCRIPTION OF TESTS AND METHOD OF ANALYSIS</td>
<td>11</td>
</tr>
<tr>
<td>Slam description</td>
<td>11</td>
</tr>
<tr>
<td>Velocity measurements</td>
<td>11</td>
</tr>
<tr>
<td>Pressure measurements</td>
<td>11</td>
</tr>
<tr>
<td>Horizontal impact tests – Smooth cylinders</td>
<td>12</td>
</tr>
<tr>
<td>Spanwise pressure measurements</td>
<td>12</td>
</tr>
<tr>
<td>Circumferential pressure measurements</td>
<td>12</td>
</tr>
<tr>
<td>Force measurements</td>
<td>12</td>
</tr>
<tr>
<td>Inclined impact tests – Smooth cylinders</td>
<td>14</td>
</tr>
<tr>
<td>Pressure measurements</td>
<td>14</td>
</tr>
<tr>
<td>Force measurements</td>
<td>14</td>
</tr>
<tr>
<td>Fouled cylinder tests</td>
<td>15</td>
</tr>
<tr>
<td>Disturbed water tests</td>
<td>15</td>
</tr>
<tr>
<td>Aerated water tests</td>
<td>16</td>
</tr>
<tr>
<td>Double K-frame tests</td>
<td>16</td>
</tr>
<tr>
<td>Model structure tests</td>
<td>17</td>
</tr>
<tr>
<td>Description of test rig</td>
<td>17</td>
</tr>
<tr>
<td>Calibration</td>
<td>18</td>
</tr>
<tr>
<td>Strain measurements</td>
<td>18</td>
</tr>
<tr>
<td>DISCUSSION OF RESULTS</td>
<td>21</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>25</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>26</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>27</td>
</tr>
<tr>
<td>TABLE 1</td>
<td></td>
</tr>
<tr>
<td>TABLE 2</td>
<td></td>
</tr>
<tr>
<td>FIGURES</td>
<td></td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>I Strip theory of inclined impact</td>
<td></td>
</tr>
<tr>
<td>II Dynamic analogue of slam response</td>
<td></td>
</tr>
<tr>
<td>III Details of marine fouling of test cylinders</td>
<td></td>
</tr>
</tbody>
</table>
INDEX OF FIGURES AND TABLES

Figure No.
1. Diagram of test rig
2. Block diagram of path of signals through instrumentation
3. Typical velocity records from smooth cylinder tests
4. Typical pressure records
5. Circumferential spray root rise from pressure measurements
6. Circumferential pressure distributions
7. Spanwise pressure distributions from horizontal impacts
8. Pressure histories at cylinder midspan for various inclinations
9. Pressure histories at cylinder ends for various inclinations
10. Typical force records from a smooth cylinder
11. Analogue force record
12. Typical force records from a fouled cylinder
13. Typical force records from a smooth cylinder slammed into disturbed water
14. Typical force records from a smooth cylinder slammed into aerated water
15. Typical force records from a double K-frame
16. Horizontal impact loads from measurements on smooth cylinders with inclined impact loads from strip theory
17. Inclined impact loads from force measurements on a smooth cylinder
18. Horizontal impact loads from force measurements on fouled cylinders with inclined impact loads from strip theory
19. Inclined impact loads from force measurements on fouled cylinders
20. Impact loads from force measurements on a smooth cylinder slammed into disturbed water
21. Typical impact loads from force measurements on a smooth cylinder slammed into aerated water
22. Peak impact loads from force measurements on a smooth cylinder slammed into aerated water
Figure No.

23. Nominal horizontal impact loads from force measurements on a double K-frame

24. Inclined impact loads from force measurements on a double K-frame

25. Interference impact loads for a double K-frame from differences between force measurements (Fig. 24) and strip theory

26. Diagram of model structure test arrangement

27. Typical strain records from a model structure

28. Computed static bending moment coefficients for $\theta = 1^\circ$ inclined impact with the spray root at various positions

29. Computed static bending moment coefficients for inclined impact with the spray root at various positions.

30. Static bending moment distributions from strain measurements on a model structure at various inclinations - 1st fixity fundamental mode

31. Static bending moment distributions from strain measurements on a model structure at various inclinations - 2nd fixity fundamental mode

32. Dynamic magnification factors from model structure tests and a dynamic analogue

33. Static bending moment distributions from strain measurements on a model structure at various inclinations - 1st fixity higher frequency modes

34. Static bending moment distributions from strain measurements on a model structure at various inclinations - 2nd fixity higher frequency modes

35. Geometry of inclined impact

36. Dynamic analogue of experiment

Table No.

1. Results from calibrations on model structures

2. Frequencies and fixities from model structure tests
SUMMARY

Experiments were conducted to measure pressures, forces and strains when cylinders slammed into water. Horizontal and inclined impacts were investigated for smooth and marine fouled cylinders and for the intersection of a framework of cylinders. Tests were also conducted in disturbed and aerated water.

The hydrodynamic load histories were determined and it has been shown that strip theory, simple bending theory and single degree of freedom dynamic analogues can be used to provide good estimates of the response of structures to slam loading.
NOMENCLATURE

A, B, C  Constants

c  Damping coefficient  \( C_p = \frac{p}{\frac{1}{2} \rho V^2} \)

\( C_p \)  Slam pressure coefficient  \( C_p = \frac{p}{\frac{1}{2} \rho V^2} \)

\( C_{pA} \)  Slam air pressure coefficient  \( C_{pA} = \frac{p_A}{\frac{1}{2} \rho A V^2} \)

\( C_s \)  Slam force coefficient - horizontal impact  \( C_s = F_s / \frac{1}{2} \rho V^2 LD \)

\( C_{sB} \)  Bouyancy contribution to slam coefficient

\( C_{si} \)  Slam interference force coefficient  \( C_{si} = F_{si} / \frac{1}{2} \rho V^2 D^2 \)

\( C_{so} \)  Slam force coefficient - inclined impact

D  Cylinder diameter

E  Young's modulus

\( F_s \)  Slam force

\( F_{si} \)  Interference contribution to slam force - K-frame

\( F_{so} \)  Slam force for constant impact velocity

k  Stiffness coefficient

\( K_d \)  Dynamic magnification factor  \( K_d = \text{peak dynamic response/peak static response} \)

\( K_m \)  Bending moment coefficient  \( K_m = \text{moment}/F_s L \)

KE  Kinetic Energy

L  Cylinder length

m  Hydrodynamic added mass

\( m_0 \)  Hydroelastic added mass

\( m_2 \)  Effective mass of test cylinder

\( m_1 \)  Effective mass of test rig

\( N_F \)  Froude number

p  Natural frequency

\( t \)  Time from start of slam on an element of a cylinder

\( t_1 \)  Time from start of slam on a cylinder

\( t_r \)  Rise time to peak slam force
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>Slam velocity oscillating component</td>
</tr>
<tr>
<td>U</td>
<td>Slam velocity normal to water surface</td>
</tr>
<tr>
<td>U₀</td>
<td>Slam velocity constant component</td>
</tr>
<tr>
<td>Γ</td>
<td>Slam speed component of U normal to cylinder</td>
</tr>
<tr>
<td>x,y,z</td>
<td>Rectangular cartesian coordinate</td>
</tr>
<tr>
<td>z'</td>
<td>Immersion of cylinder</td>
</tr>
<tr>
<td>z₁,₂</td>
<td>Oscillatory displacements of test cylinder rig</td>
</tr>
<tr>
<td>β</td>
<td>Half angle subtended by water plane intersection at centre of cylinder</td>
</tr>
<tr>
<td>θ</td>
<td>Angle of entry of inclined cylinder</td>
</tr>
<tr>
<td>ρ</td>
<td>Mass density of water</td>
</tr>
<tr>
<td>σ</td>
<td>Standard deviation of normal distribution</td>
</tr>
</tbody>
</table>
INTRODUCTION

The following report describes the programme of work to measure parameters affecting slamming which was initiated by Agreement numbered OT/F/309 from the Department of Energy through the Offshore Energy Technology Board.

The work followed experiments conducted under the ONSLAG 2A programme and described by Campbell et al (1977).
BACKGROUND TO THE PROBLEM

Experimental approach
Slam loading is of a transient nature, and in the case of horizontal cylinders the load rises suddenly. This makes measurement of the hydrodynamic load and pressure histories difficult, since they are masked by the transducer responses. The force and pressure measurements require careful analysis if accurate estimates of the slam loads are to be obtained, as some induction is inherent in the process. Also during wave impact slamming, buoyancy, drag and inertia loads successively act on a body and experiments can only provide a measure of the resultant load history. Miller (1977) has considered the loading regimes and concluded that slamming loads predominate for Froude numbers greater than 0.6. Also (in 1979) he has reviewed the results of eleven slam experiments. These lack complete agreement, and some show considerable scatter in the data. Several experimenters have attributed the scatter to an indeterminate rise in the slam load associated with unknown inclinations of the cylinder axis at impact. Tests using generated waves are particularly susceptible to this problem and may also suffer because of an inability to reach high Froude numbers which thereby makes it difficult to isolate the slam load from the resultant load. High Froude numbers can be achieved with drop tests; however the problem then becomes one of obtaining a high enough response frequency from the force transducers in order to follow the fast rise and decay of the slam load. Furthermore, as Froude numbers and response frequencies increase, smaller misalignments affect the response, and even $\theta = 5^\circ$ was found to be significant in the present series of tests. Hence, any slam experiment requires careful design if accurate measurements are to result.

Theoretical approach
Mathematical theories have unfortunately produced a variety of results, not only for the well discussed initial slam coefficient, but also for the subsequent decay. The discrepancies are due to differences in assumptions, but their effect appears to have proved difficult to quantify in the absence of experimental evidence. Moran (1965) in his review of theories has considered most of the analytical potential flow solutions as well as numerical methods and the analysis of effects from variable entry speed, gravity, water compressibility, and air density.

He noted that all conventional solutions had sources of error. Briefly, Wagner's "wetting correction" to the free surface shape, applied by Schnitzer and Hathaway (1953) to cylinders, doubled the initial slam load predicted by Von Karman (1929) using added mass considerations and linearised theory; however, flat plate fitting to body boundary conditions involved singularities at the spray root. These were avoided by Fabula (1957) using ellipse fitting, but there remained, as a result of the linearised theory, a singularity at the point of impact. Chou's method (1946), applied by Fabula and Ruggles (1955) to cylinders, also yielded a non-singular pressure at the spray root and satisfied the dynamic free surface boundary conditions, but ignored the kinematic free surface boundary condition.
The analysis of some of the more recent slam investigations has in part been based on the foregoing theories. Miller (1977) considered the effect of rise times on structural response by extending Von Karman’s analysis to inclined impact, and used this as an input to a dynamic analogue with which he compared his experimental results. Sarpkaya (1978) considered the effect on slam load of velocity changes during wave passage using the added mass of a circular arc lens given by Taylor (1930). He also checked his experimental results against a dynamic analogue. Faltinsen et al (1977) extended Fabula and Ruggles’ method using slender body theory to fit the body boundary conditions. However, the predicted slam load was less than that found in experiments by Sollie, quoted in the same paper. The predicted slam load was then used in calculations on the dynamic structural bending of cylinders, and the results were compared with experiments, but again discrepancies were found. Arhan et al (1978) sought to correlate the slam impulse from experiments with cylinder size and velocity, but without success.

So it appears that investigators have failed to confirm the accuracy of any particular slam theory, and in some cases have resorted to assuming the fit of a theory in order to unravel their experimental data. This indicates the difficulties involved in correlating hydrodynamic loads with transient responses measured in experiments.
DESCRIPTION OF TEST RIG AND INSTRUMENTATION

The tests were conducted on a development of the rig used by the Wolfson Unit for the OSFLAG 2A experiments described by Campbell et al (1977). A diagram of the test rig is given in Figure 1. The rig was stiffened and a light alloy cylinder used to improve the frequency response of the force transducers.

Investigations revealed that:

i) the vibration response of the test rig was of a complex distributed and lumped mass nature;

ii) it was difficult to improve the frequency response of the rig although the heave response, measured through the force transducers, was increased by approximately 100 Hz to 550 Hz;

iii) changes in the force transducer stiffness had little effect on their frequency response.

The test rig was also modified to allow the 4in diameter test cylinder with attached force transducers to be inclined to the water surface at angles up to \( \theta = 15^\circ \) with an accuracy of \( \pm \frac{1}{2}^\circ \).

In the OSFLAG 2A tests, spanwise pressure measurements had shown a disturbance from the end plates, so test cylinders for the programme described herewith were left with plain ends. The cylinders were also machined round, since a check on those used for the OSFLAG 2A tests had shown them to be slightly bowed.

The Kulite XTMS pressure transducers were of the type previously used, but a velocity inductance transducer was installed in place of the rotary displacement potentiometer. This transducer gave good resolution with no significant noise, and the typical records, shown in Figure 3, indicate the velocity fluctuations through a slam.

The instrumentation was as used for the OSFLAG tests except that hard copies of data from the digital transient data stores were recorded on an X-Y plotter. Also, some of the model structure data was transferred to a PET microcomputer and stored digitally on magnetic tape. A block diagram of the instrumentation is given in Figure 2.
DESCRIPTION OF TESTS AND METHOD OF ANALYSIS

The experimental procedures adopted were similar to those used in OSFLAG 2A tests, but the data analysis was somewhat refined.

Slam description
A high speed film was taken at 1,000 frames/sec of a cylinder slamming without end plates. This showed two steadily rising sheets of water projecting out from the spray roots on either side of the cylinder, but with little disturbance from the ends. An underwater view showed that after approximately half immersion streams of bubbles formed along the cylinder, apparently from discrete points, indicating cavitation or ventilation. Measurements from pressure transducers indicated that the initial rise of the spray root was approximately twice that of static water level penetration. Faltinsen et al (1977) also reported photographing slamming and found the top of the cylinder to be dry at full water level penetration, but described the sheet spray as waves.

Velocity measurements
The improved measure of velocity showed that the mean value changed by approximately 5% during the slam period up to a value of Ut/D = 1, although in the case of horizontal impact tests a constant mean velocity was achieved during the initial slam period to Ut/D = 0.4. Superimposed on the mean velocity were small oscillations reflecting the vibration of the test rig. The instantaneous value of the mean velocity was used in normalising the measured forces and pressures to coefficient form, and this reduced the scatter in the data as immersion increased.

Pressure measurements
Records were typically of 5-20ms, enabling phase and rise times to be determined to 5us. The pressure transducers were statically calibrated following each test series and were occasionally found to have changed sensitivity by up to 15% possibly as a result of gauge slip. Prior to each test the cylinder was wiped dry as drips were found seriously to affect the response. The water was also checked to be free from surges of greater than 0.005in amplitude.

Accurate measurements of the rise of the spray root were possible from the phase of the rise in the pressure transducer response. The results in Figure 5 were recorded with an accuracy of ±0.0002 Ut/D, and the scatter at very early immersions may be attributable to small initial disturbances in the water surface or to a depression from air cushioning.

The pressures from transducer measurements at the bottom of a cylinder, $\beta = 0^\circ$, were characterised by a slight initial rise, \( C_{P_A} < 26 \), followed by a rapid rise to the peak within 20us. The initial rise was also noted by Arhan et al (1978) and was attributed to air cushioning. Measurements from transducers further around a cylinder at $\beta = 6-30^\circ$ showed no initial rise, but exhibited increasing rise times, due to the passage of the spray root across the transducer diaphragm.
Whilst analysed results from a particular series of transducer measurements exhibited little scatter, as evidenced in Figures 8 and 9, considerable differences were found between the results from similar tests with different transducers. The differences in mean levels for the data presented are within ±15% and have been attributed to:

1) the low output (< 10% rated) from the transducer following the rapid decay during the spray root passage;

2) zero drift from thermal effects following impact;

3) long term changes in transducer sensitivities.

Thus, comparison of absolute pressure measurements was considered unreliable after immersions of Ut/D > 0.036, although the relative pressures presented should be valid beyond this immersion.

**Horizontal impact tests - smooth cylinders**

**Spanwise pressure measurements** These are presented in Figure 7 and indicated that there was no serious pressure variation up to 4% span from each end of the cylinder. Also, the phase of the pressure rise confirmed that alignment could be made to $\theta = \pm \frac{\pi}{4}$.

**Circumferential pressure measurements** These were made at positions of $\theta = 0^\circ$, $6^\circ$, $12^\circ$, $18^\circ$, $24^\circ$ and $30^\circ$ and at three impact speeds. The responses were similar to those measured in the OSFLAG tests, and oscillations in the decay were smoothed by curve fitting prior to normalising to coefficient form (as shown in Figure 4). The 36 normalised pressure histories were cross plotted in Figure 6. Even though small pressure transducers were used, the diaphragm size proved to be too large to enable resolution of the pressure distribution close to the spray root, where both the experimental results and predictions of Wagner (1931) and Fabula (1957) indicated rapid changes. The peak pressure could only be estimated from the mean pressure on the transducer diaphragm when it was fully wetted.

The faired pressure distributions in Figure 6 were integrated graphically to produce an estimate of slam load, and the results given on Figure 16 indicate the fairness of the distributions.

**Force measurements** The change to a cylinder without end plates also affected the force records which showed a sharp rise on impact, as evidenced in Figure 10, instead of a slower initial rise observed in the records from the OSFLAG tests.

The responses from the force transducers exhibited oscillations associated with the vibration of the test rig, as can be seen in Figure 10. These responses varied in character depending on the condition of the test, although there was a dominant oscillation at approximately 550 Hz, and generally higher frequency oscillations superimposed. In some instances
long cycle beating was observed, and care was required when comparing with analogue responses to distinguish between beat decay and damping.

The tests were at Froude numbers from 1.9 to 5.6 and Reynolds numbers from 0.8 to $4.4 \times 10^5$, with and without end plates, but no correlation was found between these parameters and the scatter in the load histories.

Hyperbolic curves were fitted to the horizontal impact force records instead of the cubic curves used in the OSFLAG tests. The hyperbolae were fitted to match the decay of the slam force better than exponentials and did not have inflections near the start of slam as with cubics. However, a small linear correction was added in order to improve the fit over the later period of the slam. Both the data from the 4in diameter cylinders without end plates and the OSFLAG tests - on 2in, 3in, 4in and 5in diameter cylinders - were analysed and the results are given in Figure 16. The comparatively slow response of the force transducers compared with the sudden rise of the slam load caused the mean load to be least determinable over the first cycle of the vibration response, which corresponded to $Ut/D < 0.05$, and is reflected in the greater scatter in slam coefficient data at the instant of impact than at subsequent immersions, as can be seen in Figure 16. The fit of the mean curves was checked by comparing measured responses with those predicted from a dynamic analogue presented in Appendix II.

The analogue idealised the test rig as a single mass connected to a rigid test cylinder by two springs representing the force transducers.

Predictions of damping and added mass terms, associated with variable impact velocity, were included, and the response in the force transducers was compared with an input slam load applied to a cylinder. A typical result from the analogue is given in Figure 11, and it can be seen that, although the predicted response was greater than that measured, the fitted curve was close to the original input slam load. The mass ratio factor of $m_1/(m_1+m_2+m_0)$ discussed in Appendix II was applied in scaling the slam load to correct for the reduction in measured force, due to the finite rig mass. The factor, also considered by Watanabe (1933), varied from 1.065 to 1.582 and was found to improve the correlation of results from tests at different rig masses.

The maximum possible contribution of buoyancy to the slam coefficient was $\pi/2N^2 F$, i.e. $C_{SB} = 0.05$ to 0.54. However, the presence of spray root rise, sheet spray, and cavitation or ventilation, leaves doubt as to how buoyancy may be subtracted from the measured resultant load. Most previous experiments have assumed the buoyancy load to rise with the penetration of static water level, although this can only be an approximation, and, for example, in ship motion calculations corrections are made to the hydrostatic pressures for attenuation due to the presence of waves. Also, most conventional theories assume zero gravity and neglect cavitation effects, as discussed by Moran (1965), and so offer no guidance. The slam load data given in Figure 16 at immersions greater than $Ut/D = 0.6$ were derived at a Froude number of $N_F = 2.58$, with $C_{SB} = 0.24$, for which no correction has been made. The possible error in Figure 16 through neglecting buoyancy at immersions less than $Ut/D = 0.2$, when the slam load is high, is likely to be < 5%.
A single curve was fitted to the data in Figure 16 and it can be seen that this lay close to the integrated pressure data and was within the scatter of the force data.

The equation which describes this mean load history is:

\[ C_s = \frac{5.15}{(1 + 19Ut/D)} + 0.55Ut/D \]  \hspace{1cm} (1)

**Inclined impact tests - smooth cylinders**

**Pressure measurements** The pressure histories from selected transducers were compared at various inclinations to \( \theta = 8^\circ \), and the results are given in Figures 8 and 9. The oscillations in the transducer response reduced with inclination, rendering curve fitting almost unnecessary, as can be seen from Figure 4.

It can be seen from the results that there was little significant variation in the pressure histories with inclination. Exceptions were at early immersions (\( Ut/D < 0.006 \)) where the steep decay made analysis inaccurate, and at the raised end. The phase of the rise of spanwise pressures corresponded to the penetration of static water level to within 10%, and the phase of the rise of circumferential pressures was similar to those obtained from horizontal impacts, as can be seen from Figure 5.

The pressure data were therefore in agreement with the assumptions of inclined impact strip theory given in Appendix I.

**Force measurements** As the cylinder was inclined the rise of the slam load to a maximum was less sudden, until at approximately \( \theta = 15^\circ \) it could be matched by the transducer response. The subsequent oscillations in the transducer response were far less severe than in the case of horizontal impacts, and the peak slam load was easily obtained by curve fitting. At inclinations from \( \theta = 1^\circ \) to \( 15^\circ \) the peak response steadily reduced.

Slam load histories derived from measurements at inclinations up to \( \theta = 8^\circ \) are given in Figure 17. The results were obtained principally at a Froude number of \( N_F = 2.58 \), with some checks at \( N_F = 3.66 \). It can be seen that the rise in slam load was not linear and that the peak load decreased with inclination. The strip theory in Appendix I was used to compute inclined impact load histories based on the empirical result from the horizontal impact equation (1). The results are given in Figure 16 and it can be seen that there is good correlation between the measured and predicted rate of rise and peak slam loads, with slight discrepancies for rise times and rates of decay. Since the method of analysis developed gave good correlation between pressure and force data for horizontal impacts, and between strip theory and force data for inclined impacts, subsequent experiments concentrated on the measurement of forces.
Fouled cylinder tests
Two 4in diameter aluminium cylinders were fouled with slimes, soft and hard fouling and associated infauna as described in Appendix III. Whilst the fouling was still alive, force measurements were made from horizontal and inclined impacts, and typical records are given in Figure 12. The dynamic response to horizontal impacts can be seen to be less than in the case of smooth cylinders. However, at inclinations above \( \theta = 1^\circ \), where there were several vibration cycles during the rise time of the slam, the fouling tended to cause minor excitations and the dynamic response was slightly greater than for smooth cylinders. Since the fouling was light and uneven, the base cylinder diameter was used in normalising to slam coefficients. Figure 18 gives the resulting load histories from horizontal impacts, and a single curve was fitted to this data.

The equation which describes this mean load history is:

\[
C_s = \frac{4.1}{(1 + 8.3Ut/D)} + 0.45Ut/D
\]

(2)

Inclined impact load histories predicted using the above equation in the strip theory from Appendix I are also given in Figure 18. The results compare well with the load histories derived from measurements and given in Figure 19.

Disturbed water tests
The smooth 4in diameter cylinder was slammed horizontally and inclined into water disturbed by a small paddle wavemaking shown in Figure 1. The wavemaker operated at a frequency of 4 Hz and produced waves approximately 0.4in high x 4in length, with their crests at 90° to the cylinder axis. The waves reflected from the tank sides to produce an irregular short crested surface. This was intended to represent capillary and high frequency disturbances on a real sea.

Typical force records are shown in Figure 13 and it can be seen that the dynamic responses were similar to those from fouled cylinders. The disturbances caused a slower rise in the force under horizontal impacts than in the case of calm water and the dynamic response was consequently less. However, at inclinations above \( \theta = 1^\circ \) the disturbances caused minor excitations during the slam, and the dynamic response was greater than for smooth cylinders.

Mean curves were fitted to the data by the same method used for smooth cylinders and the resulting load histories are shown in Figure 20. The strip theory in Appendix I was modified by representing the surface as a half sinusoidal standing wave form, and the calm water slam load (equation 1) was used for each element. The resulting prediction for horizontal impact is given in Figure 20 and is within 19% of the load history from measurements. Comparing the shape of the rise in load with that measured, it appeared likely that the difference was due to inaccurate representation of the water surface in the strip theory.
Also shown in Figure 20 are the peak loads for inclined impact predicted by calm water strip theory, and comparison with those from the disturbed water measurements showed that rise times were within 2% and that the greatest difference in peak slam coefficient was 25% at $\theta = 8^\circ$ inclination.

**Aerated water tests**

The smooth 4in diameter cylinder was slammed horizontally and inclined into water aerated from porous pipes at the bottom of the tank, as shown in Figure 1. Tests were performed using pipes of two pore sizes giving mean bubble diameters at the surface of 0.033in and 0.060in. These sizes were chosen to be representative of aeration in ocean waves. Monohan and Zeitlow (1969) found that the peak in the distribution of bubble sizes occurred at 0.040in diameter.

The airflow was also adjusted to give air concentrations of between 1.3% and 10.5% by volume at the surface. The airflow induced a water circulation in the tank and caused a disturbed water surface with a pronounced hump under the centre of the test cylinder.

Typical force records are shown in Figure 14 and it can be seen that the dynamic response to a horizontal impact was similar to that from the disturbed water tests. However, for impacts at inclinations greater than $\theta = 1^\circ$ the slam load did not rise smoothly as in the case of calm water, and consequently the dynamic response was increased. Typical impact loads derived using the curve fitting techniques are shown in Figure 21, and the discontinuities in the rise of the impact load can again be seen.

The last peak in the rise of the impact load was taken from each load history and is shown plotted in Figure 22 at the associated rise time. The peaks from tests at all bubble sizes, air concentrations and speeds can be seen to be close to the locus of the peaks from inclined impact in calm water.

**Double K-frame tests**

Work conducted by Dr. B.L. Miller at the National Maritime Institute identified that slam loading data were required for the intersection of cylinders in frameworks.

A frame was fabricated by welding 4in diameter cylinders which intersected on three axes mutually at 60°. The double K plan form of the frame is shown in Figure 1, and can be seen to consist of four stub cylinders and a single long cylinder which was connected to the test rig via the two force transducers. The frame was fitted to the test rig such that the underside of all the cylinders impacted at approximately the same instant. Manufacturing tolerances lead to the slight differences in the timing of the slam on each cylinder. The whole frame could be inclined.

Typical force records are shown in Figure 15. Mean curves were fitted to the data by the same method used for smooth cylinders. The data were normalised using the total projected length of the frame, and the slam load histories are given in Figures 23 and 24. The force response to horizontal impacts was similar to that from tests on smooth cylinders.
However, the slam load was somewhat greater than that predicted from smooth cylinder data using strip theory to account for the slight geometrical differences between the cylinders. This result is also shown in Figure 23, and the difference was attributed to an interference between the cylindrical members of the frame. This interference slam load was normalised using the square of the cylinder diameter so as to be independent of cylinder length, and the result is given in Figure 25.

The force response from inclined impact was, as can be seen from Figure 15, rather different from previous cases. The slam load initially rose at a rate similar to that found from the smooth cylinder tests, and then, as the stub cylinders of the frame impacted, the slam load increased to give a local force response similar to that for horizontal impact. Strip theory was again applied to give an inclined impact prediction for the slam load on the frame. In this case, changes in geometry due to the rotation of the test rig arm about its pivot point were neglected. Thus the stub cylinders slammed at approximately half the inclination angle of the main cylinder. The difference between the slam load from measurements and strip theory was normalised to an interference load form, and is shown plotted in Figure 25 for each inclination tested. Since the interference load was associated with the intersection of the frame, the phase of the rise in loads was reduced to zero. This approximately corresponded to the instant of impact of the centre of the long cylinder.

It can be seen from Figure 25 that the interference load histories after $V_t/D = 0.05$ were similar. In the early part of the slam of the frame intersection ($V_t/D < 0.05$) the peak load generally reduced with inclination, although it was low for horizontal impacts. It was possible that in this case the curve fitting techniques were inadequate to identify from the force response a rapidly decaying interference load superimposed on the rapidly decaying slam load. This analysis was easier in the case of inclined impact, as the rapid rise in interference load was superimposed on a slower rising inclined impact slam load.

Model structure tests

**Description of test rig**

The arrangement of the model structures is shown in Figure 26, and consisted of a 2in diameter horizontal steel tube, 40in long, welded at each end into 4in diameter vertical tubes, bent to the radius of the test rig arm so that they penetrated the water through the same points during the slam. The vertical tubes were attached to the test rig arm via a structure made from two 6in x 3in steel channels bolted to the lead filled cross member. The whole arrangement could be pivoted about the arm for inclined impact tests.

The 2in diameter horizontal tube had a small flat, milled top and bottom, to accept foil strain gauges which were positioned longitudinally at 1%, 21%, 50%, 79% and 99% of the tube span. In addition, four gauges were fitted on the hoop axis at 50% span. The tube shape was then made good using a casting resin.

Two end conditions were tested. In the first, the horizontal tube penetrated through the vertical tubes and was welded to both walls. In the second, the outer weld was trepped away, and for these tests a
pressure transducer was fitted close to a vertical tube. This involved machining a 0.625in diameter hole through the top surface of the horizontal tube.

**Calibration** Each item of the instrumentation was separately calibrated. The model structure shown in Figure 26 was then placed in an Avery test machine, a load was applied at the centre of the horizontal tube and the outputs from the strain gauge bridges were monitored through the instrumentation. The results are given in Table 1.

Simple bending theory shows that the degree of end fixity does not affect the shape of the bending moment diagram, but causes a relative shift of the zero moment base line. Thus the absolute calibration of measured strains with simple bending theory was checked by comparing the mean strain ranges between the ends and the centre of the tube. The degree of fixity was then obtained by comparing the calibrated values of strain at the ends with theory. It can be seen from Table 1 that whilst the results from the first fixity model compare well with theory, those from the second were some 32% lower than expected and gave considerably different bending moments at the two ends where similarity was expected from symmetry. No straightforward explanation has been identified for these discrepancies, although several possibilities have been explored, namely:-

1) Some hysteresis appeared in the calibrations which might have arisen from bolt slippage in the model structure. If this were attributed to drift in the instrumentation it should then not have affected the strain results because of the short duration of the tests.

2) The pressure transducer hole could have affected the strain distribution in way of the top gauge at 1% span.

3) The ½ bridge calibrations indicated slight differences between top and bottom strains which may have been the result of axial tension. However, this would have supported a small proportion of the calibration load compared with that resisted by bending.

4) Low strains at the ends of the horizontal tube might have resulted from a complex stress field around the intersection with the vertical tubes.

**Strain measurements** Signals were recorded from the top and bottom strain gauges wired in ½ bridge form to give the bending strain at each position along the tube. At inclinations up to 40° (Vtbody/D = 0.23) the strain oscillations were essentially in phase or antiphase. The one result at 1° inclination showed that the peak strain at the raised end occurred after those at the middle and low end. In this case the dynamic response was small. As can be seen from Figures 28 and 29, the predicted static response of a beam to inclined slam load shows that the
peak strains at different positions along the beam occur at different times and indeed before the beam is fully wetted.

The dynamic strain response from each model was mainly composed of signals at two frequencies given in Table 2. The higher frequency signal was of greatest amplitude at 21% and 79% span, where the amplitude of the fundamental signal was small. There was also a sharp change of the higher frequency when the models were tested inclined. As can be seen from Figure 34 these higher frequency components decayed with inclination, and in general the dominant component of the dynamic strain response was at the fundamental frequency.

The frequency of the ringing mode of the tube measured with the four central strain gauges is also given in Table 2. The amplitude of the response was again small compared with that of the bending of the tube.

The results from the strain gauge measurements given in Figures 30 and 31 were obtained by smoothing out the response at the higher frequency and then taking the peak values. These were factored using the calibration previously discussed and normalised to bending moment coefficient form $K_m$ using the measured velocity and a peak slam coefficient from equation 1 for the inclination angle set. The dynamic magnification factor was abstracted by comparing the experimental mean strain range between the ends and centre of the tube with simple bending theory, as in the calibration. Figure 32 shows a comparison of these dynamic magnification factors with those obtained from the simple dynamic analogue presented in Appendix II. It can be seen that the dynamic magnification factors from the first fixity model were within 15% of the prediction. However, those from the second fixity model were on average 28% higher than predicted. This result was obtained after applying the calibration factor of 1.48 to the measurements. Since there is no clear physical explanation of this factor, a tolerance should be applied to the test data of the order of the difference between measurement and prediction. The measurements indicated a peak dynamic magnification factor at an inclination which gave the ratio of $2 \times \text{slam rise time/response period} = 1.25$

compared with the predicted ratio = 0.85, whereas for a simple beam with a travelling point load the peak response occurs at a ratio of 1.00.

Bearing in mind that the prediction was made using a simple spring, mass, damper analogue the correlation was good.

It can be seen from Figures 30 and 31 that the measured bending moment distribution of the fundamental mode was similar to that given by simple beam theory. In the case of the first fixity the bending moments were similar at both ends for horizontal impact, and then the bending moment increased at the raised end as the model was inclined. This effect was predicted by the simple beam calculations mentioned earlier and is demonstrated by the results in Figures 28 and 29. In the case of the second fixity there was a similar difference between the end bending moments to that identified by the calibration; however, the trend of increasing bending moment with inclination at the raised end was again apparent.
Estimations of the degree of fixity are given in Table 2. It can be seen that the second model had a lower fixity than the first. One estimate of fixity was obtained by comparing the measured fundamental frequency with that calculated, using the Rayleigh method, for a simple beam. This result was somewhat different to that obtained from the bending moment distributions. However, in the case of the second fixity the difference might be less than shown if the asymmetry in the strain measurements at the ends were not taken to indicate different bending moments at the ends. Unfortunately this point could only have been investigated by making further detailed strain measurements.
DISCUSSION OF RESULTS

It has been shown from pressure measurements along the test cylinder that horizontal impact could be achieved within $\pm 1\%$ alignment and that there was no significant end effect.

The circumferential pressure distributions (Figure 6) were considered a good estimate from the measured pressure histories because:

i) the distributions were an average of measurements taken at three speeds and from six locations;

ii) the pressure phase was accurately measured;

iii) since the transducer size prevented measurement of the peak pressure, the mean pressure over the diaphragm was used;

iv) the distributions were cross faired.

The slam loads obtained by integrating the pressure distributions were also close to a fair curve and were considered good estimates.

Analysis of the horizontal impact force responses by fitting hyperbolic curves and applying a mass ratio correction gave slam load histories with little scatter. The initial part of the slam load history was difficult to determine from force measurements, but the results from the integrated pressure distributions were within the scatter of those from force measurements.

Scatter in the slam load histories was reduced at immersions greater than $Uf/D = 0.4$ by normalising the load using the instantaneous mean impact speed. Since the tests were conducted at a relatively high Froude number, the buoyancy load was small compared with the slam load.

A single mean curve (equation I) was fitted to the horizontal impact slam load data from both pressure and force measurements. This curve was used in a strip theory (Appendix I) to predict the slam load histories for inclined impact, and showed good agreement with the slam loads from inclined impact force measurements. More confidence could be placed on the slam loads from force measurements for inclined impact than for horizontal impact since the slam load exhibited a finite rise to its peak which could be matched by the transducer response. Both the measurements and prediction indicated that the rise in the inclined impact load was non-linear. This could be attributed to the non-linear decay in the horizontal impact slam load, and so verified the use of curve fitting to horizontal impact force responses. Further verification was provided by the dynamic analogue (Appendix II).

Pressure histories were largely unaffected by inclination and the spray root moved along the cylinder at a rate which corresponded approximately to the penetration of the static water level. These results were consistent with the assumptions of strip theory.
Thus, from analysis of horizontal and inclined impact tests, the following points were established:

i) A good estimation of the slam load history - equation 1.


iii) Confirmation of strip theory predictions for inclined impact load histories.

It is worth noting the following points which emerged from the strip theory:

1. The peak slam coefficient for inclined impact occurs when the cylinder underside is fully wetted. This results from normalising the slam load by the overall cylinder length.

2. The value of the peak slam coefficient is directly dependent upon the rise time parameter $V_t/D = L\tan\theta/D$. Therefore, the inclinations shown by peaks in the test results only apply to the $L/D$ ratio of the tests.

3. The whole slam load history, and not just the initial peak, was significant in determining the inclined impact peak coefficients.

Results from tests on fouled cylinders were analysed by the same method developed for smooth cylinders. The slam load history for horizontal impact (equation 2) showed a slightly lower peak coefficient than for smooth cylinders, but a slower decay. This was again confirmed by comparing inclined impact test data with strip theory. As a result of the slower decay the peak coefficients for inclined impact were generally higher than for smooth cylinders.

The fouling caused a slight rise time to the peak load from horizontal impact, as indicated by the slow rise in the force response shown in Figure 12. Since the rise time was indeterminate it was excluded from the analysed horizontal impact data shown in Figure 18. However, this was probably the cause of the low peak coefficient as compared with smooth cylinder data. The increased peak coefficients for inclined impacts may have resulted from drag effects. Alternatively, had the results been normalised using a diameter 10% larger than that of the cylinder, the data would have been similar to that from smooth cylinders. However, the uneven and soft nature of the fouling made it difficult to identify a suitable mean diameter prior to analysis.

Disturbed water also caused a reduction in the peak load from horizontal impacts. In this case the water was rough and the cylinder smooth, whereas for fouling the situation was reversed. A similar slight rise could be seen on the force response of Figure 13. The disturbed water had little effect on the load histories from inclined impacts, which were very similar to smooth water data.
Aeration of the water also disturbed the surface, but with a wave length greater than in the disturbed water tests. However, neither the aeration nor the disturbance appeared to alter the peak slam loads significantly, as can be seen from Figure 22. The results were similar to those from calm water tests when compared at similar rise times. The rise did not necessarily correspond to the times calculated from the pre-set inclination, and this presumably resulted from differences in entry conditions at impact.

As in the cases of fouling and disturbed water, the peak loads did not reach that corresponding to horizontal impacts in calm water. Also, the force responses to inclined impact were considerably greater than those from calm water, and a series of discrete slams could be identified during the rise in load as can be seen in Figure 21.

In order to obtain the interference slam load from the double K-frame results it was necessary to assume that the slam load on each leg of the frame could be estimated from the smooth cylinder data. The foregoing discussion has indicated this to be a reasonable assumption. Sharply decaying interference loads given in Figure 25 were thus identified, and these were of similar shape for all the inclinations tested, so adding to the confidence in the data.

The aim of the tests so far discussed was to derive the hydrodynamic slam loads on cylinders. The aim of the model structure tests was rather different in that the structural response to the slam was studied and compared with simple predictions using the slam loads identified from the earlier tests. Exact comparison of measured and predicted bending strain amplitudes was not possible because of unresolved discrepancies in the calibration of the strain gauges on the models. In spite of this problem there was agreement between the strain amplitudes of the fundamental frequency of within 28% on average for the second fixity case and 15% for the first fixity. Comparison was on the following basis:

1. The measured peak strain distribution along the tube under test was normalised to bending moment coefficient form using the peak slam coefficient associated with the test inclination and a factor from static calibrations.

2. A mean dynamic magnification factor was obtained by dividing the measured mean coefficient range between the centre and ends of the tube, by that from simple bending theory for a uniformly distributed load.

3. A dynamic magnification factor was predicted from the response on a single degree of freedom lumped mass analogue, given in Appendix II, to inclined impact load histories from strip theory, given in Appendix I.
In addition to the results from the foregoing discussion other features of the structural response were identified, namely:

i) The bending moment distribution at the fundamental frequency was similar to that from simple beam theory, as can be seen from Figures 30 and 31. The bending moment at the raised end increased with inclination. This was also predicted by using a load distribution associated with inclined impact strip theory. Typical results are given in Figures 28 and 29.

ii) In inclined impacts the maximum static bending moment, i.e. that which would apply if there were no dynamic response, was shown to occur before the underside of the cylinder was fully wetted.

iii) It was difficult to specify the exact fixity of the models although this may have been partly due to the discrepancies in the calibrations.

iv) Strains also occurred at higher frequencies than the fundamental. However, these strains were at a minimum where those at the fundamental frequency were greatest. It appeared that a symmetric mode was excited by horizontal impacts and an asymmetric mode by inclined impacts. These higher frequency strains also decreased rather faster with inclination than those at the fundamental frequency.

The results from the model structure tests have shown that reasonable estimates of structural responses to slamming can be made using the data contained in this report.
CONCLUSIONS

Analysis of pressure and force measurements from horizontal and inclined impacts has shown that the slam load history for cylinders impacting horizontally with a calm water surface may be closely defined by the empirical equation

\[ C_s = \frac{5.15}{1 + 19U_t/D} + 0.55U_t/D \]  

(1)

This equation is independent of Froude number over the range tested and includes only a small but indeterminate buoyancy load contribution, which was likely to be < 5% during the initial high load phase of the slam. In cases where buoyancy load would be significant, i.e. at low Froude numbers, it would need to be added in some way to the slam load.

The slam load histories for inclined impacts can also be closely defined by applying the above equation to elements of a cylinder and integrating to find the total load, i.e. by strip theory. A typical method is given in Appendix I.

Inclined impact load histories for cylinders slammed into disturbed or aerated water were similar to those for slams into calm water, and so could be closely described by strip theory. However, secondary excitations occurred during the loading history which could produce greater dynamic structural responses than those from calm water.

The strip theory could be extended by defining the disturbed water surface to produce a load history for horizontal impacts which closely matched those measured. The resulting peak loads were less than for calm water horizontal impacts.

As in the case of smooth cylinders, the slam load histories for marine fouled cylinders when inclined could be closely defined by applying strip theory using the horizontal impact data. Similar secondary excitations were observed to those from disturbed and aerated water tests.

Load histories for the marine fouled cylinders could be predicted from the smooth cylinder data (equation 1) providing that the diameter was suitably increased in proportion to the fouling.

Tests on a double K-frame showed that an interference load was associated with the cylinder intersections. This load was in addition to that predicted using equation 1 with the total projected length of the frame. The interference load histories are given in Figure 25.

Peak strain measurements from model structures were within 28% of values predicted by both simple bending theory and the response of a single degree of freedom dynamic analogue, given in Appendix II, to horizontal and inclined slam load histories, from equation 1.
ACKNOWLEDGEMENTS

The experiments were conducted with the assistance of
Mr. J.L. Robinson.
Dr. J.F. Wellicome provided advice on theoretical aspects.

Mr. G. Swain advised on aspects of marine fouling and the
Central Dockyard, Portsmouth, gave permission for use of
the rafts at the Exposure Trials Station, Eastney.

Liaison was maintained with Dr. B.L. Miller to coordinate
with the work on slamming conducted at the National
Maritime Institute.

The project was funded by the Department of Energy through
the Offshore Energy Technology Board as part of an overall
research programme into fluid loading on offshore structures.
REFERENCES


Miller B.L. (1979) Wave slamming loads on offshore structures. N.M.I. Rep. to Dept. of Energy (to be published)


10th Annual O.T.C., Houston, Texas

N.A.C.A. TN2889

Taylor J.L. (1930) Some hydrodynamical inertia coefficients.
Phil. Mag. 9 (series 7) 161-183

Symposium on mechanics of wave-induced forces on cylinders, Bristol, U.K.

N.A.C.A. TN321

N.A.C.A. TN622

Watanabe S. (1933) Resistance of impact on water surface: Parts I-VII.
Sc. Pap. I.P.C.R., Tokyo
<table>
<thead>
<tr>
<th>1st fixity</th>
<th>X/L</th>
<th>0.01</th>
<th>0.21</th>
<th>0.50</th>
<th>0.79</th>
<th>0.99</th>
<th>0.01-0.50</th>
<th>0.01</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>theory (no end rot')</td>
<td></td>
<td>0.112</td>
<td>0.012</td>
<td>-0.132</td>
<td>0.012</td>
<td>0.112</td>
<td>0.244</td>
<td></td>
<td></td>
</tr>
<tr>
<td>measured (1/2 bridge)</td>
<td></td>
<td>0.083</td>
<td>0.008</td>
<td>-0.142</td>
<td>0.012</td>
<td>0.095</td>
<td>0.231</td>
<td>1.056</td>
<td>0.78</td>
</tr>
<tr>
<td>theory (encastré)</td>
<td></td>
<td>0.120</td>
<td>0.020</td>
<td>-0.125</td>
<td>0.020</td>
<td>0.120</td>
<td>0.245</td>
<td></td>
<td></td>
</tr>
<tr>
<td>measured (1/2 bridge)</td>
<td></td>
<td>0.036</td>
<td>-</td>
<td>-0.119</td>
<td>0.000</td>
<td>0.057</td>
<td>0.166</td>
<td>1.480</td>
<td>0.44</td>
</tr>
<tr>
<td>measured (1/2 bridge) top measured (1/2 bridge) botton</td>
<td></td>
<td>0.034</td>
<td>-</td>
<td>-0.122</td>
<td>-</td>
<td>0.052</td>
<td>0.165</td>
<td>1.485</td>
<td>0.42</td>
</tr>
<tr>
<td>measured (1/2 bridge) botton</td>
<td></td>
<td>0.038</td>
<td>-</td>
<td>-0.114</td>
<td>-</td>
<td>0.062</td>
<td>0.164</td>
<td>1.494</td>
<td>0.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2nd fixity</th>
<th>X/L</th>
<th>0.01</th>
<th>0.21</th>
<th>0.50</th>
<th>0.79</th>
<th>0.99</th>
<th>0.01-0.50</th>
<th>0.01</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured (1/2 bridge) botton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 1** RESULTS FROM CALibrATIONS ON MODEL STRUCTURES
<table>
<thead>
<tr>
<th>Model Structure</th>
<th>Measured frequency, Hz</th>
<th>Average end fixity ratio to encastre beam with uniform load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fundamental</td>
<td>higher</td>
</tr>
<tr>
<td>1st fixity</td>
<td>220</td>
<td>1200(h)</td>
</tr>
<tr>
<td>2nd fixity</td>
<td>180</td>
<td>1100(h)</td>
</tr>
</tbody>
</table>

(h) horizontal impact

(i) inclined impact

TABLE 2 FREQUENCIES AND FIXITIES FROM MODEL STRUCTURE TESTS
Block Diagram of Path of Signals Through Instrumentation
TYPICAL VELOCITY RECORDS FROM SMOOTH CYLINDER TESTS

Plot 606  \( \theta = 0^\circ \)  \( N_F = 2.6 \)

Plot 771  \( \theta = 4^\circ \)  \( N_F = 2.6 \)
Typical Pressure Records

Plot 679  $\theta = 0^\circ$  $\beta = 12^\circ$  $N_F = 2.6$

Plot 761  $\theta = 1^\circ$  $\beta = 12^\circ$  $N_F = 2.6$
CIRCUMFERENTIAL SPRAY ROOT RISE
FROM PRESSURE MEASUREMENTS

THEORIES

Wagner
flat plate

static water level

Fabula ellipse

Ut/D

(1 - cos β)

Horizontal impact data

+ σ mean

- σ

Inclined impact data

△ θ = 1°

+ 2°

○ 3°
CIRCUMFERENTIAL PRESSURE DISTRIBUTIONS

Figure 6

Faired distribution at $Ut/D = 0.006$

Mean data from pressure histories

Faired mean pressure when transducer just immersed

$0.012$

$0.018$

$0.024$

$0.030$

$0.036$

$C_p$

$\sin \beta$
SPANWISE PRESSURE DISTRIBUTIONS FROM HORIZONTAL IMPACTS

Data from pressure histories

\[ \pm \sigma \text{ mean at } N_F = 2.2, 3.1, 3.8 \]
Figure 8

Pressure Histories at Cylinder Midspan for Various Inclinations

$\beta = 6^\circ$

$\beta = 12^\circ$

$\beta = 24^\circ$

Data from pressure histories $N_r = 2.6$

Least square fits at intervals of $Vt/D = 0.006$
Figure 9

Pressure Histories at Cylinder Ends for Various Inclinations

$\beta = 12^\circ$

$C_p$

raised end $Vt = 0.006$

low end $Vt = 0.006$

Data from pressure histories $N_F = 2.6$

Least square fits at intervals of $Vt/D = 0.006$
Typical Force Records from a Smooth Cylinder

Plot 609  \( \theta = 0^\circ \)  \( N_F = 2.6 \)

Note: peak clipped by instrumentation

Plot 772  \( \theta = 4^\circ \)  \( N_F = 2.6 \)
Figure 12

Typical Force Records from a Fouled Cylinder

Plot 813  $\theta = 0^\circ$  $N_F = 2.6$

$C_S$  
(Ut = 0)

$\frac{C_S}{D}$

$0.1$ $0.2$ $0.3$ $0.4$ $0.5$ $0.6$ $0.7$ $0.8$ $0.9$ $1.0$

Plot 827  $\theta = 4^\circ$  $N_F = 2.6$

$C_{S0}$  
(Ut = 0)

$\frac{C_{S0}}{D}$

$0.1$ $0.2$ $0.3$ $0.4$ $0.5$ $0.6$ $0.7$ $0.8$ $0.9$ $1.0$
TYPICAL FORCE RECORDS FROM A SMOOTH CYLINDER SLAMMED INTO DISTURBED WATER

Plot 935  \( \theta = 0^\circ \)  \( N_F = 2.6 \)

Plot 959  \( \theta = 90^\circ \)  \( N_F = 2.6 \)
Figure 14

Typical Force Records from a Smooth Cylinder Slammed into Aerated Water

Plot 865  \( \theta = 0^\circ \)  \( N_F = 2.6 \)

3.9% of air, large bubbles

\( C_s \)  \( (Ut = 0) \)

\( C_{s\theta} \)  \( (Vt = 0) \)

Plot 882  \( \theta = 4^\circ \)  \( N_F = 2.6 \)
Figure 15

Typical Force Records from a Double K-Frame

$\frac{C_S}{D}$ (Ut = 0)

$\theta = 0^\circ$  $N_F = 3.66$

$\frac{C_S \theta}{D}$ (Ut = 0)

$\theta = 4^\circ$  $N_F = 2.6$
Horizonal Impact Loads from Measurements on Smooth Cylinders with Inclined Impact Loads from Strip Theory

Figure 16

Inclined Impact Loads from Force Measurements on a Smooth Cylinder

Figure 17
Horizontal Impact Loads from Force Measurements on Fouled Cylinders with Inclined Impact Loads from Strip Theory

Figure 18

Fitted load histories

$+\sigma$ Mean $N_F = 2.6 - 3.7$

$-\sigma$

Empirical mean line eqn(2)

Strip theory of inclined impact

Figure 19

Inclined Impact Loads from Force Measurements on Fouled Cylinders

Fitted load histories

cylinder 1 $N_F = 2.6$

cylinder 1 $N_F = 3.7$

cylinder 2 $N_F = 2.6$

Peaks from strip theory
Impact Loads from Force Measurements
on a Smooth Cylinder Slammed into Disturbed Water

Fitted load histories $N_F = 2.6$

Strip Theory

Disturbed water horiz. impact

Smooth water peaks

$Vt/D$
**Figure 21**

Typical impact loads from force measurements on a smooth cylinder slammed into aerated water.

Fitted load histories
- 3% air, large bubble size
- $N_F = 2.6$
- $N_F = 3.7$

**Figure 22**

Peak impact loads from force measurements on a smooth cylinder slammed into aerated water.

Locus of peak inclined impact loads from strip theory

<table>
<thead>
<tr>
<th>Symbol</th>
<th>% air</th>
<th>Mean bubble size</th>
</tr>
</thead>
<tbody>
<tr>
<td>•</td>
<td>1.3</td>
<td>0.060&quot;</td>
</tr>
<tr>
<td>☒</td>
<td>3.0</td>
<td>0.060</td>
</tr>
<tr>
<td>☒</td>
<td>3.9</td>
<td>0.033</td>
</tr>
<tr>
<td>☒</td>
<td>4.6</td>
<td>0.060</td>
</tr>
<tr>
<td>☒</td>
<td>6.1</td>
<td>0.033</td>
</tr>
<tr>
<td>☒</td>
<td>10.5</td>
<td>0.033</td>
</tr>
</tbody>
</table>

- $N_F = 3.7$ otherwise $N_F = 2.6$
Nominal Horizontal Impact Loads from Force Measurements on a Double K-Frame

![Graph showing fitted load histories with different symbols for N_f values and lines for empirical mean and strip theory for smooth cylinders from eqn.(1)]
Inclined Impact Loads from Force Measurements on a Double K-Frame

\[ C_{sl} \]

including interference load

\[ \theta = 1^\circ \]

\[ \theta = 2^\circ \]

\[ \theta = 3^\circ \]

\[ \theta = 4^\circ \]

\[ \theta = 6^\circ \]

\[ \theta = 8^\circ \]

-- Fitted load histories \( N_F = 2.6 \)

-- Empirical mean line from Fig. 23

\[ V_t/D \]
Interference Impact Loads for a Double K-Frame from Differences between Force Measurements (Fig. 24) and Strip Theory
DIAGRAM OF MODEL STRUCTURE TEST ARRANGEMENT

- Pivot
- Lead filled cross member
- Drive from arm
- 1st fixity construction
- 2nd fixity construction
- Vertical tube
- Horizontal tube
- Strain gauges
- Pressure transducer

Scale 1:10
TYPICAL STRAIN RECORDS FROM A MODEL STRUCTURE

2nd fixity $\gamma_1 = 0.21$

**Figure 27**

**Plot 1073**  $\theta = 0^\circ$

Strain $\mu \varepsilon$

0  10  20  30  time ms

**Plot 1102**  $\theta = 24^\circ$

Strain $\mu \varepsilon$

0  10  20  30  time ms
Computed Static Bending Moment Coefficients for $\theta = 1^\circ$ Inclined Impact with the Spray Root at Various Positions
Figure 29

Computed Static Bending Moment Coefficients for Inclined Impact with the Spray Root at Various Positions

0.75 fixity

Bending moment coefficient $K_m$

0.99 span

0.01 span

0.4 0.6 0.8 1.0

spray root position $y/L$

$\theta = 2^\circ$

0.50 span

$\theta = 0.5^\circ$

-0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08
Static Bending Moment Distributions from Strain Measurements on a Model Structure at Various Inclinations

1st fixity, fundamental mode

$K_m$ (Bending moment coefficient)

$\theta = 1^\circ$ peak at $y/L = 0.99$

$30^\circ$

$0^\circ$ av. at 3 values $N_F$

$1^\circ$ peak at $y/L = 0.50$

Simple theory for uniform load and fixity = 0.8
Static Bending Moment Distributions from Strain Measurements on a Model Structure at Various Inclinations

2nd fixity, fundamental mode

Bending moment coefficient $K_m$

$\theta = 40'$

32'

24'

16'

0'

8'

Span $y/L$

Simple theory for uniform load and fixity = 0.5
Dynamic Magnification Factors from Model Structure Tests and Dynamic Analogue

Experimental results
2nd fixity
slam decay time = $D_p/V = 3.5$
response time $V$

Analogue results
2nd fixity
$D_p/V = 3.5$
1st fixity
$D_p/V = 4.3$
  = 3.8
  = 3.3

Experimental results
1st fixity
$D_p/V = 4.3$
  = 3.8
  = 3.3

$2 \times \text{slam rise time} = 2L \tan \theta \cdot p$
response period $V$
Static Bending Moment Distributions from Strain Measurements on a Model Structure at Various Inclinations
Static Bending Moment Distributions from Strain Measurements on a Model Structure at Various Inclinations

2nd fixity, higher frequency modes

Bending moment coefficient $K_m$

$\theta = 0^\circ$

$\theta = 16'$

$\theta = 8'$

$\theta = 24'$

$\theta = 40'$

$\theta = 32'$

Span $y/L$
**Figure 35**

Geometry of Inclined Impact

- $V = U \cos \theta$
- $U \sin \theta$
- $dF_s$
- Element $dy$
- Spray root
- $y_1$
- $L$
- $D$

**Figure 36**

Dynamic Analogue of Experiment

- $U_0$
- $m_1$
- $k_{2/2}$
- $c_{2/2}$
- $z_1$
- $z_2 > z_1$
- $m_2$
- $F_s$
APPENDIX I

Strip theory of inclined impact
Consider a cylinder of finite length \( L \) slamming into a water surface at an inclination \( \theta \) with a velocity \( U \) normal to the water surface, as shown in Figure 35.

Assume that the normal force history on the cylinder element \( dy \) may be determined from two-dimensional slam data, which is unaffected by the axial component of the impact velocity \( U \sin \theta \). At time \( t_1 \) after impact (\( t_1 = 0 \) when \( y_1 = 0 \))

\[
dF_S = \frac{1}{2} \rho U^2 D C_S(t) \, dy \quad \text{and} \quad L \, \tan \theta = Vt_r
\]

where \( t_r \) is the rise time to peak force (\( y_1 = L \)).

Normalising with respect to \( V \) and \( L \), the average inclined impact slam coefficient

\[
C_{S_\theta} = \frac{1}{L} \int_0^L C_S(t) \, dy
\]

where \( t \) is the local time from the start of slam on element \( dy \).

Putting

\[
C_S = \frac{A}{1 + BVt/D} + \frac{CVt}{D}
\]

gives for \( \frac{Vt_1}{D} \leq \frac{Vt_r}{D} \)

\[
C_{S_\theta} = \frac{A}{BVt_r/D} \ln(1 + BVt_1/D) + \frac{C}{2Vt_r/D} \left(Vt_1/D\right)^2
\]

and for \( \frac{Vt_r}{D} \geq \frac{Vt_1}{D} \)

\[
C_{S_\theta} = \frac{A}{BVt_r/D} \ln \left(1 + BVt_1/D\right) + C(Vt_1/D - Vt_r/2D)
\]

The above results are plotted in Figure 16 based on the constants from the mean empirical equation (1).
Appendix II

Dynamic analogue of slam response

**Effects of variable entry speed** The structural vibration resulting from slamming is shown below to affect the slam loading. This effect is important, both in the analysis of data from slamming experiments and in the design prediction of structural response.

Using the general 'added mass' approach to the prediction of slam loading:

\[
\text{Kinetic Energy } KE = \frac{1}{2} \rho m u'^2
\]

(6)

where added mass \( m = m(z') \) and immersion \( z' = z'(t) \).

For the case of constant speed entry \( U = U_0 \):

\[
F_0 z' = \dot{E} = \frac{1}{2} \rho u'^2 \frac{dm}{dz'} \quad \dot{z}'
\]

\[
F_0 = \frac{1}{2} \rho u'^2 \frac{dm}{dz'}
\]

(7)

Conventional slam theories continue to find \( \frac{dm}{dz'} \) as a function of the immersion \( z' \).

For the case of a cylinder vibrating, as a result of the slam, the speed can no longer be considered constant. Putting \( U = U_0 + u(t) \),

\[
F_S z' = \frac{1}{2} \rho \frac{d}{dt} (mU_0^2 + 2m U_0 u + mu^2)
\]

from linearised theory

\[
F_S z' = \frac{1}{2} \rho \left\{ U_0 \frac{dm}{dz'} + 2m U_0 \frac{\dot{z}'}{2} + 2U_0 \frac{dm}{dz'} \frac{d}{dz'} + u^2 \frac{dm}{dz'} + 2mu \frac{\dot{u}}{z'} \right\}
\]

\[
F_S = \frac{1}{2} \rho \left\{ U_0 \frac{dm}{dz'} + 2U_0 u \frac{dm}{dz'} + u^2 \frac{dm}{dz'} + 2m \frac{(U_0 + u)}{z'} \right\}
\]

Comparing with (7)

\[
F_S = F_0 + \frac{2F_0 u}{U_0} + \frac{F_0 u^2}{U_0^2} + \frac{2}{U_0} \frac{F_0}{z'} (U_0 + u) \dot{u}
\]

(8)
Equations of motion  The vibration of the test rig was of a complex distributed mass nature, as indeed are many structural problems associated with slamming. However, the simple lumped mass system shown in Figure 36 was used to demonstrate the main features of the data analysis. Similar analogues were used by Campbell et al (1977), Miller (1977) and Sarpkaya (1978). However, differences in the present study were that: the rise of the slam load was known, the rig mass \( m_1 \) was free in space, and the slam load included variable entry speed effects.

Using the notation in Figure 36

\[
F_o - \frac{2F_o z_2}{U_o} - \frac{F_o z_2^2}{U_o^2} - \frac{2\int F_o dz'(U_o + u)z_2}{U_o^2 z_1} = m_2 \ddot{z}_2 + c_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) \tag{9}
\]

\[
m_1 \ddot{z}_1 - c_2(\dot{z}_2 - \dot{z}_1) - k_2(z_2 - z_1) = 0 \tag{10}
\]

From the above equations it can be seen that \( 2F_o \dot{z}_2 / U_o^2 \) and \( F_o z_2^2 / U_o^2 \) are in effect damping terms and were significant in reducing the response peaks. \( 2\int F_o dz'(U_o + u)z_2 / U_o^2 z_1 \) is the hydroelastic added mass \( m_o \) and affected the response frequency.

The equations were solved by computer using the mean empirical equation for \( F_o \) and Wagner's estimate of \( \int F_o dz'(U_o + u)z_1 \). No estimate was made of viscous damping since this could be accounted for in the measured value of \( F_o \) which included viscous drag. See Verley and Moe (1978) for further discussion of hydrodynamic damping.

A typical result is shown in Figure 11, and the discrepancy between the measured and predicted responses was attributed to physical differences from the simple lumped mass approach and the presence of long cycle beat decay.

The mean force level in the transducers \( k_2(z_2 - z_1) \) was shown to differ from the slam load \( F_o \) by a mass ratio factor of \( m_1 / (m_1 + m_2 + m_o) \) due to the finite rig mass.
APPENDIX II:

DETAILS OF MARINE FOULING OF TEST CYLINDERS

Two 4in diameter test cylinders were manufactured ready for installation on the test rig. The cylinders were then submerged on the rafts at the Exposure Trials Station in Portsmouth Harbour from June to December 1978.

Both cylinders became well covered with fouling which could be divided into the following four categories:-

1. Slimes
   Tenuous slime films were present over the whole cylinder. These were composed of diatoms and bacteria with particulate sediment additions. Their consequence to the bulk fouling of the cylinder was negligible.

2. Soft Fouling
   This may be defined as plant and animal species whose specific gravity is close to that of seawater.

   Plant species were represented by the sea lettuce, Ulva lactuca, immature brown algae of the genera Fucus sp or Pelvetia sp, small clusters of Ectocarpus sp, and various small filamentous red algae.

   The animal species were dominated by colonial tunicates, possibly Diplosoma listerianum, and colonies covered areas of several square centimetres.

   Clusters of the hydroid Tubularia larynx were present and Bryozoa formed mats over the cylinder surface.

3. Hard Fouling
   The hard fouling may be defined as dense shelled animals with a specific gravity of about 1.3 - 1.4.

   This type of fouling was only represented by the barnacle Balanus sp. Some quite large individuals were present but their numbers were few.

4. Associated infauna
   This is defined as the non-sedentary animals which use the attached fouling as a habitat. They include shrimps, small crabs and worms.

   The dominant genera were the amphipods Jassa sp and Gammarus sp, the former being present in large numbers.

   Just prior to testing, the cylinders were removed from the rafts and transported to Southampton University where they were stored in holding tanks.
Distribution

List No. 1:-

Head of Petroleum Engineering Division
Mr. J.N. Mansfield, Petroleum Engineering Division
Head, Branch 3 (Dr. J.E.P. Miles)
RTS, Department of Industry (Mr. J. English)
Deputy Controller, Establishments and Research (A) Min. of Defence
Dr. F.J.P. Clarke, Atomic Energy Research Establishment
Head, Marine Technology Support Unit
Mr. A.J. Hinksman, Health and Safety Executive
Library, Department of Energy
Library, Marine Division, Department of Trade
Library, Offshore Supplies Office
Technology Reports Centre, Department of Industry
Offshore Technology Unit, Dept. of Energy (Mr. M.T. Robinson)
Project Officer's file (Mr. S.J. Burnett)
Offshore Research Focus (Mr. T. Shepherd)

Members of the Advisory Group on Environmental Forces:-

Mr. C.J. Antonakis
Mr. J. Crease
Mr. D.J. Dowrick
Dr. J.E.P. Miles
Mr. D.C.G. Firbank

Mr. D. Harris
Prof. P. Holmes
Mr. J.R.A. Lang
Mr. E.S. Mallett
Mr. R.C.M. Russell

Mr. E.J. Smit
Mr. R.G. Voysey
Mr. G.A.J. Young
Secretary's file (S.J. Burnett)

Other Department of Energy distribution:-

Mr. M. Arkan
Mr. R.A. Bazely
Mr. R.L. Bruce
Mr. J. Burgess
Mr. H.J.S. Canham
Mr. H.J. Every
Mr. O. Faltinsen
Prof. J. Gerritsma
Mr. C.O.J. Grove-Palmer
Dr. N. Hogben
Prof. P. Holmes
Mr. R.G. Houston
Prof. M. Longuet-Higgins
Mr. Loughbridge
Mr. R.A. Lyons
Mr. M.J. Mes
Prof. D. Maull
Dr. B.L. Miller
Prof. T. Sarpkaya
Dr. R.A. Stacey
Mr. P.J. Verbeek

CNEXO, France
Plymouth Polytechnic
City University
John Haynie Inc.
Admiralty Marine Technology Establishment
British Hydromechanics Research Assoc.
Institutt for Skipshydrodynamikk, Trondheim
Shipdynamics Labority, Delft Univ.
ETSU - for TAG2 and TAG3 members-10 copies
National Maritime Institute
University of Liverpool
CJB - Earl & Wright Ltd
DAMP, Cambridge University
Lanchester Polytechnic
Atkins Research & Development
McDermott Hudson Engineering, Louisiana
Cambridge University
Noble Denton & Associates
Naval Postgraduate School, Monterey
Mobil Research & Development, Texas
Shell Exploratie en Productie Laboratorium, Netherlands

Wolfson Unit for Marine Technology distribution:-

Standard internal distribution

DUPLICATION EXCEPTED

10 copies