INTRODUCTION

The Lanchester Polytechnic's 'Clam' wave energy device consists of a series of flexible air bags driving self-rectifying turbo-generators, mounted on an unjointed spine. The device is designed to be moored at about 35 degrees to approaching wave fronts because it relies on phase differences between the air bags to produce power. In ref (1) further developments are described, and a graph is presented showing the cost of electricity from various sizes of Clam. Currently an 80 metre prototype is funded for study. A variety of cross-sections are being considered: their drawings are included in the appendix.

At Edinburgh University's Wave Power Project, we have been studying 'ducks' - hydraulic devices with gyroscope inertial reference. These are also mounted on a spine, but in our case, the spine is several kilometers long, with joints of controllable stiffness and damping. We have a 1:100 scale model presently undergoing tests in our wide tank.

In order to model the Lanchester spine, we took 4 spine sections of our model, with an overall length of 1.6m and diameter of 125 mm, and deemed the scale to be 1:50. This corresponds therefore to a full scale spine of length 80m and diameter 6.25m. We used the same mooring system as for our own spine; the dimensions and layout are shown below in the model description.
Because we have already carried out a wide range of experiments on longer spines, we have an established reference point: when we came to test the 1.6m spine many fascinating differences emerged. Although we have modelled neither the exact shapes of Lanchester's prototypes, nor their style of mooring system, we would argue from experience of spine appendages, and different mooring layouts, that only small effects could be expected from these details. A longer discussion of these points, and others, follows later.

The Lanchester team have calculated an upper limit on bending moments likely to be experienced by their spine in North Atlantic ocean conditions. They suggest the formula:

\[ \text{peak bending moment} = 8DL^3 \]

where \( D \) is the vertical dimension of the device, and \( L \) its length, in metres. The bending moment is given in Newton-metres. For our model of their spine, this formula gives a value for the peak bending moment of about 4 Nm. This figure should be held in mind when viewing our experimental bending moment graphs.
MODEL DESCRIPTION

Figs (1) and (2) show a dimensioned plan and elevation of the model and its mooring layout. The plan shows the model at right angles to the principal direction of approaching seas. Fig (3) shows, in plan, the model when oriented at 35° to the sea. Note that in this latter case the moorings apply a small couple to each end of the spine, resulting in static bending moments and a central shear. These effects will be removed along with other DC offsets, and second-order effects should be negligible.

Fig (4) shows a detail of the spine and joining sections. We should make clear that the reduced diameter of the joining sections will reduce the wave loading, approximately proportionately, over their length. The length of each 125mm diameter sections is 293mm, giving a total of 1172mm, whereas the joiner sections, of average diameter about 100mm, total 448mm.

Note that there are 4 spine sections and 3 joints. This is a poor representation of distributed elasticity; an alternative model has been described in a letter to Ken Major dated 23rd July 1984. The joints were arranged first of all in surge, then in heave. All experiments were performed in each orientation. Throughout the following experiments all 3 joints were controlled and recorded but only the output from the central one has been used for the graphs. Since the other two joints are closer to the ends, they produced smaller signals.

Let us define the following notation:

\[ M = \text{Bending moment} \]
\[ \theta = \text{Joint angle} \]
\[ L = \text{Section length} \]
\[ E = \text{Youngs modulus} \]
\[ I = \text{Section moment} \]
\[ R = \text{Radius of curvature} \]

It is necessary to relate the distributed deflection of an elastic beam with the lumped deflections of a group of rigid sections connected by joints. The curvatures should correspond. The relationships are:

\[ R = \frac{E I}{M} \quad \text{and} \quad R = \frac{L}{\theta} \]

Joint stiffness \( = \frac{M}{\theta} = \frac{E I}{L} \)
Fig (1)

1.6 m spine with moorings in zero degree attitude
Fig (2)  Mooring detail

MODEL

SINKER

FLOAT

ANCHOR

BUOYANCY FORCE 1.25 N

SINKING FORCE 1.25 N

sink depth ~ 930 mm

float depth ~ 570 mm

1280 mm

40°

52°

30°

52°

820 mm

1050 mm

1350 mm

43 kg

ANCHOR MASS

2000 mm
Fig (3) 1.6 m spine with moorings in 35 degree attitude
Fig (4)  Spine joint detail

Spine Unit Pitch
400 mm

Diameters: 125 110 BY
The flexural rigidity $EI$ value of each of the Lanchester prototype sections is indicated on its drawings in the appendix. In the case of the steel spines any contribution to $EI$ by ballast concrete has been neglected.

$EI$ scales as the 5th power of length, so we should divide all $EI$ values by $50 = 312,500,000$. This gives a range of $EI$ at 1:50 scale of $428 - 1784 \text{ Nm}^2$ for the steel spines, and $12,840 \text{ Nm}^2$ for the concrete spine. At this scale our model has an upper limit of $1600 \text{ Nm}^2$.

We have made no attempt to model the cross-sectional shapes of the Lanchester prototypes. We know from our work on spine appendages that changes from a cylindrical shape need to be gross before much change in bending moment is observed.

Neither have we modelled changes in freeboard. From studies of more buoyant spines we know that this can have substantial effects. An experiment in which we wrapped our 16m spine model in 18mm of closed cell foam changed the diameter from 125mm to 162mm, and the draught and freeboard to 93mm and 69mm respectively. Heave bending moments dropped 35%, surge bending moments rose 30% in monochromatic waves of 5mm amplitude.

The freeboard of the 1.6m spine was 3.3mm on the 125mm sections. That totals 26 millilitres of freeboard volume per spine unit, corresponding to a maximum upthrust of 1 Newton for the whole spine. This is reached when the spine is depressed more than 3.3mm relative to the water surface. But raising the spine by 3.3mm results in a downthrust of 2.9N. Clearly, the buoyancy under static conditions is highly non-linear with freeboard. Similarly, the wave loading on the spine, which is a function of immersed volume, will also be non-linear with freeboard. Both these non-linearities are shape dependant. However, at high wave amplitudes, the spine is nearly always below the water surface, and these non-linearities will - literally - be swamped.

We carried out computer simulations and tank experiments. For the computer work we varied length, attitude and stiffness. For the tank experiments we varied stiffness, attitude and sea state. Wavefronts in the tank are described in terms of their amplitude, frequency, angle and phase. We explored the consequences of varying each of these over the full working range of the tank.
THE WORK PROGRAMME

The spine simulations included:

1) Length and stiffness variations in a single mixed sea.

2) Length variations in a single mixed sea, with:
   (a) Spine beam on to the sea
   (b) Spine turned through 35°.

The tank experiments included:

1) Monochromatic wavefronts scanned through period and angle to produce spine system response graphs.

2) Monochromatic amplitude tests.

3) Mixed sea tests performed in Pierson-Moskowitz Mitsuyasu seas over a range of energy period

4) Freak waves.
We used a spine simulation program written by Ian Bryden, and described by him in ref (2). The program is specific to Edinburgh 125mm diameter jointed spines - all the hydrodynamic characteristics are intrinsic - but allows spine length and stiffness, and various mixed sea states, to be specified.

A Pierson-Moskowitz spectrum with Mitsuyasu angular spreading was chosen. It had a period of 1.4 seconds, corresponding at full scale to a 10 second period typical of the North Atlantic. Three separate sets of simulations were run.

1) Varied length and stiffness.
   - $EI$ varied from 400 through 3200 Nm$^2$ in steps of times 2.
   - Length from 0.8m through 3.2m in steps of 0.8m.

The resultant bending moment spatial arrays - bending moment at each point down the length of the spine - are shown in fig (5). Heave and surge are shown on each graph - heave is the lower trace except for the 0.8m spine length. It is very apparent that, at these lengths, large changes in stiffness have only a small effect on bending moment - about 14% drop for a times 8 stiffness increase for the 3.2m spine. But spine length changes have a dramatic effect - a doubling of spine length from 0.8 to 1.6m raises the bending moment by a factor of 3.9. Examination of the maximum moments over this length range indicates approximately a square law dependance on length, rather than the cube law.
Simulated heave and surge bending moment spatial arrays. Length and stiffness effects. Spine attitude zero degrees.
We ran two simulations with the principal direction of the sea at 0° and 35° to the spine normal. In each run we varied length from 0.8m to 16m in steps of 0.8m.

2) Spine at 0°

The bending moment spatial arrays are shown in fig (6). Note both the increase in overall size of the arrays with spine length, and their change in shape - above about 10m the 'crater' effect of long spines begins to appear. One can infer the presence of the single mode standing wave response in the short spines, changing gradually with length to include higher modes of standing wave, and later, as the central part of the spatial array progressively flattens, the appearance of the travelling wave. These ideas are developed later in the section entitled 'Spine Response'.

Fig (7) shows the result of plotting the largest bending moment in each spatial array against spine length. It is very clear that, up to a certain critical length, bending moment increases rapidly with spine length, and, beyond that length, remains virtually constant.

3) Spine at 35°

Fig (8) shows the bending moment spatial arrays, and fig (9) their peaks plotted against spine length. The latter graph shows us that the critical length is not appreciably changed by angling the sea, nor is surge bending moment increased. Heave bending moment, however, shows more than a 50% increase in the 5.6 to 8m region. Reference to the spatial arrays (and comparison with the spatial arrays for the 0 degree experiment) shows the presence of a large bending moment enhancement at the downwave (right on the graphs) end of the spine. This enhancement is caused by reflection from the free end of the spine, and it is interesting that it is so much larger for heave than surge.
Simulated heave and surge bending moment spatial arrays. Length effects. Spine attitude zero degrees.
Simulated heave and surge maximum bending moment versus spine length.
Spine attitude zero degrees.
Simulated heave and surge bending moment spatial arrays.
Length effects. Spine attitude 35 degrees.
Simulated heave and surge maximum bending moment versus spine length.
Spine attitude 35 degrees.
THE TANK EXPERIMENTS

For all this work a sampling rate of 20 Hz was used. In each case the sea state was allowed to stabilize for 30 seconds before sampling began. In the monochromatic seas we sampled for the nearest whole number of cycles to 12.8 seconds; in the mixed seas we sampled for 51.2 seconds.

Experiment I  Spine response

We measured the bending moment response of the spine to 240 individual wave-fronts of unique period and angle, each of 2cm amplitude, covering the range 0.5 - 2.0 seconds, in steps of 0.1 seconds, and 0 - 70 degrees in steps of 5 degrees. The experiment was performed for two stiffnesses: $EI = 400$ and $1200 \text{ Nm}^2$.

Processing these results yields a three-dimensional plot of bending moment against period and angle, normalised for 1 cm waves. The results for the negative angles specified in the experiment have been reflected about the $0^\circ$ line to give a synthesized plot for the whole field.

In ref (3) it is shown that bending moments in a spine can be derived from such 3-d plots and the equivalent representation of the given sea state.

Fig (10) shows the bending moment response surface - a 'V plot' - for a 16m spine of $EI = 800$ in surge, taken from an earlier set of experiments. Each nexus on the reticule represents by its height above the $z = 0$ plane, the bending moment produced by a 1cm amplitude wave of the indicated period and angle. Fig (11) shows the heave response of the same spine. Figs (12), (13), (14), and (15) show the equivalent graphs for the 1.6m spine with $EI = 400$, and $EI = 1200$. Note the 10-fold change in scale. The V plots for the two lengths of spine are quite different in size and shape, and consequently their interaction with scaled sea states will be different also.

One should note that the effective surge force delivered by a monochromatic wave to the spine ought to decrease as the cosine of the angle of spine and wavefront increases - clearly a wave travelling down the length of the spine should contribute no surge forces at all while heave forces should remain unchanged.
fig (10) V plot for 16 m spine. $EI = 800 \text{Nm}^2$ Surge.

fig (11) V plot for 16 m spine. $EI = 800 \text{Nm}^2$ Heave.
fig (12) V plot for 1.6 m spine. EI = 400 Nm² Surge.

fig (13) V plot for 1.6 m spine. EI = 400 Nm² Heave.
fig (14) V plot for 1.6 m spine. EI = 1200 Nm² Surge.

fig (15) V plot for 1.6 m spine. EI = 1200 Nm² Heave.
Figs (16) a, b and c show respectively: the V plot for the 16m spine; the period/angle/amplitude representation ('sea plot') of a 1 second Pierson-Moskowitz Mitsuyasu sea; and their product. The exact derivation of resultant bending moment is given in ref (3), but the volume under the surface in (c) gives a good idea of the resultant bending moment.

The same sequence is repeated in fig (17) a, b and c for the 1.6m spine, of $EI = 400$, and a 1.4 second Pierson-Moskowitz Mitsuyasu sea whose principal direction is 35 degrees. Again, note the scale differences. Not only does the 1.6m spine have a smaller bending moment response, but its location in the period/angle plane means that less of it coincides with the more energetic region of the sea-plot. So despite the much greater size of the 1.4 second P-M, (twice the Hrms) the resultant bending moment for the 1.6m spine is considerably lower.
(a) V plot for 16 m spine. EI = 800 Nm\(^3\) Surge.

(b) Sea plot for 1 second Pierson-Moskowitz Mitsuyasu sea at zero degrees.

(c) Multiplication of sea plot by v plot.
fig 17 (a) V plot for 1.6 m spine. EI = 400 Nm² Surge.

(b) Sea plot of 1.4 second Pierson-Moskowitz Mitsuyasu at 35 degrees.

(c) Multiplication of seaplot by v plot.
For our spines we can identify two kinds of resonance: a standing wave effect fig (18); and a travelling wave effect fig (19). A full spine description should include both, and in ref (2) Ian Bryden indicates how the beam equations might be solved for given conditions.

As a simpler means to comprehension, however, we can take the solutions offered in refs (4) and (5) for the travelling wave and the standing wave solved independently.

(1) travelling wave:  \[ c^2 f = \frac{2\pi}{\sqrt{\frac{E}{\gamma}}} \]

\( c \) = wave crest-length, \( f \) = wave frequency in Hz
\( \gamma \) = mass per unit length of the spine

(2) standing wave:  \[ \cos (kL) \cosh (kL) = 1 \]

yielding  \[ kL \approx \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots, \frac{(2n-1)\pi}{2} \]
\( k = \frac{2\pi}{c} \)
\( L \) = spine length
\( n \) = the number of nodes of the vibration.

Note that equation (2) is spine length dependant, and equation (1) is not; also that equation (1) is dependant on spine stiffness, and equation (2) is not. Since the V plots for the short spine scarcely vary with stiffness, we should try the standing wave solution.
fig (18) A standing wave in a spine.

fig (19) A travelling wave in a spine.
The first 2 solutions (the 2 node and 3 node) yield respectively

\[ L = \frac{3}{4} c \quad \text{and} \quad L = \frac{5}{4} c \]

In fact, simply setting \( L = c \) gives the best agreement in this case.

\[ L = c = \frac{g}{2 \pi f^2 \sin \alpha} \]

\( \alpha = \) wave angle \( g = \) acceleration of gravity \( T = \frac{1}{f} \)

yielding \( \sin \alpha = 0.965 T^2 \)

or, in tabular form:

<table>
<thead>
<tr>
<th>( T ) (seconds)</th>
<th>( \alpha ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>14</td>
</tr>
<tr>
<td>0.6</td>
<td>20</td>
</tr>
<tr>
<td>0.7</td>
<td>28</td>
</tr>
<tr>
<td>0.8</td>
<td>38</td>
</tr>
<tr>
<td>0.9</td>
<td>51</td>
</tr>
<tr>
<td>1.0</td>
<td>75</td>
</tr>
</tbody>
</table>

Comparison for the \( V \) plot in fig (12) shows good agreement.

In the 16m spine a large number of standing wave modes are possible, and the spine is also long enough to allow travelling waves. Whereas standing waves produce nodes and antinodes, travelling waves should produce equal bending moments in the central region. Fig (20) shows 3 spatial arrays for the 16m spine at 3 different frequencies, at the angles giving their respective maxima. Standing wave effects are very pronounced at low frequencies, far less so at high frequency. But in the 1.6m spine there are no frequencies high enough with short enough crest lengths in the sea state to operate as travelling waves. Note that in the 16m spine both standing and travelling wave effects are far greater than for the 1.6m spine because they coincide with the spine's mass/stiffness resonance. It might help to imagine trying to vibrate a slender wand with one's fingers; it's easier to supply energy at an antinode than at a node (a length effect); it's easiest of all to supply energy at an antinode at the particular frequency of flexural resonance. It should be noted that in these experiments no damping has been added to the models, and the only damping is hydrodynamic.
fig (20)
Spatial arrays in surge for the 16 m spine in resonance at 3 frequencies.

0.47 Hz

0.78 Hz

1.41 Hz
Experiment II  Spine bending moments and wave amplitude

We wanted to produce the highest spine bending moments possible in regular waves. Spine EI was set to 400 Nm². We chose a single wavefront for heave and surge separately, checking the respective V plots to identify the worst wave. For heave it was 0.9s at 55°, for surge, 0.8s at 35°. The tank was run over a range of amplitudes from 0 to about 5 cm root mean square amplitude in each case. Fig (21) and (22) show the Hrms measured at the model position in the absence of the model versus the commanded Hrms, and indicate that the tank is reaching its amplitude limits for these periods at the upper end.

In fig (23) the plot of bending moment versus mixed sea amplitude for the 16m spine is reproduced from ref (2). The plot is linear in heave, but shows an exponential curve in surge, which we theorise is due to wave spillage over the top of the spine with consequent reduction in force.

The graph of bending moment for the 1.6m spine in heave and surge versus the Hrms of their respective worst-case monochromatic waves is shown in fig (24). They are not well-behaved, and no attempt has been made to fit a curve to either of them.

The surge curve shows a virtual plateau between 1.8 and 3.2 cm Hrms and gets very ragged at high amplitudes. Even the heave bending moment curve shows non-linearity. Note that the curves cross and that above 2.7 cm Hrms the heave bending moments are higher than surge.

The spine was moving considerably at high amplitudes, the spine ends frequently ducking into the oncoming waves. The irregularity of the curves is therefore not surprising.

To keep the curves as smooth as possible, rms values are used for bending moment and wave amplitude. The highest heave bending moment is 2.28 Nm. If the forces on the spine were strictly sinusoidal the highest bending peak moment would be √2 times this, or 3.22 Nm. A real instantaneous peak is likely to be higher. It is notable that beyond 3.5cm Hrms, surge and heave bending moments rise at about the same rate, and show no sign
fig (21) Measured Hrms versus command. 0.8 seconds at 35 degrees.

fig (22) Measured Hrms versus command. 0.9 seconds at 55 degrees.
Bending moment in heave and surge versus $H_{rms}$ for 16 m spine in 1 second Pierson-Moskowitz sea with cosine squared angular spreading.

Bending moments for 1.6 m spine in heave and surge versus the measured $H_{rms}$ of their respective monochromatic seas.
of slowing down. It is likely that they would continue to rise in waves bigger than it is possible to make in our tank. This could be checked only by building a smaller model - which could also have distributed elasticity and the proper shape of freeboard.

Experiment III  Spines of varied stiffness in mixed seas.

In these tests we recorded the bending moments and mooring forces for the 1.6m spine in range of Pierson-Moskowitz Mitsuyasu seas, whose periods ranged from 0.6 to 1.4 seconds, with a concomitant increase in Hrms with Te squared of 0.49cm to 2.67cm.

The spine was oriented at two attitudes: beam on to the seas; and turned by 35°.

The spine was set to six different stiffnesses on a logarithmic scale, corresponding to EI = 40, 80, 160, 320, 640 and 1280 Nm².

Fig (25) shows the vertical and horizontal mooring force against Te for all 6 stiffnesses. All graphs for this experiment and the next one will use this format. The spine attitude is 0°. Vertical forces are 0.78 times the horizontal one. The arctan of this ratio is 38° confirming the static measurement in fig (2). Fig (26) shows the mooring forces for the spine at the 35° attitude - there seems scarcely any change with angle, despite the fact that the spine presents 20% less area to beam seas when at the 35° attitude. Perhaps this is because of the rather wide Mitsuyasu spread - look again at the 1.4 sec P-M Mitsuyasu sea plot in fig (17)b. Surge mooring forces on the 16m spine are about five times lower per metre of spine length.

In all these cases, mooring forces rise with the first power of Te. Hrms rises with the square of Te, and for a given amplitude, the acceleration of water particles rises as the square of frequency. These effects will tend to cancel each other. A further effect is the more rapid rate of exponential decay of water orbitals with depth at higher frequency; this will result in higher mooring forces as Te rises.

Figs (27) and (28) show the heave and surge root mean square bending moments for the 0° spine. They show the expected rise with Te - but with a slight negative curvature.
fig (25)
Horizontal and vertical mooring forces versus Te for 1.6 m spine. Spine attitude zero degrees. Six spine stiffnesses.

fig (26)
Horizontal and vertical mooring forces versus Te for 1.6 m spine. Spine attitude 35 degrees. Six spine stiffnesses.
fig (27)
Heave rms bending moment versus $T_e$ for 1.6 m spine. Zero degree attitude.
Six spine stiffnesses.

fig (28)
Surge rms bending moment versus $T_e$ for 1.6 m spine. Zero degree attitude.
Six spine stiffnesses.
Figs (29) and (30) show the maximum bending moments for the 0° spine. They show more scatter than for rms, since they express extreme statistics, but the message is the same. Peaks are about 3 times rms. Spine bending moments for the middle of a 16m spine in a 1 second Pierson–Moskowitz are 3.4 Nm rms in surge and 2.2 in heave. This corresponds to 6 times and 4 times respectively the equivalent values for the 1.6m spine.

Figs (31), (32), (33) and (34) show the rms and peak bending moment for the spine at 35°. Again, surge rms bending moment is about the same as heave, and the peaks are about 3 times the rms.

The negative curvature noted in surge for the 0° spine now appears in all the graphs – though more pronounced in surge. It is clear that the spine response – see those V plots again – is affecting the period results. The sea plots of the same section should also be recalled – the frequency and angle spread of the Pierson–Moskowitz Mitsuyasu is very wide and changes will not happen fast.

The V plot for heave shows greater high period response than does that for surge. Furthermore, the response of the spine in heave to high amplitude waves is greater than that for surge. These both contribute to the lower curvature of the heave bending moment graphs in mixed seas.

**Experiment IV Mixed seas with freak waves.**

A set of tests identical to those in experiment (4) were run except that each sea had the starting phase of its wavefronts adjusted to produce a freak wave 20 seconds into sampling. The peak to peak value of the freak wave would be about 12 times the rms value of the unfreaked sea, i.e. about double what we would expect for a record of this length.

Figs (35), (36), (37) and (38) show the peak bending moment for the 0° and 35° spines in heave and surge. As expected, the heave plots show bending moments twice those of an unfreaked sea (note the scale change). From the graph slope at high Te, it is hard to believe that bending moment would not continue to rise at still higher values of Te. Note that 1.4 seconds is only the median value for mixed seas in the North Atlantic at this scale.

In surge, however, the results are very surprising. For both the 0° and 35° spines, for most periods, the peak bending moment shows a reduction in the freaked sea. This is an extraordinary result which deserves close scrutiny.
fig (29)
Heave maximum bending moment versus $Te$ for 1.6 m spine. Zero degree attitude.
Six spine stiffnesses.

fig (30)
Surge maximum bending moment versus $Te$ for 1.6 m spine. Zero degree attitude.
Six spine stiffnesses.
fig (31)
Heave rms bending moment versus Te for 1.6 m spine. 35 degree attitude.
Six spine stiffnesses.

fig (32)
Surge rms bending moment versus Te for 1.6 m spine. 35 degree attitude.
Six spine stiffnesses.
fig (33)
Heave maximum bending moment versus Te for 1.6 m spine. 35 degree attitude. Six spine stiffnesses.

fig (34)
Surge maximum bending moment versus Te for 1.6 m spine. 35 degree attitude. Six spine stiffnesses.
fig (35)
Heave maximum bending moment versus $T_e$ for 1.6 m spine in freak wave. Zero degree attitude. Six spine stiffnesses.

fig (36)
Surge maximum bending moment versus $T_e$ for 1.6 m spine in freak wave. Zero degree attitude. Six spine stiffnesses.
fig (37)
Heave maximum bending moment versus $T_e$ for 1.6 m spine in freak wave. 35 degree attitude. Six spine stiffnesses.

fig (38)
Surge maximum bending moment versus $T_e$ for 1.6 m spine in freak wave. 35 degree attitude. Six spine stiffnesses.
CONCLUSIONS

1. Bending moments for the 1.6m spine in mixed seas are 5 times lower than for the 16m spine.

2. Mooring forces for the 1.6m spine in mixed seas are 5 times higher than for the 16m spine.

3. Whereas mixed seas described by the Pierson-Moskowitz rule show an increase in Hrms with the square of the energy period the mooring forces for the 1.6m spine show an increase with only the first power of the energy period.

4. Large changes in spine flexural rigidity produce only small changes of bending moment. This is in contrast with the effects in long spines.

5. It is possible to construct 3 dimensional graphs - 'V plots' - which show the bending moment response of the spine to a range of periods and angles of monochromatic waves of constant amplitude.

The V plot altitudes for the 1.6m spine are small. Their plan shape is determined by the criterion that the highest bending moments are produced when the crest length of the monochromatic sea coincides with the length of the spine.

6. The V plot altitudes for the 16m spine are much larger because the spine length is sufficient to allow the flexural response of the spine to be excited by waves of particular frequency and angle.

7. The bending moment of the 1.6m spine rises with amplitude for monochromatic waves. The graphs for both heave and surge show negative curvature, but are not smooth, particularly so in surge, and at high amplitude.
8. The performance of the spine in mixed seas can be explained (for the most part) by reference to the V plot and the amplitude curves. Heave bending moments rise with energy periods up to the limit of \( T_e \) possible in our tank, and show no signs of slackening off.

9. The rule that peak bending moment = 8DL\(^3\) has not been confirmed by this series of experiments.

For short spines, moments rise with the square of length. For long spines, moments remain constant, or even slightly decrease, with length.

Bending moments rise with wave amplitude, to approximately the first power. In rough conditions they may rise less steeply with wave amplitude, but do not limit.

C-H RETZLER

5th September 1984
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APPENDIX

Spine section from drawing number HDO-1029

Surge $EI = 4012 \text{ GNm}^2$  Heave $EI = 3842 \text{ GNm}^2$

END VIEW / SECTION THROUGH

CONCRETE SPINE X 80 METRES 0/ALL
Spine section from drawing number HDO-1030

Surge EI = 238 GNm²  Heave EI = 134 GNm²

Spine section from drawing number HDO-1031

Surge EI = 486 GNm²  Heave EI = 558 GNm²
Spine section from drawing number HDO-1032
Surge EI = 282 GNm² Heave EI = 400 GNm²

Spine section from drawing number HDO-1033
Surge EI = 194 GNm² Heave EI = 194 GNm²