LONG SPINES WITH APPENDAGES

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Spines are generic to a number of wave energy devices. Ducks use round spines with very low freeboard. Other devices use spines which are, for example, rectangular in section, or have higher freeboards.

This report describes experimental investigations into the effects of adding appendages to the Edinburgh spine model. Some appendages were constructed to be similar in section to other devices, some were chosen because they were hydrodynamically interesting. They comprised:

- corners: right-angle sections added to square off the spine cross-section.
- fins: 4 fins mounted along the spine axis.
- decks: plastic foam layers added to the top surface of a squared-off spine to give a range of freeboard.
- skins: plastic foam layers wrapped round the spine to increase radius.
- harbours: rectangular plates mounted normal to the spine.

The spine models were all 16 metres long, using 40 spine units joined by controlled hinges allowing movement alternately in heave and surge. Appendages were fixed to every spine unit.

The decks were tested in a range of mixed seas in the freeboard experiments. The other configurations were tested for their response to wave frequency and angle, and for their performance in the 46 spectra representing the annual wave climate off South Uist. Tests were performed at two spine stiffnesses. The plain spine was tested under the same conditions for comparison.

While the choice of sections was necessarily limited, we collected sufficient data to feel confident that we could extend our test results to other shapes.
MAIN CONCLUSIONS

APPENDAGES

1) Fins and harbours decreased the spine bending moments, but in general the spine showed greater bending moments with appendages than without. Adding skins gave the largest increases of all – up to 50%.

2) The increases were greater at higher stiffnesses.

3) The increases in heave were greater than those in surge.

FREEBOARD

4) Adding freeboard to the spine increased the bending moment in a mixed sea. The rate of increase diminished with increasing freeboard.

5) The graph of bending moment against sea size shows an initial region of high slope, followed by one of shallower slope. The point at which this change occurs is proportional to freeboard. We believe that it relates to the extent that waves are able to break over the top of the spine.

6) Spine motion and mooring force in heave show good linearity with sea-size. Linearity in surge in the wave frequency band is also good. But there is substantial low frequency contribution to surge motion, which is very poorly related to sea size, and greatly affected by freeboard. We believe this to be the response to wave groups.

7) Spine drift changes smoothly with sea size. For low freeboard in small seas there is a small aft drift; in large seas a substantial fore drift. For higher freeboards the drift is always aft.

8) Spine designs with a freeboard close to zero show low bending moments because: (a) buoyancy and inertial forces tend to cancel in heave (b) wave overtopping reduces inertial forces in surge.
These were lengths of plastic of right-angle section, attached to the spine with waterproof adhesive tape to form a square cross-section.

In this drawing, and in the drawings of other appendages, the core section of the round spine is shown, and the level of the water surface indicated.

The corners were cut to the same length as the main cylinder section of each spine unit, namely, 293 mm. They had a mass of 125 g, and 20 g of tape held them in place.

Figure 1.1 Corners appendage
Fins

These were constructed by turning the previously-used corners inside-out and adhesive taping them to the spine. To allow purchase for the tape, the ends of the fins were notched, reducing their length to 213 mm. Their mass was 125 g, and a further 20 g of tape was required to hold them in place.

Figure 1.2 Fins appendage
3 Layer Deck

This high freeboard appendage was an extension of the corners appendage. Three half-inch layers of closed-cell foam plastic were added to the top of the spine and taped into place.

Each layer was 120 mm wide and 293 mm long. Each weighed 20 g and required 10 g of tape to hold it in place. The total mass of the appendage was 235 g. An immersion test showed that a layer of the foam took up less than 0.4 g of water, and that this was confined to the cut surface of the foam - no water was absorbed into the body of the plastic.

Figure 1.3 3 layer deck appendage
Skins

This appendage was composed of 2 layers of closed-cell foam plastic, quarter and half-inch thick, wrapped around the spine and secured with adhesive tape.

The mass of the foam was 110 g, and 20 g of adhesive tape was required to hold it in position. Its length was 293 mm and its volume 2520 ml.

Figure 1.4  Skins appendage
Harbours

'Harbours' is a direct translation of the Norwegian term for the vertical concrete flanges set at the entrance to an oscillating water column. They are used to broaden the bandwidth of wave power absorption.

We constructed similar appendages to mount on the spine. They were made from 18 mm marine 5-plywood, coated with polyurethane varnish. Each was fixed to the middle of a spine unit by two thick rubber bands which passed over hooks on either side of the wood, and round the back of the spine.

The vertical dimension of the harbour was calculated so that it had close to neutral buoyancy. In practice, there was a small amount of downthrust, and consequently a slight sinking and rotation of the spine. The top surface of the harbour was adjusted to be level when the spine was in the water.

The mass of the harbour and the rubber bands was 470 g, and the volume 590 ml.
Figure 1.5  Harbours appendage
Table 1.1 collates the specifications of all the spines with appendages. Only a static description of the models is given, and it is important to offer a commentary on the hydrodynamic consequences.

Some appendages cause obvious changes in the model specifications - for example, the corners enclose water and so increase the mass of the model. Fins do not enclose water, and so are shown in the table as increasing the mass very little. However, they will entrain water as the model moves, and therefore increase the hydrodynamic added mass.

Clearly those models with increased submerged volume will be influenced more by the water. We were also interested in how increasing the exposed volume would change wave forces on the spine. The deck models provide a range of freeboard with very little change in draft and submerged volume. They are used in the experiments described in Section 4.

Shapes with increased water plane area will experience increased heave restoring forces.

Shapes which are less hydrodynamically fair - fins, corners, harbours - experience increased drag, and hence increased damping of their motion.

Changes in the stiffness and mass of the spine will alter the frequency and angle of the waves to which the spine is most sensitive. Changes in the damping will influence the shape of the resonance response curve.
Table 1.1: SPINE AND APPENDAGE SPECIFICATIONS

<table>
<thead>
<tr>
<th></th>
<th>Plain</th>
<th>Fins</th>
<th>Harbours</th>
<th>Skins</th>
<th>Corners</th>
<th>1 Deck</th>
<th>2 Decks</th>
<th>3 Decks</th>
</tr>
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<tr>
<td>mass/section g</td>
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<td>4045</td>
<td>4370</td>
<td>4030</td>
<td>4540</td>
<td>4570</td>
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<td>volume/section ml</td>
<td>4000</td>
<td>4145</td>
<td>4590</td>
<td>6520</td>
<td>4640</td>
<td>5090</td>
<td>5540</td>
<td>5990</td>
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<tr>
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<td>292</td>
<td>163</td>
<td>170</td>
<td>179</td>
<td>189</td>
<td>198</td>
</tr>
<tr>
<td>maximum radius mm</td>
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<td>81.5</td>
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<td>94</td>
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<td>113</td>
</tr>
<tr>
<td>freeboard mm</td>
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<td>14</td>
<td>55</td>
<td>70</td>
<td>5</td>
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<td>exposed volume ml</td>
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<td>520</td>
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<td>1360</td>
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<td>water plane area m2</td>
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<td>0.016</td>
<td>0.004</td>
<td>0.057</td>
<td>0.035</td>
<td>0.035</td>
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<td>0.035</td>
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<tr>
<td>occupied fraction of spine length</td>
<td>0.00</td>
<td>0.53</td>
<td>0.05</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
</tbody>
</table>
The photograph shows sections of the four models with, from left to right:

- Fins
- Corners
- Harbour
- Skins
The photograph shows sections of the four models used for variable freeboard experiments. They include the basic corners model, and the higher deck versions made by the addition of layers of impermeable foam to the corners model.
We characterise the bending moment response of a spine to waves by the three-dimensional graphs shown on the following pages. The two horizontal axes are wave frequency and wave angle. The elevation of each node of the graph represents the average of the root-mean-square bending moment of all the heave or surge joints at that particular frequency and angle.

We define wave crests parallel to the spine as being at zero degrees.

The sampling time was 12.8 seconds, the sampling rate 20 Hz. The frequency interval was chosen so that a whole number of wave cycles was sampled. The frequency range was 0.47 to 1.95 Hz. The bending moment response was Fourier filtered, so that only the signal at the exciting frequency was measured. Because the finite tank-depth reduces the velocity of long waves, wavefront angles were adjusted to maintain the correct wavecrest velocity down the spine. The graphs therefore are corrected to appear as if the experiment had been performed in water of infinite depth. The same wave amplitude of 20 mm peak to peak was used for all frequencies.

Positive angled waves reflect off the glass front wall of the tank, causing a small area of standing wave effects. So for these experiments only negative angles were used, and the resultant graphs reflected about the zero degree line. Plotting the graphs like this gives two views of the spine response.

Spines show a bending moment resonance when the component of wave crest velocity down the spine coincides with the velocity of the natural flexural wave in the spine. A characteristic response curve is therefore produced where the resonant wave has an increasing angle to the spine as its frequency decreases. Because of their shape, we call these graphs 'V plots'. The resonance does not represent any hazard to spines with intelligently controlled joints, which can usefully absorb the flexure wave energy.
In figures 2.1 to 2.4, the V plots for the plain spine, and all the spines with appendages, are shown. The experiments were run with the spines at two stiffnesses: 800, and 80 Nm2. The damping was set to zero.

The scale of each graph is indicated on the graph at the bottom right hand corner of the same page. The number on the top right of each graph is the maximum graph elevation, ie, the spine's maximum average rms bending moment, in Newton-metres.

We begin by considering the case of the 800 Nm2 stiffness. In every case, adding an appendage to the spine increased the maximum bending moment.

Fins

In both heave and surge the response of the spine, particularly at low frequencies, is increased. The response is smooth - in heave, it is smoother than that of the plain spine.

Harbours

In heave the maximum response relative to the round section spine is more than doubled. The increase is mainly in the central region between 0.6 and 1.6 Hz, and is very peaky. In surge there is not nearly such a dramatic increase, but again, the peakiness is accentuated.
Figure 2.1 Model bending moment responses. 800 Nm2
Corners

In heave the square spine shows a smoothing of the response compared to the plain spine, and a shifting of maximum response to lower frequencies. In surge, there is a large increase in response, but the basic shape remains similar.

Freeboard

In heave, the response shows an increase mainly in the low frequency region. Surge displays a considerable increase, again at low frequency.

Buoyancy

Here the changes are dramatic. The peakiness of both heave and surge response increases and the maximum response in surge is more than double that of the plain spine.
Figure 2.2 Model bending moment responses. 800 Nm2
**Low stiffness**

Note the 4-fold change of vertical scale for these low-stiffness graphs. As is apparent from the following 'V plots', a ten-fold decrease in stiffness to 80 Nm² produces about a 3 to 4-fold decrease in bending moment. The shapes are similar to their counterparts at the higher stiffness, but in every case a widening of the 'V' is apparent. The skins appendage shows this effect most clearly.

The widening of the 'V' means that the resonance at any frequency is shifted to a greater angle. At the lowest frequency, the resonance peak can be pushed off the graph completely. Consequently, all the low stiffness models show a lower response at low frequency relative to the mid frequencies than do the high stiffness models.

The V plot for the plain spine in heave has a sharp peak around 1.5 Hz. The responses for fins, corners and deck are smoother, and show a smaller peak bending moment. However, their total response over the frequency/angle plane is greater. The only model to show a lower overall response than the plain spine is the harbour in surge.
Figure 2.3  Model bending moment responses.  80 Nm2
Figure 2.4 Model bending moment responses. 80 Nm2
SECTION 3  THE 46 SPECTRA

We measured the bending moment for each model configuration in each of the 46 spectra. The sampling rate was 20 Hz, the sampling time was 51.2 seconds. Full details of these spectra can be found in the 1984 Long Spine report.

Figure 5.7 shows the rms bending moment spatial arrays for the plain spine in surge at high stiffness. The spatial arrays for all configurations at both stiffnesses in heave and surge are included in the appendix in Section 5.

Comparing one configuration with another at the same stiffness, in heave or surge, one sees there are differences in the degree of tilt of the spatial arrays, and in their peakiness. Both of these will be at a maximum when the sea consists of a swell component whose frequency and angle correspond with the peak of the model frequency/angle response. Additional components in the sea state may increase the overall size of the spatial array, but will dilute the tilt and peakiness.

However, the chief difference between the various configurations is in the overall size of the arrays. This is shown best in graphs of average bending moment for the whole spine.
Figure 5.7  Plain.  Surge.  800 Nm2
In figures 3.1 to 3.4 the bending moment spatial array for each appendage in each sea state has been averaged to a single value. Each graph therefore consists of 46 points - one for each spectrum. The abscissa of each point is the average bending moment for the plain spine, the ordinate is the average bending moment for the spine with appendage.

The graphs are square and the two axes have the same scales. The diagonal line superposed on each graph represents identicality: any point lying on the line indicates that the spine with appendage has the same average bending moment as the plain spine in that particular sea state.

The order of appendages is the same as for the V plot diagrams shown in figures 2.1 to 2.4; the layout of graphs is identical, and so a page to page comparison can be made.

In each case the appendage is indicated by its icon. For the four graphs with the circle icon, the bending moment results for the plain spine are being compared with a repeated version of the same experiment. The virtually total coincidence of points with the diagonal line demonstrates that repeatability is good. This gives confidence that the deviations apparent in the other graphs have a physical meaning.
Figure 3.1  46 spectra average bending moment plots.  800 Nm2
Figure 3.2  46 spectra average bending moment plots.  800 Nm2
Figure 3.3 46 spectra average bending moment plots. 80 Nm2
Figure 3.4  46 spectra average bending moment plots. 80 Nm2
The rest of the comparison graphs make it plain that, in general, adding an appendage increases the spine bending moments. This is true for most sea states and for nearly all configurations.

For those configurations with higher freeboard, the increases in bending moment are greater in larger seas - a result which is explained by the 'freeboard effect' described later in this report.

The degree of scatter of the points varies considerably from one graph to the next. For example, in surge, the harbour appendage produces a graph of very low scatter; while in heave the scatter is high. This is true at both stiffnesses.

Checking the 'V plots', one sees that the surge response is similar in size and shape to that of the plain spine. But in the heave case, the differences are large: the spine with harbour has a considerably larger response than its plain spine counterpart, and of quite a different shape. It is the shape differences which produce scatter on the comparison graphs.

Adjacent bending moment arrays for the plain spine in figure 5.7 can vary greatly - even though the mixed seas which produced them differ little in $H_{rms}$. Since each array is the product not simply of $H_{rms}$, but also the wave frequency/angle composition of the sea, and the spine frequency/angle response, clearly changing the latter changes the average bending moment of each of the 46 spectra in very different ways. Increases or decreases of tens of percent may result, so when plotted against results for the plain spine, considerable scatter appears.
The comparison graphs may be condensed still further, to an average bending moment over a whole year, using the appropriate weighting for each sea state. The results are shown in Table 3.1, and give the absolute annual bending moment at model scale for each appendage.

To make the changes more apparent, table 3.2 has been drawn to show the factor of increase in bending moment compared to that of the plain spine at the two stiffnesses and in heave and surge.

Nearly all the cases show an increase in bending moment. The exceptions are the harbour in surge, which shows about a 10% drop at both stiffnesses, and the fins in heave at low stiffness, although the drop is of questionable significance.

In general it is clear that:
- adding appendages increases spine bending moment;
- increases in heave bending moment are greater than those in surge;
- increases in both heave and surge bending moment are greater at greater stiffness.
Table 3.1 YEARLY WEIGHTED AVERAGE RMS BENDING MOMENTS (Nm) IN THE 46 SPECTRA

<table>
<thead>
<tr>
<th></th>
<th>Plain</th>
<th>Fins</th>
<th>Harbours</th>
<th>Corners</th>
<th>3 Decks</th>
<th>Skins</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 Nm² Heave</td>
<td>0.30</td>
<td>0.29</td>
<td>0.37</td>
<td>0.32</td>
<td>0.34</td>
<td>0.39</td>
</tr>
<tr>
<td>80 Nm² Surge</td>
<td>0.44</td>
<td>0.45</td>
<td>0.40</td>
<td>0.46</td>
<td>0.47</td>
<td>0.48</td>
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<tr>
<td>800 Nm² Heave</td>
<td>0.82</td>
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<td>0.96</td>
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<tr>
<td>800 Nm² Surge</td>
<td>1.49</td>
<td>1.62</td>
<td>1.33</td>
<td>1.60</td>
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<td>1.81</td>
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Table 3.2 FACTORS OF INCREASE OF BENDING MOMENTS IN THE 46 SPECTRA

<table>
<thead>
<tr>
<th></th>
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<th>Fins</th>
<th>Harbours</th>
<th>Corners</th>
<th>3 Decks</th>
<th>Skins</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 Nm² Heave</td>
<td>1</td>
<td>0.96</td>
<td>1.26</td>
<td>1.09</td>
<td>1.15</td>
<td>1.32</td>
</tr>
<tr>
<td>80 Nm² Surge</td>
<td>1</td>
<td>1.03</td>
<td>0.90</td>
<td>1.05</td>
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</tr>
<tr>
<td>800 Nm² Heave</td>
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<td>1.08</td>
<td>1.29</td>
<td>1.18</td>
<td>1.34</td>
<td>1.54</td>
</tr>
<tr>
<td>800 Nm² Surge</td>
<td>1</td>
<td>1.09</td>
<td>0.89</td>
<td>1.08</td>
<td>1.16</td>
<td>1.22</td>
</tr>
</tbody>
</table>
We measured bending moment, motion, and mooring forces of the spine for four levels of freeboard. The sea used was a one second Pierson-Moskowitz spectrum with cosine squared directional spreading.

For a Pierson-Moskowitz, selecting an energy period $T_e$, with a corresponding energy wavelength $L_e$, fixes the root-mean-square wave height so that the wave steepness remains constant - i.e:

$$\frac{H_{rms}}{L_e} = \frac{1}{115}$$

However, in order to discover the effects of wave amplitude, we tested the model in seas larger and smaller than the Pierson-Moskowitz norm.

To produce the range of freeboard, we added half-inch slabs of foam plastic to the 'corners' configuration. The cross-sections are shown in figure 4.1 and the water level and freeboard indicated.

The foam had a density of about 50 kg/m$^3$. Each slab weighed 20 g, and 10 g of adhesive tape was needed to hold it on. This weight caused the spine to submerge about a millimetre for each slab added, corresponding to less than 1% change in draught and submerged volume. The adhesive tape was quite sufficient to hold the foam: even in the largest waves, there was no motion of the slabs relative to the spine.
Figure 4.1  The range of freeboard used in the experiments
Because the circular symmetry of the spine is lost once this range of appendages is added, the model can absorb and dissipate energy in the water by pitching. In the largest seas used, there was indeed considerable pitching motion, and a resultant mean rearward tilt. Consequently, readings of surge torque contain a contribution from heave forces, and vice-versa.

In these results we plot the modulus of the bending moments: the rms value of the modulus will not change whatever the extent of mixing of heave and surge forces.

Because the lines of the position gauge attach not to the spine centre, but to its circumference, there is a second-order response in heave to spine pitch motion. For small angles it is negligible; for angles larger than a radian, it becomes comparable with the spine radius. Surge readings are unaffected.

The graphs that follow show the various parameters plotted against the Hrms of the mixed sea, which covered the range 0 - 30 mm. The nominal one second Pierson-Moskowitz sea has an Hrms of 13.6 mm; the largest of the South Uist 46 spectra has an Hrms of 17.1 mm.

On each graph, the results for all four freeboard heights are plotted, together with the result for a plain circular spine as reference. The symbols for the cross-sections are identified by icons at the top of each graph.

The sampling rate was 20 Hz, the sampling period 25.6 seconds. Spine stiffness was 800 Nm² in all the experiments.
Bending moment

The modulus of the bending moment at each heave joint is synthesised from the heave bending moment, and the simultaneous bending moments experienced by the two adjacent surge joints. This synthesis is discussed in Section 4A of our 1984 Long Spine Report.

The average bending moment for the whole spine is calculated by taking the root-mean-square value of all the modulus readings for all the joints.

In figure 4.2 these average bending moments are plotted against $H_{rms}$. The data sets for each configuration form distinct curves. There is a monotonic increase in bending moment with increase in $H_{rms}$. The data sets all feature the same initial slope, but with varying negative curvature; the round spine shows greatest curvature of all. When a straight-edge is placed along each set of data points, it is clear that there is a definite point at which the slope changes. This break-point is progressively farther along the line the higher the freeboard.
Figure 4.2 Average bending moment versus Hrms
Table 4.1 summarises the bending moment curves of figure 4.2.

The freeboard of each appendage is shown in the top line of the table. Next, the break-point of the curve on the graph for each appendage is indicated. The slopes of each curve above and below the break-point are shown on the final two lines.

It is clear from the graph that the curve for each freeboard shows the same initial slope, and the calculated slopes in the table confirm this - the slopes are all very close to 280 Nm/m. Above the break-point the slopes vary over a range of about 35% - the rectangles cover a range of 17%.

The table shows that for the three appendages with decks, the break-point is very close to half the freeboard. Looking at the model and the waves in the course of the experiment one sees that at this $H_{rms}$ some of the waves are just starting to pass over the top of the model.

The plain spine has a smooth rounded top and so waves tend to go over the top of it more easily. This accounts for the lower than expected break-point. The square section shows a rather higher break-point than expected. All the rectangle sections tend to pitch in the larger waves. This increases the freeboard, and so for the square section there will be a disproportionate increase in freeboard.

These results imply that bending moment in spines increases with sea size, but that the rate of increase slows when the waves are high enough to go over the top of the spine. The slope difference is 35% for the plain spine, 22% for the square, dropping to 3% for the 3 layer deck.
<table>
<thead>
<tr>
<th>Spine type</th>
<th>Plain</th>
<th>Square</th>
<th>1 Deck</th>
<th>2 Decks</th>
<th>3 Decks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeboard  mm</td>
<td>8</td>
<td>5</td>
<td>15</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>Breakpoint mm</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>Graph slope Nm/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below break-point</td>
<td>278</td>
<td>282</td>
<td>282</td>
<td>281</td>
<td>281</td>
</tr>
<tr>
<td>Above break-point</td>
<td>198</td>
<td>233</td>
<td>253</td>
<td>265</td>
<td>273</td>
</tr>
</tbody>
</table>
Spine position

Figure 4.3 shows how the mean surge position of the spine changes with Hrms. Although only the position of the central joint was measured, the spine showed no long term curvature, and therefore the graphs indicate the position of the spine as a whole.

For the rectangular sections there is an aft drift in all seas. The section with the single deck shows a drift limit above 15 mm Hrms, the two taller sections continue to show increasing drift up to the limit of Hrms tested.

The round and square section spines show a small aft drift in small seas, then at Hrms above 15 mm show a forward drift.

Again, it would seem that for all sections, aft drift occurs up to the point of wave overtopping, after which the trend gradually reverses. The overtopping reduces momentum forces on the spine.

Interestingly, the square section shows greater fore drift than the round section - in the case of bending moments the round spine showed a distinctly lower breakpoint than the square spine. However, bending moments depend on the difference in motion between spine units, and here we measured overall spine motion.

Note how the drift is many times greater than the sea size. It is however dependant on the mooring stiffness - which can be made larger if necessary.

The corresponding mean mooring forces are shown in fig 4.4. They appear very much the same as the mean position plots - as indeed they should since the mooring response is reasonably linear over this range of motion.
Figure 4.3 Drift versus Hrms
Figure 4.4  Mean mooring force versus Hrms
Spine motion

In figure 4.5 the root-mean-square of the alternating motion in heave is plotted against $H_{rms}$. All the spine sections show a monotonic increase. Some curvature of the data sets is apparent, but not nearly so pronounced as the bending moment curves.

The amount of motion is about half the motion of the waves themselves. Crest averaging due to stiffness is reducing local motion of the spine.

The data sets fall into two obvious groups: those model configurations with decks in one, and the round and square sections in the other.

A possible explanation is that both the round and square sections have the same, very small, exposed volume. As soon as this volume is submerged, the absolute limit of upthrust is reached. Consequently, there will be less force available to keep the spine moving with the water surface, and less motion will result.
Figure 4.5  Rms heave motion versus Hrms
In figure 4.6 the root-mean-square alternating motion in surge is plotted against $H_{rms}$. The plots are dramatically different from those in heave, with very poor correlation of motion with $H_{rms}$. Note the increase in scale over the heave results in figure 4.5.

At large $H_{rms}$ the spine response is particularly ragged, but as in the heave case, the round and square section responses are similar, and very different from the deck sections.

The deck sections show very abrupt breakpoints in their curves beyond which the spine motion decreases with increasing $H_{rms}$. Again, the breakpoint rises with freeboard, though not in such a neatly arithmetical way as in the case of the bending moment curves.

Averaged over the whole amplitude range, the models move about one and a half times as much as the water. The next section attempts to track down the source of this extra motion.
Figure 4.6  Rms surge motion versus Hrms
The non-linear response of the spine motion to wave forces will, in addition to producing mean drift of the spine, also produce alternating motion lower in frequency than that of the waves. This motion corresponds to beat frequencies of the components of the wave spectrum.

To quantify this effect, the motion time series were Fourier transformed, and the rms of the frequency components above and below 0.4 Hz for each sea size were separately plotted against Hrms.

The Pierson-Moskowitz spectrum contained no components below 0.5 Hz, and so cannot contribute directly to low-frequency spine motion.

The graphs for heave are shown in figures 4.7 and 4.8. There is a measurable low-frequency response, about 6 times smaller than the motion in the wave frequency band. Both high- and low-frequency components are fairly linear with Hrms. The high-frequency motion is about half that of the water itself.
Figure 4.7  Rms heave motion versus $H_{rms}$. High frequency
Figure 4.8  Rms heave motion versus Hrms.  Low frequency
Figures 4.9 and 4.10 show the spine motion in surge, above 0.4 Hz and below it. The spine motion in the high-frequency band is about two-thirds of the motion of the water itself, and is fairly linear with \( H_{rms} \).

In the low-frequency band, the picture is completely different. Averaged over the whole of the amplitude range, the spine motion is larger than the water motion, which argues for the presence of a resonance, probably of the moorings. The graphs are very poorly behaved with \( H_{rms} \). The data sets for each configuration show break-points with complete reversals of slope. These break-points occur at higher \( H_{rms} \) the higher the freeboard, but little other systematic response is obvious.
Figure 4.9  Rms surge motion versus Hrms. High frequenc
Figure 4.10  Rms surge motion versus Hrms. Low frequency
Summary.

The freeboard experiments demonstrate that spine bending moment, spine mean position, and mean mooring force change very smoothly with Hrms. The alternating data from the position gauge in heave confirms the linearity of the spine motion with Hrms when a strong restoring force is provided by buoyancy. The data for surge, where low-rate moorings provide the restoring force, shows a highly non-linear response with possible resonances.

The spine bending moment curves are well-behaved enough for us usefully to infer the onset of wave overtopping - the data display distinct breakpoints which are arithmetically related to the freeboard. Mooring and position measurements confirm that the general effect of adding freeboard is to increase forces overall, and to delay the point at which wave overtopping can be expected to reduce those forces.
The bending moment spatial arrays in the 46 spectra, for all the model configurations at two stiffnesses in heave and surge.

Data on plain spines in other seas are given in the 1984 Long Spine Report.
Figure 5.1 Plain. Heave. 800 Nm2
Figure 5.2  Corners.  Heave. 800 Nm2
Figure 5.4  3 layer Deck. Heave. 800 Nm2
Figure 5.5  Skins.  Heave.  800 Nm2
Figure 5.6 Harbours. Heave. 800 Nm2
Figure 5.7  Plain. Surge. 800 Nm2
Figure 5.8  Corners.  Surge.  800 Nm2
Figure 5.9  Fins.  Surge.  800 Nm2
Figure 5.10  3 layer Deck. Surge. 800 Nm2
Figure 5.11  Skins.  Surge: 800 Nm2
Figure 5.12  Harbours.  Surge.  800 Nm2
Figure 5.13  Plain.  Heave.  80 Nm2
Figure 5.14  Corners.  Heave.  80 Nm2
Figure 5.15  Fins.
Heave.  80 Nm2
Figure 5.16  3 layer Deck. Heave. 80 Nm2
Figure 5.17  Skins.  Heave.  80 Nm2
Figure 5.18  Harbours.  Heave.  80 Nm2
Figure 5.19 Plain. Surge. 80 Nm2
Figure 5.20  Corners.  Surge.  80 Nm2
Figure 5.21  Fins.  Surge.  80 Nm2
Figure 5.22  3 layer Deck. Surge. 80 Nm2.
Figure 5.23  Skins.  Surge.  80 Nm2
Figure 5.24  Harbours.  Surge.  80 Nm2