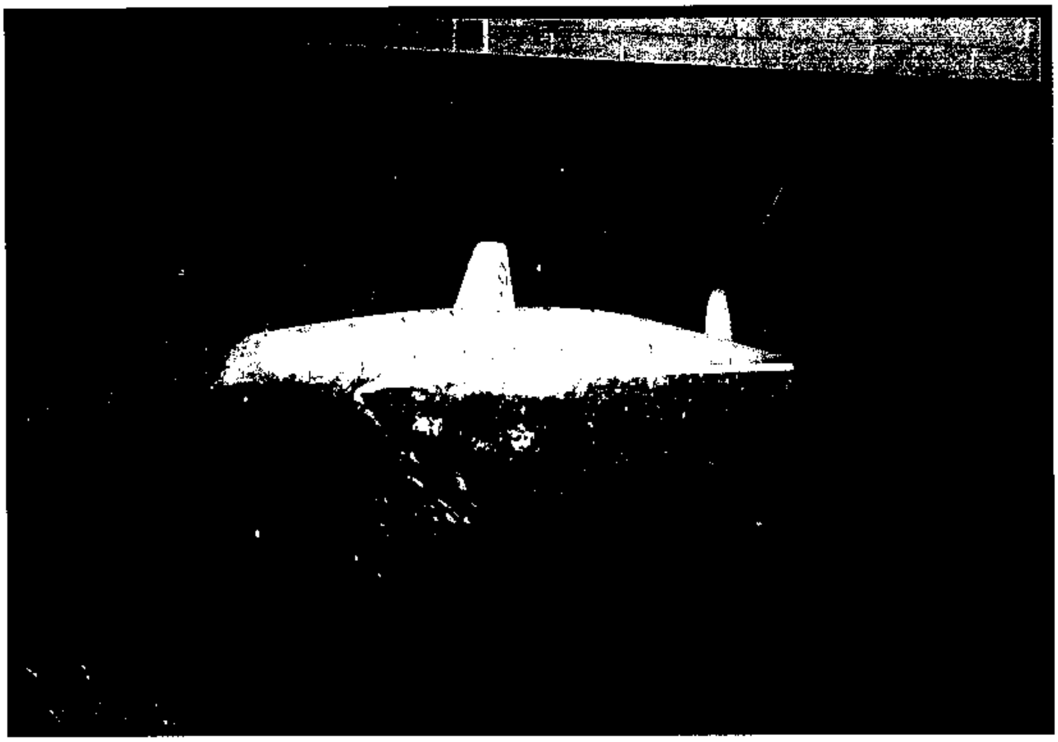
An Investigation into the Influence of the Angle of Limiting Stability on the Self-Righting of *Business Post Naiad*

Report to N.S.W. Police for Sydney Hobart Yacht Race Coroner's Inquiry



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An Investigation into the Influence of the Angle of Limiting Stability on the Self-righting of *Business Post Naiad*

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EXECUTIVE SUMMARY

During the 1998 Sydney/Hobart race, a number of yachts were capsized by the force of the waves. One of these, the Business Post Naiad, remained inverted for a lengthy period.

Subsequent investigations revealed that this yacht's IMS measured condition resulted in a limit of positive stability that was less that that required by the race regulations and as a result, an investigation was conducted into the effect of the yacht's limit of positive stability on the likelihood of it self-righting.

Experiments were conducted on a 1/12.5 scale model of the Business Post Naiad in waves in the towing tank at the Australian Maritime College. Two different experimental procedures were used: capsizing/self-righting the model in a single breaking wave; and self-righting the model in steep irregular waves.

Four variations of the limit of positive stability were tested, together with one condition which had a different roll radius of gyration, without water on board the model. In addition, two variations of the limit of positive stability were tested to represent the condition with 4000kg of water on board.

The following conclusions were drawn from these tests:

1. if the limit of positive stability is decreased from 119° to 104.7° the yacht requires a smaller wave to capsize it in beam breaking waves;
2. if the limit of positive stability is decreased from 119° to 104.7° the yacht is much less likely to self-right under the action of waves; and
3. when the yacht has 4000kg of water on board, the effect of the limit of positive stability on the size of wave required to capsize it is much less, however the effect of the limit of positive stability on the likelihood of it self-righting is similar to the effect when there is no water on board.

1. INTRODUCTION

Background

During the 1998 Sydney/Hobart race, a number of yachts were capsized by the force of the waves. One of these, the Business Post Naiad, remained inverted for a lengthy period.

Subsequent investigations revealed that this yacht's IMS measured condition resulted in a limit of positive stability that was less that that required by the race regulations.

As a result, an investigation was conducted into the effect of the yacht's limit of positive stability on the likelihood of it self-righting.

Effect of vertical centre of gravity on yacht stability

The forces acting on a yacht floating in water are shown in Figure 1.1. Here it can be seen that the upward force acts through the centre of buoyancy and the downward force acts through the centre of gravity.

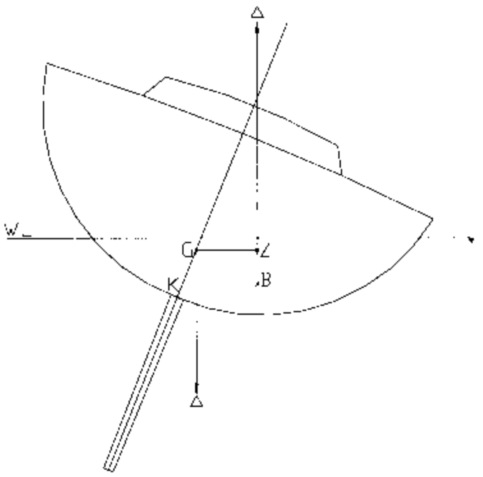

Figure 1.1 Forces acting on a heeled yacht

When the yacht is heeled, as shown in the diagram, a righting moment can occur which is the product of the distance between the lines of action of these forces (GZ) and the magnitude of the force, which is the vessel's weight, or displacement (Δ).

As the yacht's displacement remains constant, but the value of GZ, or righting lever, varies with heel angle a convenient way to view the stability of the yacht is to plot GZ against heel angle as shown in Figure 1.2.

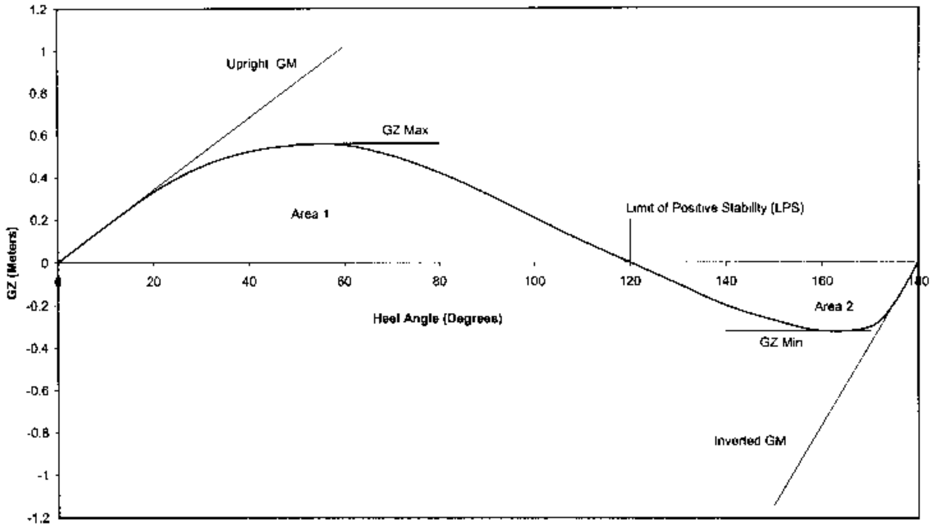

Figure 1.2 GZ curve

It is generally accepted that the critical issues effecting the likelihood of a yacht capsizing are:

GM: the slope of this curve at zero degrees of heel (known as the metacentric height);
LPS: the heel angle at which the curve crosses the axis (known as the Limit of Positive Stability);
GZ_{max}: the maximum value of the GZ curve; and
$Area_1$: the area under the GZ curve from zero degrees to the Limit of Positive Stability.

Although not as much is currently understood about the factors effecting the likelihood of self-righting, it is reasonable to assume that they will be influenced by:

GM_{inv}: the inverted GM,
LPS: the Limit of Positive Stability;
GZ_{min}: the maximum negative GZ value; and
$Area_2$: the area between 180° and the Limit of Positive Stability.

Clearly, the vertical position of a yacht's centre of gravity will have a significant impact on the GZ curve, including the above parameters, and hence on the likelihood of it capsizing and self-righting.

If the position of the vertical centre of gravity is raised, as shown in Figure 1.3, the GM is reduced, the LPS is reduced and the area under the curve between 0° and LPS will be reduced – all tending to make the yacht more likely to capsize. Also, the inverted GM will be increased, the value of the maximum negative GZ will be increased, and the area between 180° and the LPS will be increased – which, together with the decrease in LPS will make the vessel less likely to self-right.

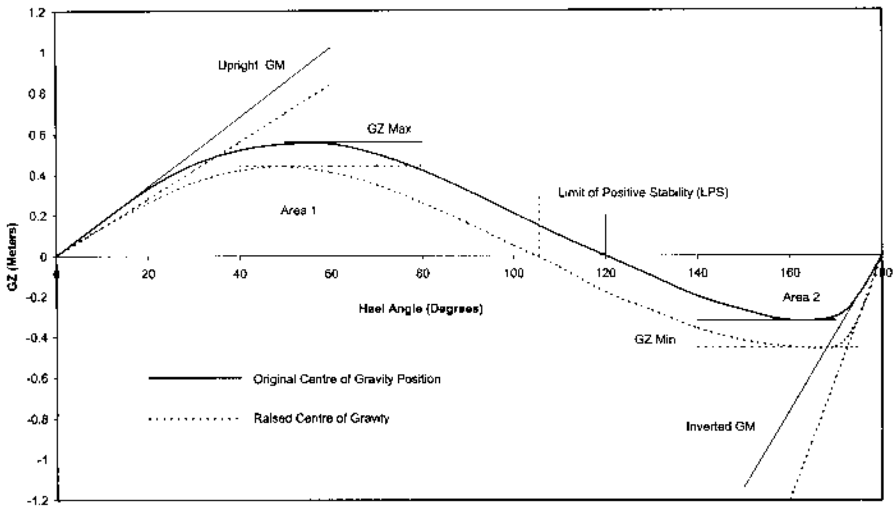

Figure 1.3 Effect of Vertical Position of the Centre of Gravity on GZ Curve

From this it can be seen that there is a direct link between the vertical position of the centre of gravity and the stability critical parameters, including the LPS. As the IMS regulations specify the required maximum value of LPS they are, in effect, specifying the maximum vertical position of the centre of gravity for the particular yacht at the specified displacement.

Race stability regulations

Yachts competing in races governed by the IMS rule are required to meet stability criteria as specified by the Ocean Racing Council (Ocean Racing Council, 1999).

A yacht's eligibility for entry in IMS races of ORC Special Regulations Categories 0, 1, or 2 may be limited by the Notice of Race or Sailing Instructions on the basis of her Stability Index.

The Stability Index minima in the table below are recommended. Because the ORC race categories are stated in general terms, the special circumstances of any particular race may make deviations from these recommendations appropriate.

ORC Race Category	Stability Index*
0	120°
1	115°
2	110°

* For the 1998 Sydney Hobart Race for IMS yachts, Cat 1 races call for a Limit of Positive Stability (LPS) or a Stability Index of 115° or greater. The CYCA's Notice of Race modifies this requirement with a grandfathering clause that exempts yachts that have competed in a previous Sydney Hobart race to have an LPS of 110°. (CYCA, 1999.)

Aims of this investigation

The aims of this investigation were as follows:

1. to determine the effect of the Limit of Positive Stability (LPS) on the capsizability of the Business Post Naiad; and

2. to determine the effect of the Limit of Positive Stability (LPS) on the self-righting ability of the Business Post Naiad,

at a displacement of 7,161kg (IMS sailing trim displacement) with and without 4,000kg of water on board.

Method

The investigation was based on testing a scale model of the Business Post Naiad in waves in the towing tank at the Australian Maritime College. To determine the effect of the LPS on both the capsizability and the self-righting ability, a range of tests were conducted with different vertical centre of gravity positions.

Capsize due to a wave induced knockdown is a very rare event. This depends on the vessel encountering a severe breaking wave at exactly the wrong instant. The size of the breaking wave required to cause a capsize will depend on its relative position to the yacht, and on the yacht's initial condition prior to the impact.

In order to test this in a realistic manner in the towing tank, the wavemaker was used to create a single breaking wave, which was arranged to break next to the model. Prior to the breaking wave encountering the model it was in calm water, with a constant initial condition. A number of tests were carried out for each wave height, with the model located at a slightly different position in each. This was then repeated for a range of wave heights and the largest wave which did not capsize the model was determined for each LPS condition modelled.

Self-righting occurs after a relatively short period of time. This time was determined statistically by running irregular waves corresponding to those existing at the time of the capsize in the towing tank.

The yacht model was initially inverted and the wavemaker generated irregular waves corresponding to a particular significant wave height. The length of time it took for the model to self-right was obtained. This was repeated a number of times to ensure statistical reliability, and then repeated for a range of significant wave heights to obtain a graph of average time taken for the yacht to self-right against significant wave height.

In addition, the technique using a single breaking wave was also applied to the inverted model and the maximum size of wave that would not self-right the model also determined.

2. TEST PROGRAM

The tests consisted of two parts:

1. testing in a single breaking wave; and
2. testing in steep irregular waves.

Tests were limited to the beam sea condition, with the wave approaching the model from the port side when it was upright and the starboard side when it was inverted.

Test program in a single breaking wave

The tests in the single breaking waves were primarily used to determine the maximum size of wave that would not capsize the vessel, regardless of its position in the breaking wave.

Although initially it was intended only to use this procedure to determine the capsizing boundary, it was also used to determine the self-righting boundary for comparison with the tests in steep irregular waves.

Test program in steep irregular waves

Steep irregular waves were used to self-right the model. A two parameter JONSWAP spectrum was used for all the tests, as this is known to be appropriate to coastal conditions with short steep breaking seas.

The two parameters required to specify the spectrum were the peak frequency, f_p, and the significant wave height, $H_{1/3}$. Suitable breaking waves were generated with f_p held constant at 0.2Hz. $H_{1/3}$ was varied to generate different sized waves.

The time to self-right the model for each condition was measured. For each condition, sufficient runs were made to give at least ten self-rights and the times were averaged to obtain the average result. The measured wave characteristics were also averaged over the same runs to give the average value for that condition.

Conditions tested

The model was tested with four different LPS values varying from the assumed value at the time of the incident of 104.7° to a maximum value of 119° with a constant displacement and as close to a constant roll radius of gyration as possible. Two different roll radii of gyration were tested with constant LPS to ensure that the small changes in roll radius of gyration did not influence the results.

In addition, the model was tested with the equivalent of 4000kg of water on board at two different LPS values to ensure that the conclusions from the tests with the model dry are not significantly effected by the presence of water on board.

Details of the conditions tested are given in Tables 3.2 and 3.3.

3. MODEL PARTICULARS

A 1/12.5th scale model was constructed to the lines plan provided by the NSW Water Police Branch. It was fitted with a complete coachroof and cockpit which could be removed to enable the internal ballast weights to be moved during the ballasting process. This was sealed using vasciline and waterproof tape and was removed and resealed periodically to remove the small amounts of water that seeped into the model during the tests. The model was weighed regularly and testing ceased if its displacement increased by more than 15g.

Figure 3.1 is a copy of the body plan, and a photograph of the completed model is shown in Figure 3.2. Note that the details of the cockpit of the actual vessel differed from the drawings provided, however the model maker consulted with members of the crew of the yacht to ensure that the model represented the actual vessel.

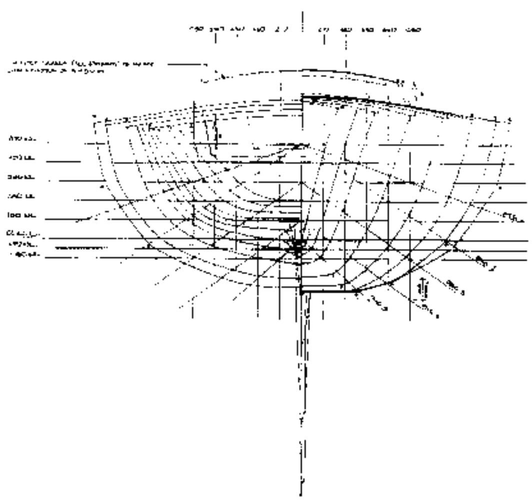

Figure 3.1 Body Plan

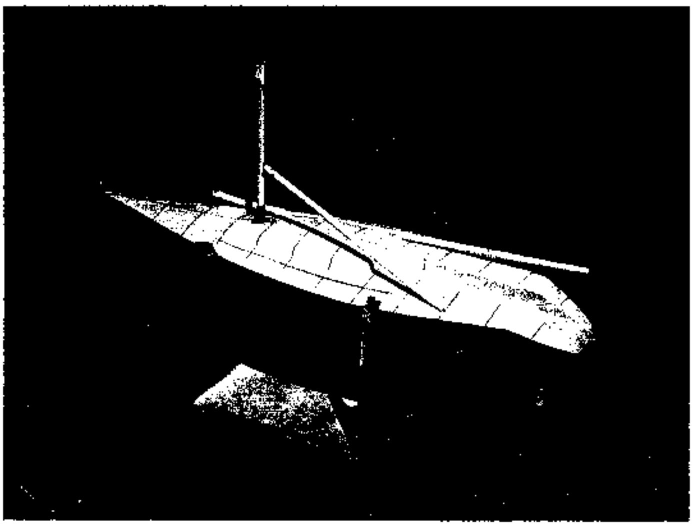

Figure 3.2 Photograph of completed model

The model was fitted with a mast and boom which were arranged to simulate the configuration at the time of the incident.

To enable a realistic roll radius of gyration to be obtained it was necessary to keep the weight of the model as low as possible and so it was constructed from carbon fibre. As a result of preliminary tests which showed that it was difficult to simulate the lowest centre of gravity position, the model was fitted with a solid lead keel. For the higher centre of gravity positions, holes were drilled in the lead keel and filled with filler making it possible to raise the centre of gravity, as shown in Figures 3.3 and 3.4. The lead was later replaced for the tests with the lowest centre of gravity with water on board.

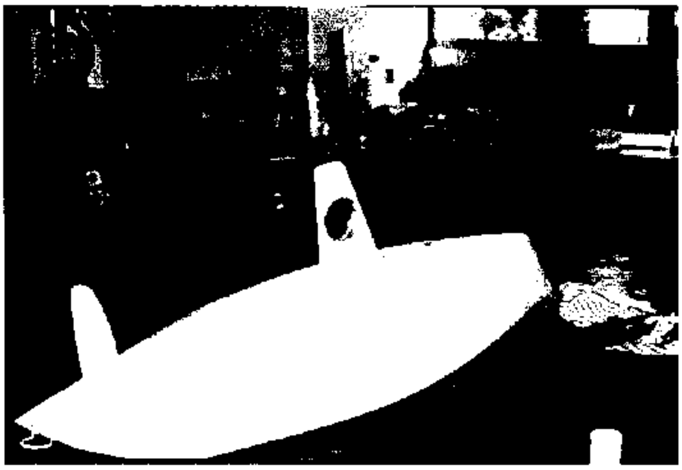

Figure 3.3 Photograph showing hole in the lead keel

Figure 3.4 Photograph showing modifications to lead keel being filled

For the experiments with no water on board the model, five different conditions were tested. Four of these corresponded to different vertical centre of gravity positions, relating to the different Limit of Positive Stability (LPS) values, and the remaining condition was tested to check the influence of the roll radius of gyration on both capsizing and self-righting.

All the tests were conducted at a single displacement corresponding to 7,161kg full scale, (IMS sailing trim displacement) which was assumed to be the displacement at the time of the incident.

Two different conditions were tested representing 4,000kg of water on board, corresponding to different vertical centre of gravity positions.

The required vertical centre of gravity positions for the incident condition were calculated from the specified LPS values as follows. First the vertical centre of gravity for the yacht in the sailing condition which would give the desired LPS value using the IMS assumption of a flat deck was obtained from hydrostatic calculations. (See Appendix A) Next, the centre of gravity shift from the sailing condition to the incident condition was estimated as described in Appendix B. Note that this is a constant value independent of initial centre of gravity position.

The resulting required vertical centre of gravity values are given in Table 3.1 as distances from an assumed baseline through the lowest point of the canoe body and parallel to the design waterline.

IMS LPS Value (Degrees)	VCG (Sailing Condition) (m above assumed baseline)	VCG (Incident Condition) (m above ssumed baseline)
119	0.502	0.196
115	0.597	0.292
110	0.686	0.381
104.7	0.777	0.472

Table 3.1 Vertical Centre of Gravity Values (Full Scale)

For each condition the vertical centre of gravity of the model was set using a swinging frame as shown in Figure 3.5.

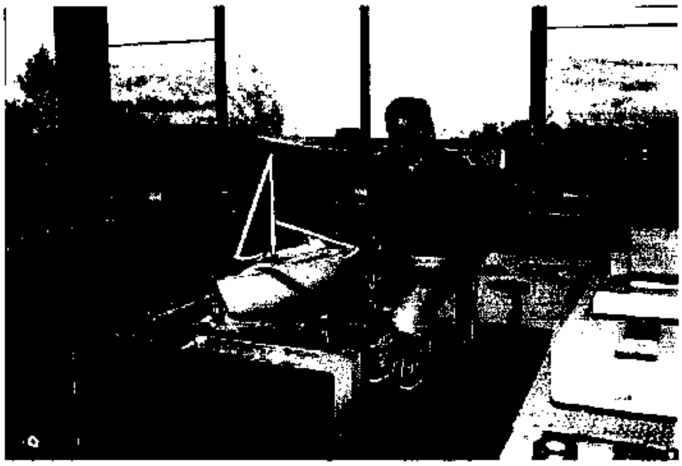

Figure 3.5 Photograph of model in swinging frame

The procedure was first to adjust the cradle vertically such that when the model was placed in it, the desired position of its centre of gravity would be in line with the centreline of the cradle's pivot shaft. The frame was then balanced with the cradle, but no model, in this position.

Next, the model was placed in the cradle, taking care to ensure it was always located in the cradle in the correct longitudinal position. Then its centre of gravity was adjusted vertically until the cradle and model were balanced around the shaft centreline. It was estimated the vertical centre of gravity of the model could be set to within ±1 mm using this procedure.

The longitudinal position of the centre of gravity was checked by ensuring the model floated at a level trim ±0.2°.

Once the vertical centre of gravity was set accurately, the roll radius of gyration was obtained by moving a known mass on the frame a known distance vertically downwards, and timing the roll period with and without the model in the frame. An average of at least 10 swings each of 3-5 cycles was used to establish the period. Details of the calculations are given in Appendix C. Masses were then moved vertically as required to adjust the radius of gyration as required. Each time this was done the vertical centre of gravity was carefully reset as described above prior to the model being swung.

The resulting values of roll radius of gyration for each LPS condition are given in Table 3.2.

Condition	IMS LPS Value (Degrees)	VCG (Incident Condition) (m above assumed baseline)	Radius of Gyration (m full scale)
A	119	0.196	1.20
B	115	0.292	1.23
C	110	0.381	1.21
D	104.7	0.472	1.29
E	104.7	0.472	1.02

Table 3.2 Actual values of roll radii of gyration (full scale) for tests without water on board

Note that conditions D and E have the same LPS value, corresponding to the same vertical centre of gravity (KG), with different Roll Radii of Gyration. All other conditions have a similar Roll Radius of Gyration.

The vertical centre of gravity, corresponding IMS LPS values, and roll radii of gyration for the two conditions tested with water on board are given in Table 3.3. Note that these values are for the dry model. For these tests it was not possible to achieve the same values as for the tests without water on board as the keel had been modified.

Condition	IMS LPS Value (Degrees)	VCG (Incident Condition) (m above assumed baseline)	Radius of Gyration (m full scale)
F	118	0.209	1.20
G	104.7	0.472	1.08

Table 3.3 Actual values of roll radii of gyration (full scale) for tests with water on board. Values are for dry vessel.

Note that conditions F & G do not correspond exactly to any of the earlier conditions. This is because these tests were conducted after the modifications were made in the keel and hence it was impossible to exactly duplicate the earlier conditions.

4. WAVE PARTICULARS

Single breaking wave

To generate a single breaking wave the wavemaker was programmed in the time domain to generate two sinusoidal waves with slightly different frequencies. As the second wave with the lower frequency travelled faster than the first one with the higher frequency, the second wave overtook the first one, resulting in a steep breaking wave.

Details of the paddle movement to create the single breaking wave are given in Table 4.1. Note that as the size of the wave was altered, the relative sizes of the two waves remained the same. Thus, the first paddle movement is expressed as a percentage of the second one.

	1st Paddle Movement	2nd Paddle Movement
Period (seconds)	1.423	1.583
Amplitude (%)	81	100

Table 4.1 Details of paddle movement to create single breaking wave

Irregular waves

A two parameter JONSWAP spectrum was used for these tests. The peak frequency, f_p, remained constant corresponding to a full scale value of 0.2Hz. The significant wave height, $H_{1/3}$, was varied over the range of 2.2m to 3.4m full scale. This gave steep breaking waves which were considered to be representative of the portion of the wave spectrum which was most likely to self-right the vessel.

Note that the long high waves which would have existed at the time of the incident were not modelled. These would have had limited influence on the self-righting of the vessel and were impossible to model in the towing tank. This is illustrated in Figure 4.2.

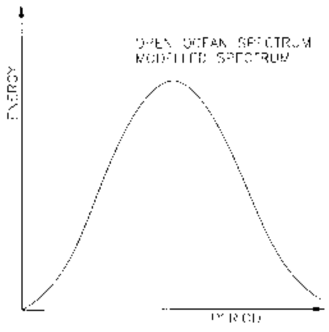

Figure 4.2 Sketch of JONSWAP spectrum compared to that which may have existed at the time of the incident

Care was taken to ensure the waves for each run were different. At the end of the prior run the shift register was saved and used as the initial register value for the next run. This ensured that the signal did not repeat until the end of the repeat period which was set to a full scale value of over 11 hours.

For each test configuration the spectra obtained for each individual run were ensemble averaged to give the average spectrum for that condition.

5. EXPERIMENTAL PROCEDURE

Single wave capsize

Prior to each test the model was set up at a known distance from the wavemaker as shown in Figure 5.1. Its position in the tank was constrained using the system of ropes as shown in the photograph.

For all these tests the port side of the model was closest to the wavemaker, and the video camera was mounted on the sub-carriage which was located down wave from the model.

A single breaking wave was generated as described in section 4 and just prior to it reaching the model the model was released from the constraint. The mechanism used is similar to the release mechanism for parachutes and ensured the model was not given a disturbance prior to the wave hitting it. A close up of the release mechanism is shown in Figure 5.2.

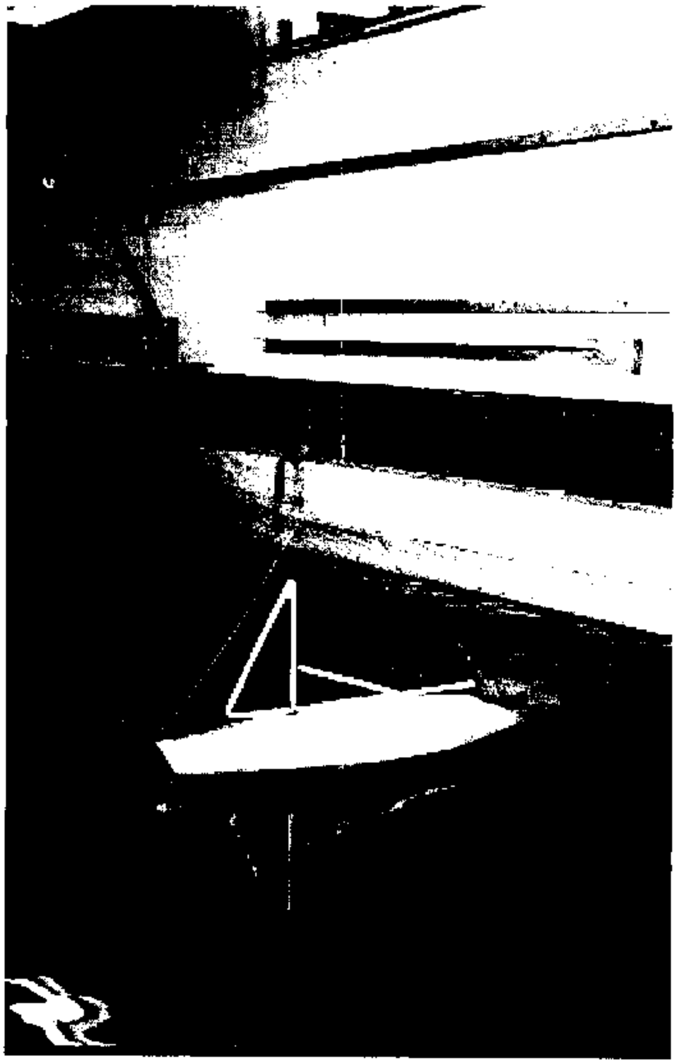

Figure 5.1 Photograph of model set up for single wave capsizing test

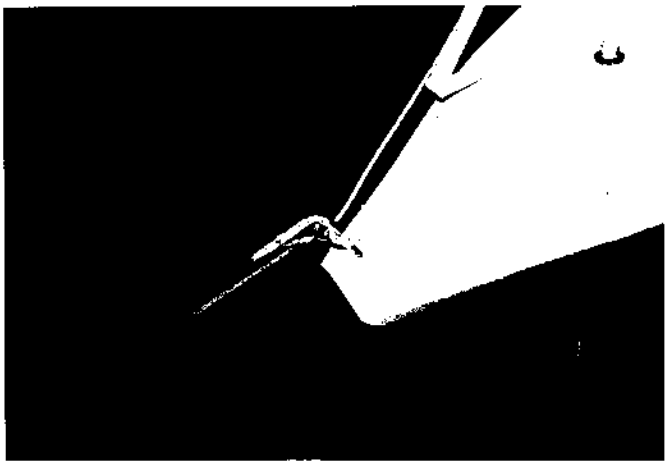

Figure 5.2 Photograph of release mechanism

The procedure was first to capsize the model in a breaking wave. Then it was re-righted and set up in the same initial position with respect to the breaking wave and the size of the wave reduced by a small amount. This process was repeated until the wave did not capsize the model.

Then, the initial position of the model with respect to the breaking wave was adjusted and the same wave was run. If this wave did not capsize the model, the tests were repeated with the same wave and a range of different initial positions of the model with respect to the breaking wave.

If it did capsize the model in any of the new positions, the wave height was reduced, and the process repeated until the largest wave which would not capsize the model – regardless of its initial position with respect to the wave – was determined.

Immediately following the above procedure the same wavemaker setting was used to generate an identical wave without the model. This wave was recorded on video twice with a marked grid in the background to enable its height to be determined. This was defined as the distance between the lowest point in the trough prior to the crest and the top of the breaking crest. The spray around the crest was ignored. Note that the lowest point and the highest point did not occur at either the same longitudinal distance from the wavemaker, nor at the same time. (See Figure 5.3)

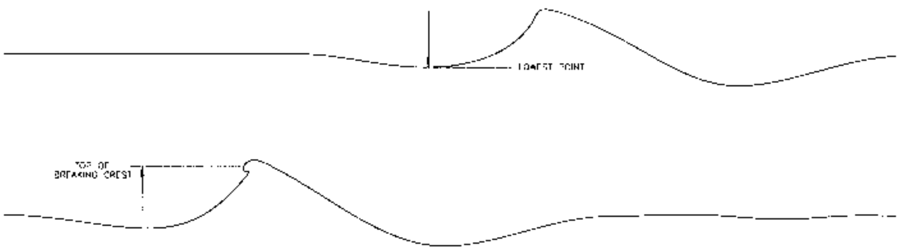

Figure 5.3 Sketch showing definition of wave height for breaking wave

The wave height was determined by playing back the video using the freeze frame facility and the average of the two runs obtained. Generally, there was less than 5mm model scale difference between the two waves.

Single wave self-right

The procedure for the self-righting experiments in a single breaking wave was similar to that used for the capsizing experiments. For this case it was not possible to constrain the model prior to the tests, so it was free floating. Care was taken to ensure it remained at the desired distance from the wavemaker prior to the wave impact.

For these tests the starboard side of the model was closest to the wavemaker, and the video camera was mounted on the sub-carriage which was located down wave from the model.

Self-righting in irregular waves

Prior to each test the model was placed in an inverted position beam on to the direction of wave travel, approximately 16 m from the wavemaker as shown in Figure 5.4. The starboard side of the model was towards the wavemaker.

The sub-carriage with video was positioned between the model and the wavemaker.

The zero value for the wave probe was obtained and checked against the previous zero value. Then the video recorder was started and the board with the run number held in a position in the field of view for a few seconds.

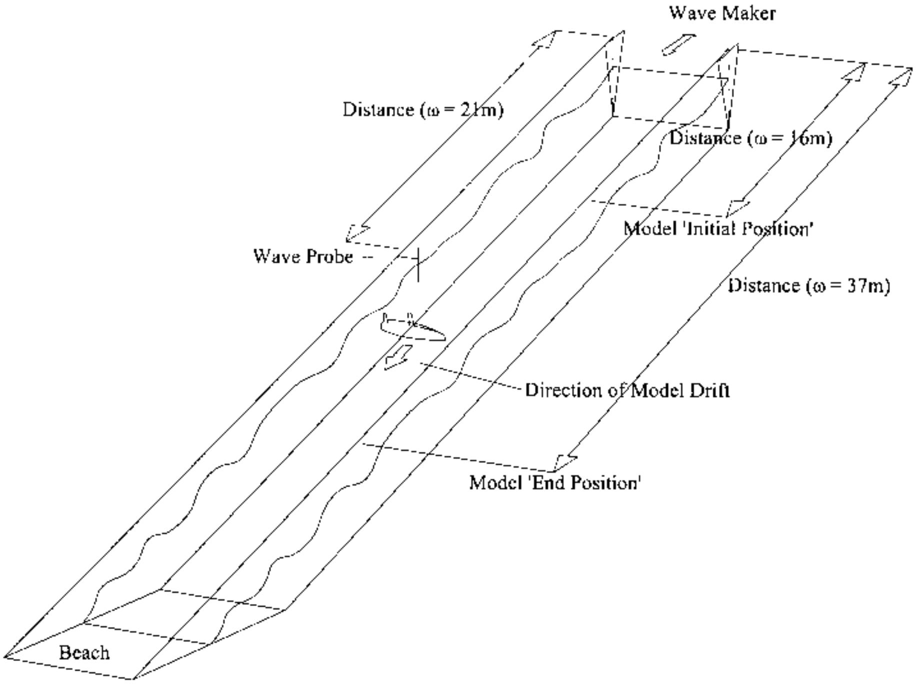

Figure 5.4 Sketch of set up for irregular wave tests

The wavemaker was started with the appropriate wave spectrum and a 2s ramp time. When the waves reached the model, timing was commenced. Once the waves had established themselves at the position of the wave probe which was approximately 21 m from the wavemaker, recording of the wave elevation started. Generally, this was approximately 10s after timing commenced. This continued automatically for 2048 samples at a sample rate of 100Hz. A photograph of the tests underway is given in Figure 5.5.

As the model drifted under the action of the waves, the sub-carriage with video camera was moved by hand to keep the model in the field of view. The model was maintained approximately (± 30°) beam on to the waves using a boat hook from the side of the tank. This was done carefully in a manner that had minimal influence on the model motions, and in particular care was taken not to contact the model just prior to or during it being impacted by a large wave.

Timing was stopped either when the model self-righted or when it reached a position 20m from the beach, as shown in Figure 5.4. If this occurred after the 2048 wave elevation samples had been taken, the wavemaker was ramped down. Otherwise, the wavemaker continued creating waves until the wave elevation samples had been recorded. During this time care was taken to position the model such that it did not interfere with the wave probe. Once the wavemaker was ramped down, the side beach was lowered to damp out wave action prior to the next run.

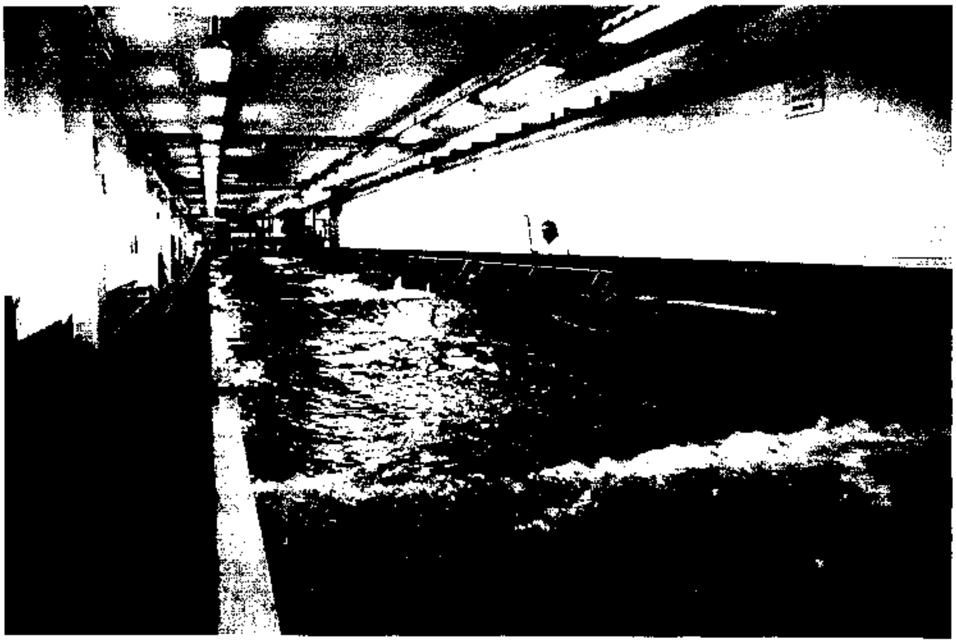

Figure 5.5 Photograph of model being tested in steep irregular waves

6. RESULTS

Results were obtained from the tests with and without water on board the model. For each of these cases the capsize and self-righting boundaries in a single wave were obtained as functions of LPS, as well as the self-righting time in irregular waves as functions of significant wave height for each LPS.

6.1 Without water on board

Single wave capsizing

The results from the single wave capsizing tests are given in Table 6.1. For convenience, the results are given in terms of the LPS in the sailing condition. See Table 3.1 for corresponding vertical centre of gravity values.

Condition	LPS (degrees)	Wave height (m)
A	119	5.06
B	115	5.38
C	110	4.44
D	104.7	4.38
E	104.7	4.19

Table 6.1 Results from single wave capsizing tests

Note that conditions A – D had similar roll radius of gyration, whereas condition E had a lower value. The corresponding values are given in Table 3.1.

The results for the conditions with the similar roll radius of gyration are presented in Figure 6.1.

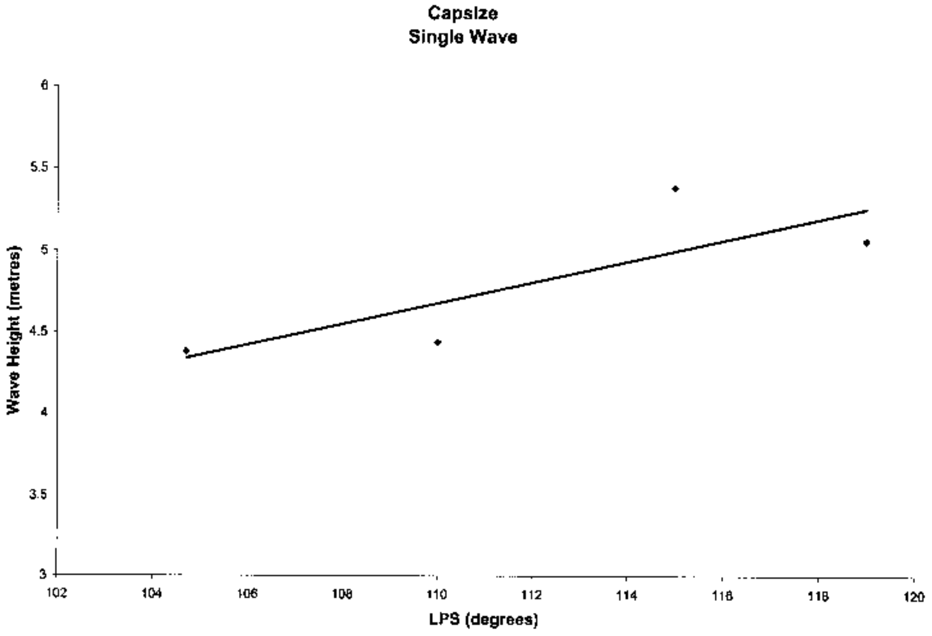

Figure 6.1 Plot of maximum single wave height that will not cause a capsize against IMS LPS value for constant roll radius of gyration (conditions A – D)

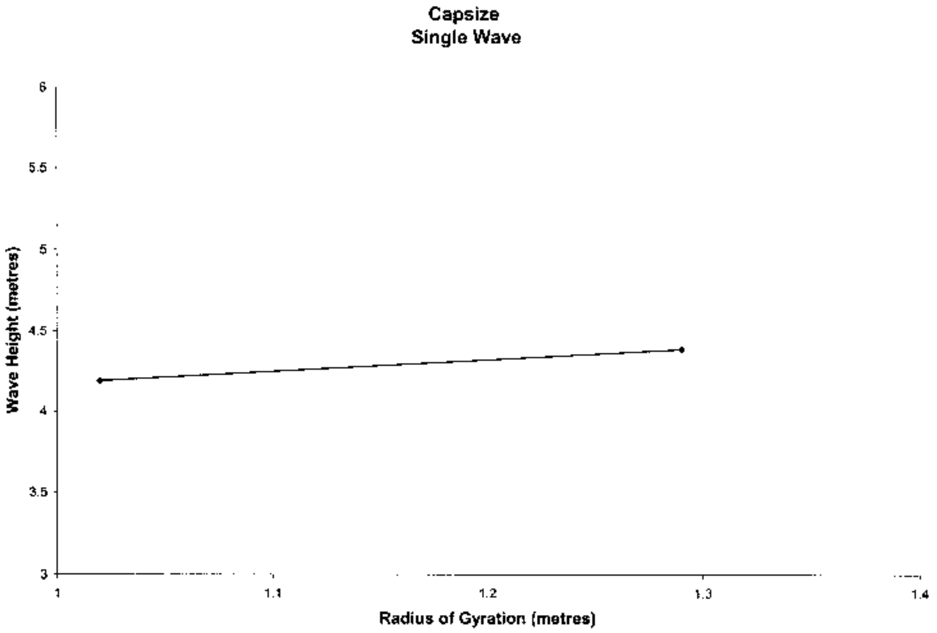

Figure 6.2 Plot of maximum single wave height that will not cause a capsize against roll radius of gyration for a constant IMS LPS value (conditions D & E)

Single wave self-righting

The results from the single wave self-righting tests are given in Table 6.2. For convenience, the results are given in terms of the LPS in the sailing condition. See Table 3.1 for corresponding vertical centre of gravity values.

Condition	LPS (degrees)	single Wave height (m)
A	119	3.25
B	115	3.75
C	110	3.91
D	104.7	3.90
E	104.7	4.00

Table 6.2 Results from single wave self-righting tests

Note that conditions A – D had similar roll radius of gyration, whereas condition E had a lower value. The corresponding values are given in Table 3.1.

The results for the conditions with the similar roll radius of gyration are presented in Figure 6.3.

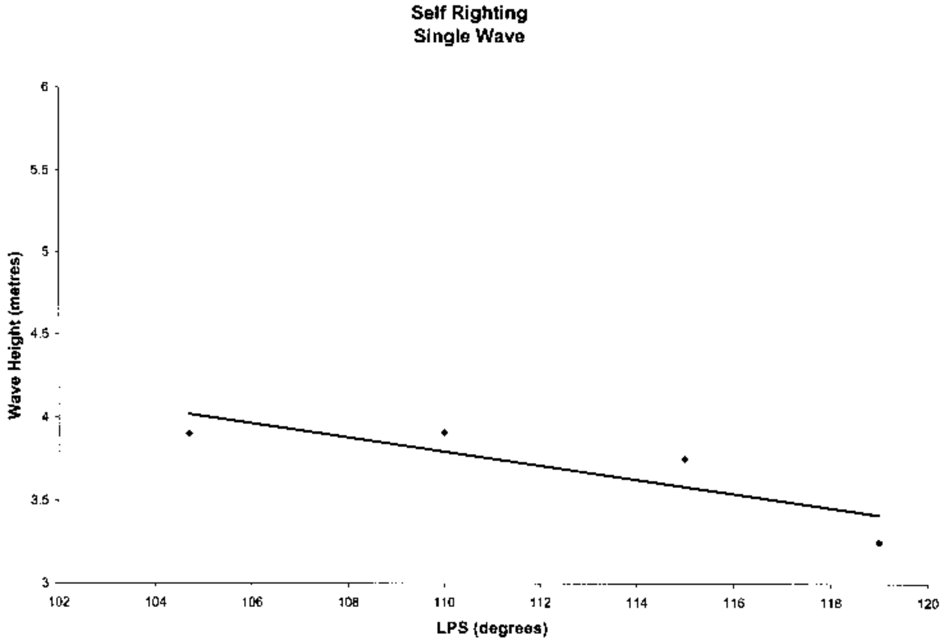

Figure 6.3 Plot of maximum single wave height that will not cause a self-right against IMS LPS value for constant roll radius of gyration (conditions A – D)

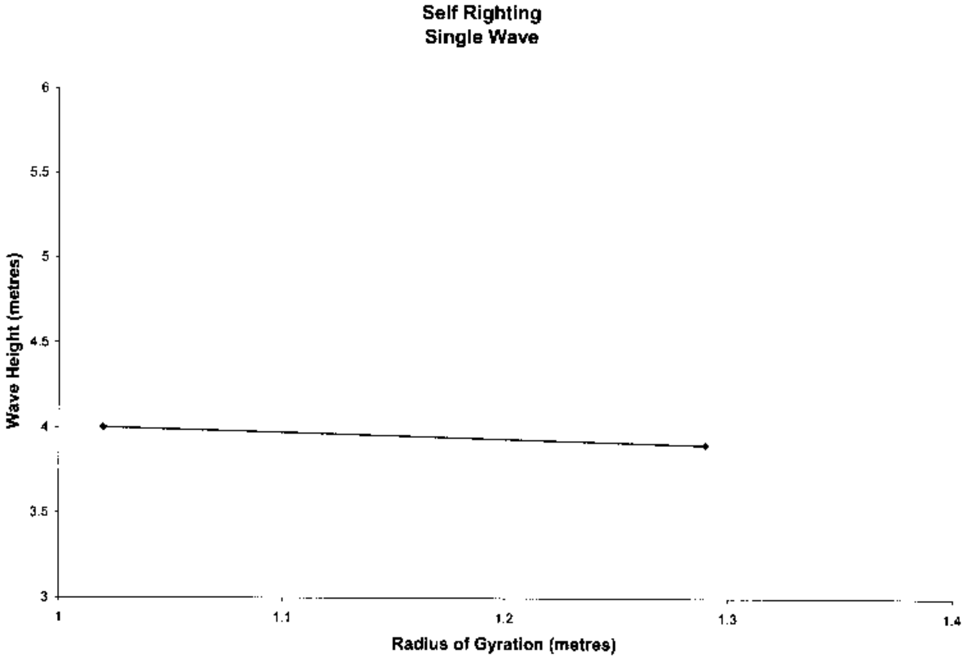

Figure 6.4 Plot of maximum single wave height that will not cause a self-right against roll radius of gyration for a constant IMS LPS value (conditions D & E)

Self-righting in irregular waves

Tests were conducted for a range of significant wave heights for each vertical centre of gravity position. Ten self-rights were obtained at each significant wave height, and the average time to self-right calculated.

The measured wave parameters for each condition were averaged and the resulting spectra are presented in Appendix D.

The individual measured self-righting times for each different condition tested are tabulated in Appendix E.

The average results for each of the four different LPS values with the similar roll radius of gyration are presented in Figure 6.5, and the effect of roll radius of gyration can be seen in Figure 6.6.

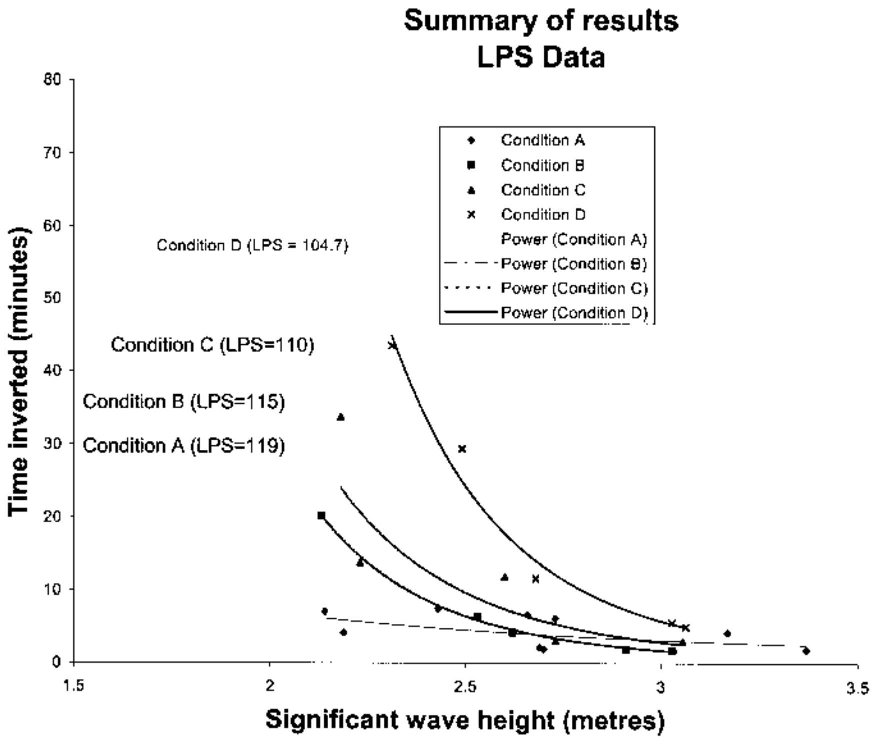

Figure 6.5 Average self-righting time (Effect of Limit of Positive Stability)

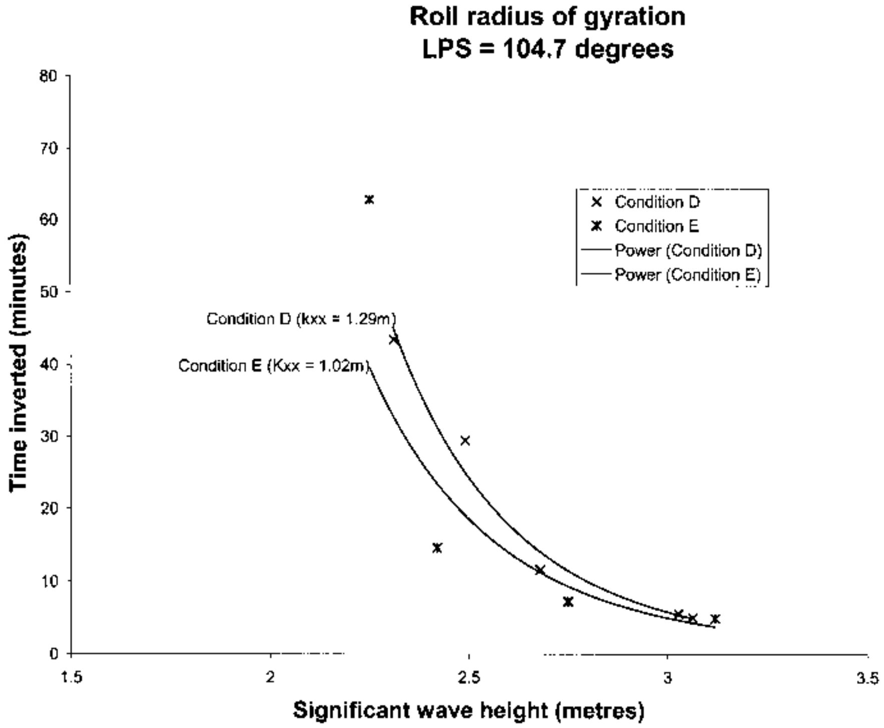

Figure 6.6 Average self-righting times (Effect of roll radius of gyration)

6.2 With water on board

Single wave capsizing

The results from the single wave capsizing tests are given in Table 6.3 and Figure 6.7. For convenience, the results are given in terms of the LPS in the sailing condition. See Table 3.2 for corresponding vertical centre of gravity values.

Condition	LPS (degrees)	single Wave height (m)
F	118	4.44
G	104.7	4.37

Table 6.3 Results from single wave capsizing tests

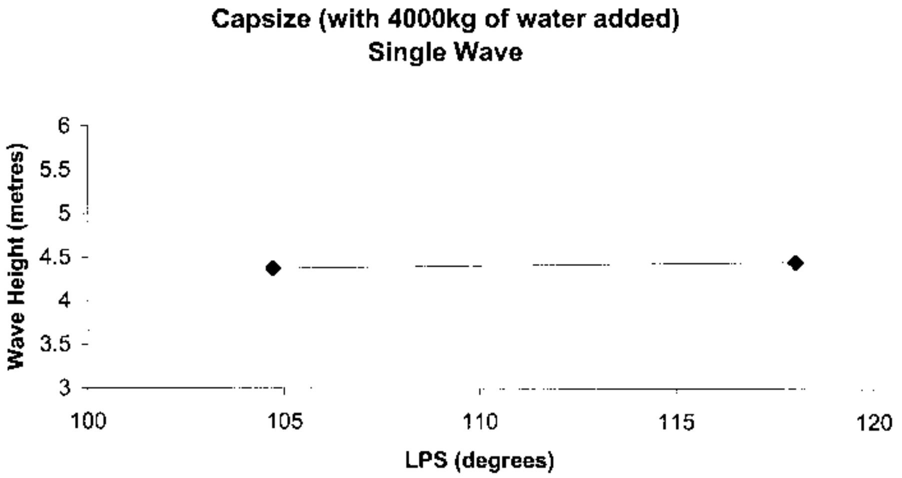

Figure 6.7 Plot of maximum single wave height that will not cause a capsize against IMS LPS value with 4,000 kg of water on board (conditions F & G)

Single wave self-righting
The results from the single wave self-righting tests are given in Table 6.4 and Figure 6.8. For convenience, the results are given in terms of the LPS in the sailing condition. See Table 3.2 for corresponding vertical centre of gravity values.

Condition	LPS (degrees)	single Wave height (m)
F	118	3.59
G	104.7	4.12

Table 6.4 Results from single wave self-righting tests

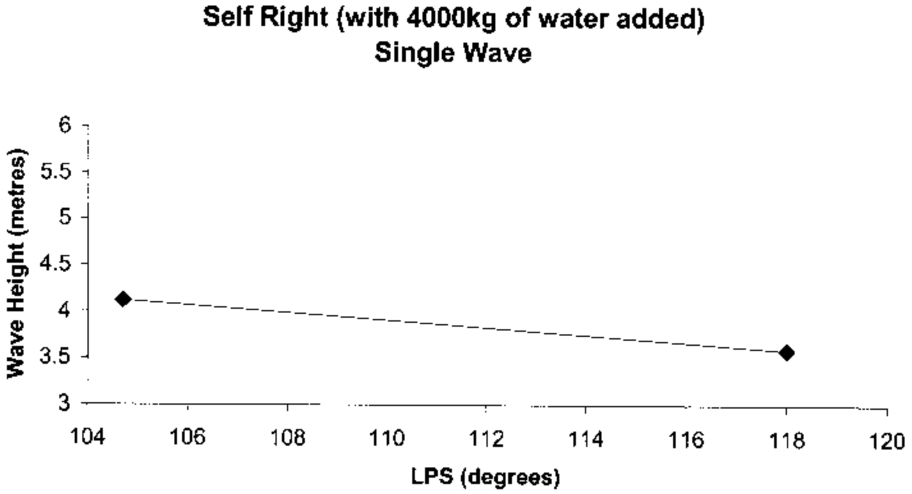

Figure 6.8 Plot of maximum single wave height that will not cause a self-right against IMS LPS value with 4,000 kg of water on board (conditions F & G)

Self-righting in irregular waves

Tests were conducted for a range of significant wave heights for each vertical centre of gravity position. Ten self-rights were obtained at each significant wave height, and the average time to self-right calculated.

The measured wave parameters for each condition were averaged and the resulting spectra are presented in Appendix D.

The individual measured self-righting times for each different condition tested are tabulated in Appendix E.

The average results are presented in Figure 6.9.

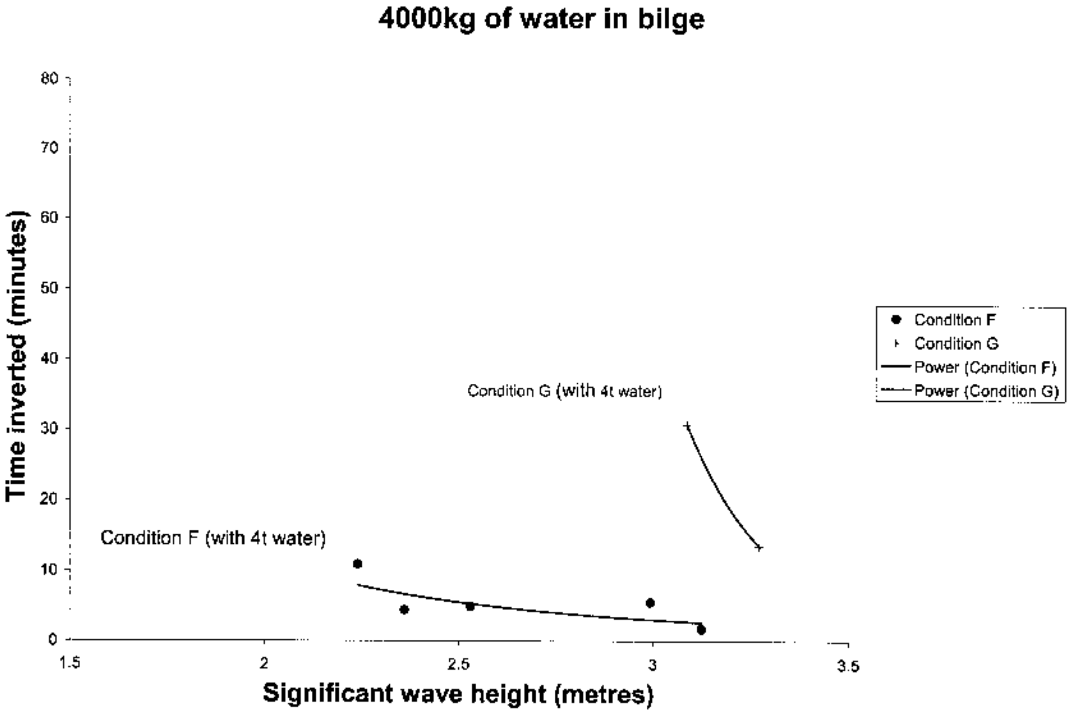

Figure 6.9 Average self-righting times with water on board

7. DISCUSSION

Effect of LPS on capsizing tendency
As can be seen from Table 6.1 and Figure 6.1, when there is a greater LPS value a larger wave is required to capsize the yacht. This is not unexpected and indicates that a yacht with a lower centre of gravity position, and hence a higher LPS value, is less likely to capsize in a beam breaking wave than one with a higher centre of gravity position.

This conclusion is less striking for the condition where there is 4000kg of water on board the vessel, as shown in Table 6.3 and Figure 6.7. In this case there is hardly any difference in the size of wave required to capsize the yacht.

Effect of Roll Radius of Gyration on capsizing tendency
As can be seen from Table 6.1 and Figure 6.2, when the yacht has a larger roll radius of gyration a slightly larger wave is required to capsize it.

This effect is much smaller than the effect of the centre of gravity for the range of roll radii of gyration tested, confirming that the differences in roll radii of gyration used for the capsize tests have not influenced the conclusion that when the yacht has a lower centre of gravity (and hence a higher LPS) it requires a larger wave to capsize it.

Effect of LPS on self-righting tendency
The effect of LPS on self-righting tendency can be obtained from either the results of the tests in the single breaking wave, (Table 6.2 and Figure 6.3) or from the results of the tests in steep irregular waves (Figure 6.5) for the case when there is no water in the yacht.

For both these test results it is clear that when the yacht has lower LPS values it is much less likely to self-right than when it has higher LPS values.

For example, at one significant wave height the average time taken to self-right increases from about 5 minutes to about 20 minutes if the LPS value is decreased from 119° to 104.7°.

When 4000kg of water is added to the yacht the effect is similar, with it being much less likely to self-right if it has a lower LPS than if it has a higher LPS value. (Table 6.4, Figures 6.8 and 6.9.)

Effect of Roll Radius of Gyration on self-righting tendency
As can be seen from Table 6.2, Figures 6.4 and 6.6, the roll radius of gyration has very little effect on the self-righting tendency. The results of the tests in the single breaking wave indicate that when the roll radius of gyration is greater a smaller wave will self-right the yacht, whereas the results from the tests in steep irregular waves indicate that when the roll radius of gyration is greater the average time to self-right the yacht is increased.

The important point about these results is that the effect of the roll radius of gyration on the self-righting tendency is very small for the range of roll radii of gyration tested. Therefore, the differences in roll radii of gyration used for the self-righting tests have not influenced the conclusion that when the yacht has a higher centre of gravity (and hence a lower LPS) it is much less likely to self-right.

8. CONCLUSIONS

From the tests conducted on a model of the Business Post Naiad in a single breaking wave and in steep irregular waves it is possible to make the following conclusions:

1. if the LPS value is decreased from 119° to 104.7° the yacht requires a smaller wave to capsize it in beam breaking waves;

2. if the LPS value is decreased from 119° to 104.7° the yacht is much less likely to self-right under the action of waves; and

3. when the yacht has 4000kg of water on board, the effect of the LPS on the size of wave required to capsize it is much less, however the effect of the LPS on the likelihood of it self-righting is similar to the effect when there is no water on board.

9. REFERENCES

CYCA, 1999, 'Report of the 1998 Sydney Hobart Race Review Committee' Published by the Cruising Yacht Club of Australia, May 1999.

Offshore Racing Council, 1999, 'International Measurement System' Published by the Offshore Racing Council, UK.

10. NOTATION

$Area_1$	Area under the GZ curve from 0° to LPS
$Area_2$	Area under the GZ curve from LPS to 180°
B	Position of centre of buoyancy
f_p	Peak frequency of wave spectrum
G	Position of centre of gravity
GM	Metacentric height
GZ	Righting lever
GZ_{max}	Maximum value of GZ curve
GZ_{min}	Maximum negative value of GZ curve
$H_{1/3}$	Significant wave height (defined as average of third highest waves)
K	Position of baseline
LPS	Limit of positive stability
r	Roll radius of gyration
VCG	Distance of vertical centre of gravity above baseline
Z	Position of intersection of horizontal line through G with vertical line through B
Δ	Vessel displacement

11. ABBREVIATIONS

AMC	Australian Maritime College
BPN	Business Post Naiad
CYCA	Cruising Yacht Club of Australia
IMS	International Measurement System
ORC	Offshore Racing Council

12. ACKNOWLEDGMENTS

The experiments reported were conducted under the supervision of Detective Senior Constable Stewart Gray and Senior Constable David Upston whose assistance and advice was highly regarded.

Mr Andy Dovell's advice during the set up phase of the experiments was invaluable, as was his assistance with the practical aspects of racing yacht design and operation, in particular with the IMS.

APPENDIX A

HYDROSTATIC CALCULATIONS

Appendix A
Hydrostatic calculations

The NSW Water Police Branch supplied the hull, keel and rudder lines of the vessel investigated.

These lines were then used to carry out the hydrostatic calculations using the same method as adopted by the IMS rules. The GZ curves for the four load conditions modelled (LPS = 104.7 – 119 degrees) are presented in Figure A1.

It should be noted, there will be small discrepancies in the hydrostatic results depending on the accuracy to which the hull is model. For this investigation, the hull was defined using 14 stations and 20 waterlines.

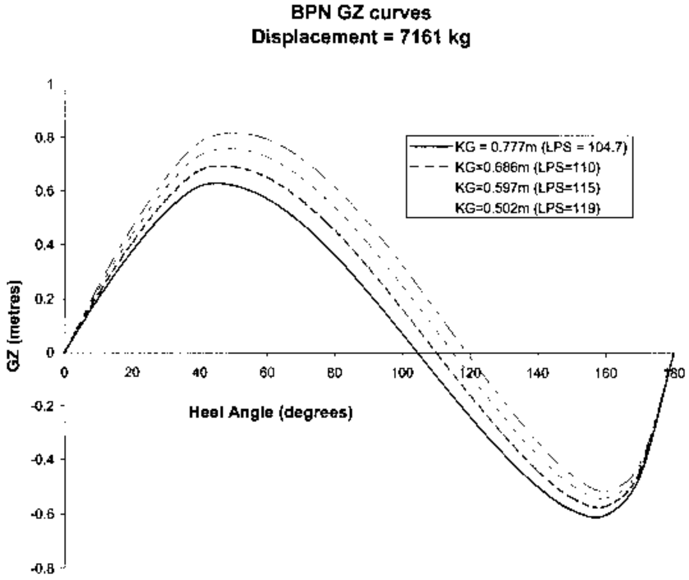

Figure A1 GZ curves

APPENDIX B

SHIFT IN THE VERTICAL CENTRE OF GRAVITY FROM SAILING TO INCIDENT CONDITION

Appendix B
Shift in the vertical centre of gravity from sailing to incident condition

For the investigation carried out, the vessel was loaded in what was considered the incident condition, that is, the loaded condition the vessel was in during the second capsize.

The incident condition encompassed the following modifications to the loaded sailing condition presented in the IMS certificate:

1. Rig and mast positioned on deck as given in the photo in Figure 3.2 (212kg moved down 6.09m).
2. Seven crew members moved from on deck to bunks/floor below deck (85kg moved down 1.5m).

This resulted in an overall downward shift in the centre of gravity of 0.305m.

The loading modification for each LPS condition modelled is presented in table B1.

Condition	IMS LPS value (Degrees)	KG (Sailing Condition) (Metres)	KG (Incident Condition) (Metres)
A	119	0.502	0.195
B	115	0.597	0.292
C	110	0.686	0.381
D	104.7	0.777	0.472
E	104.7	0.777	0.472

Table B1 Loading modification for each LPS value

Note, the vertical centre of gravity is relative to the base line passing through the lowest point of the canoe body.

APPENDIX C

RADIUS OF GYRATION USING THE TILT FRAME TECHNIQUE

Appendix C
Radius of gyration using the tilt frame technique

The tilt frame is set up with its centre of gravity in line with the rolling axis and a support for the base of the model positioned so as to locate the model within the frame to give the correct vertical centre of gravity (VCG) and static trim.

The model is then set up in the frame with its centre of gravity in line with the rolling axis. A known mass is then moved from a position on the frame slightly above the rolling axis through a known distance to a position on the frame slightly below the rolling axis. This gives a restoring moment without changing the moment of inertia of the frame. The natural rolling periods of the frame alone and the frame plus model can then be obtained.

The roll radius of gyration, *r*, is obtained from the following formula:

$$r = \sqrt{\frac{g.m.d.\left(T_2^2 - T_1^2\right)}{4.\pi^2.\Delta}}$$

Where:

m = mass moved, m
d = distance mass is moved, m
Δ = displacement of model, kg
T_1 = period of oscillation of the frame alone, s
T_2 = period of oscillation of the model plus frame, s

APPENDIX D

MODEL TEST WAVE SPECTRA

Appendix D
Model test wave spectra

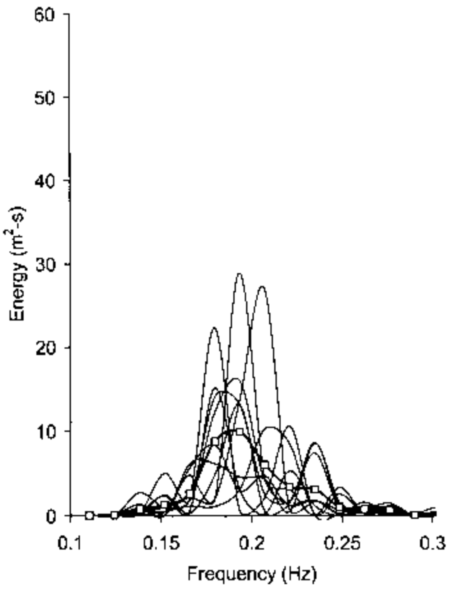

Figure D1
(Significant Wave Height = 2.66m)

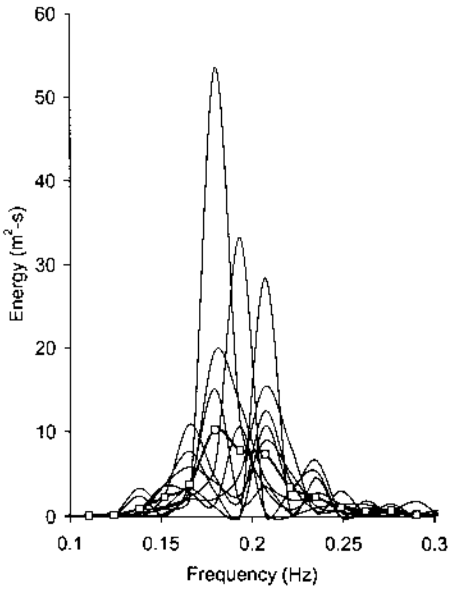

Figure D2
(Significant Wave Height = 2.73m)

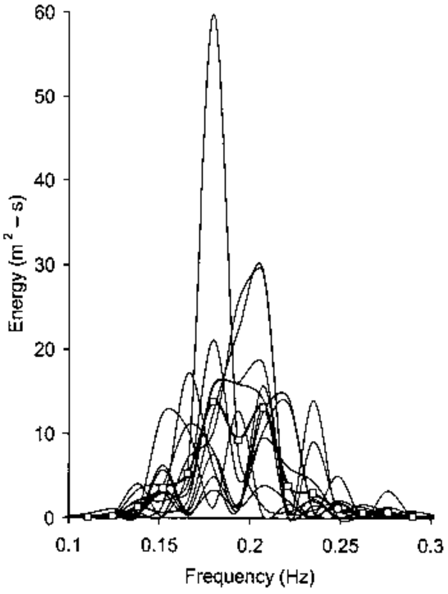

Figure D3
(Significant Wave Height = 3.17m)

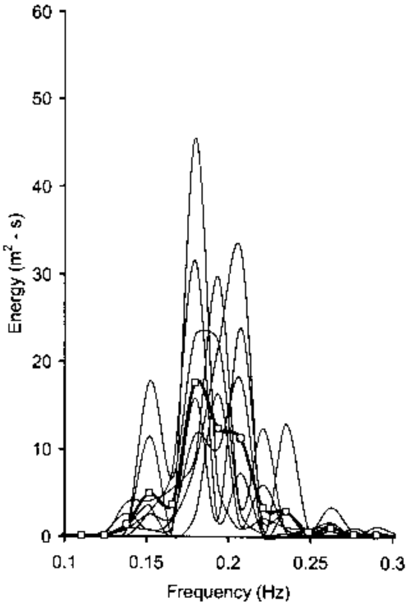

Figure D4
(Significant Wave Height = 3.37m)

—□— Average Spectrum

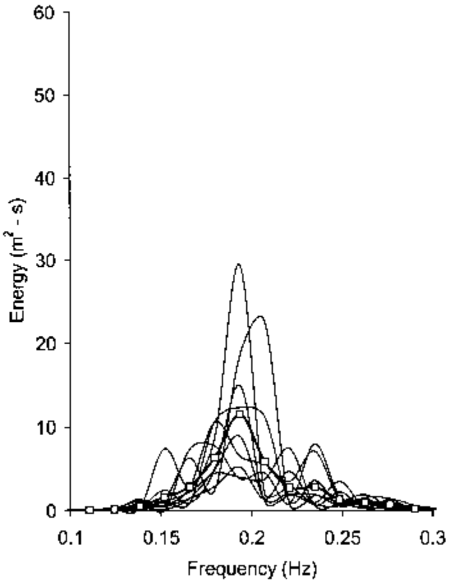

Figure D5
(Significant Wave Height = 2.69m)

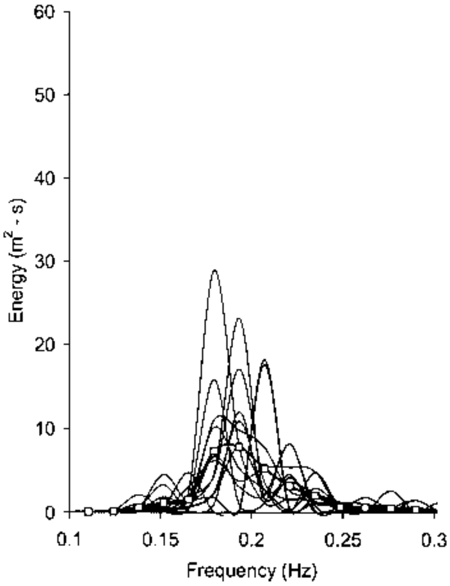

Figure D6
(Significant Wave Height = 2.43m)

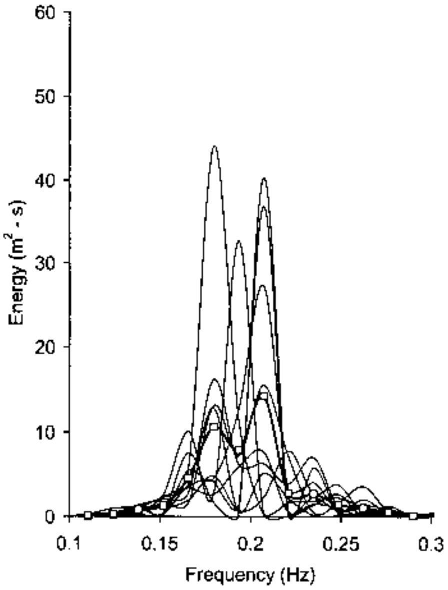

Figure D7
(Significant Wave Height = 3.03m)

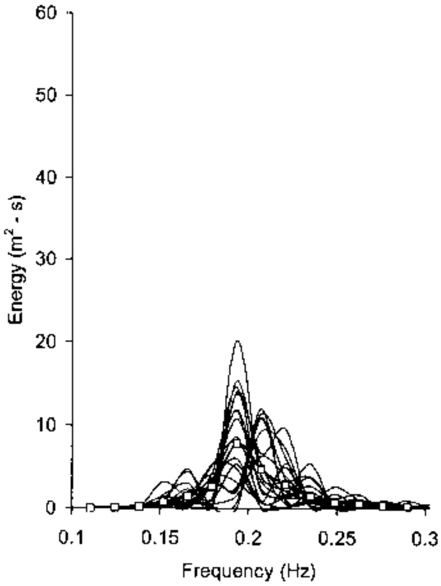

Figure D8
(Significant Wave Height = 2.13m)

—□— Average Spectrum

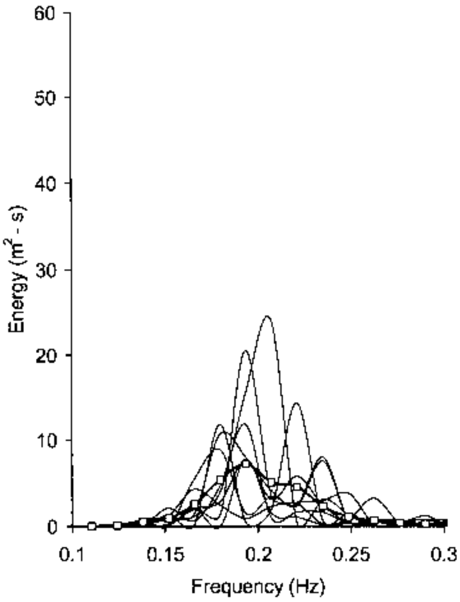

Figure D9
(Significant Wave Height = 2.53m)

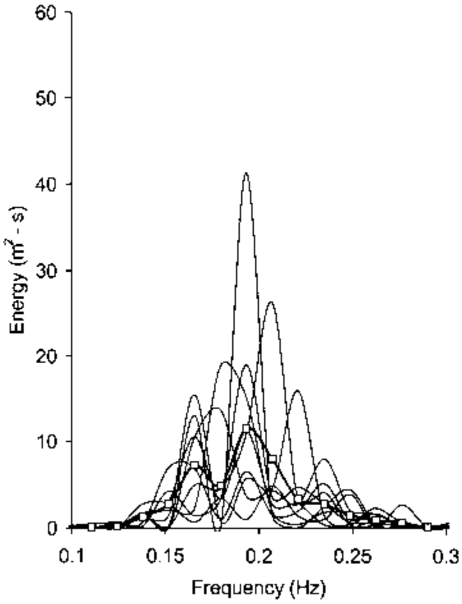

Figure D10
(Significant Wave Height = 2.91m)

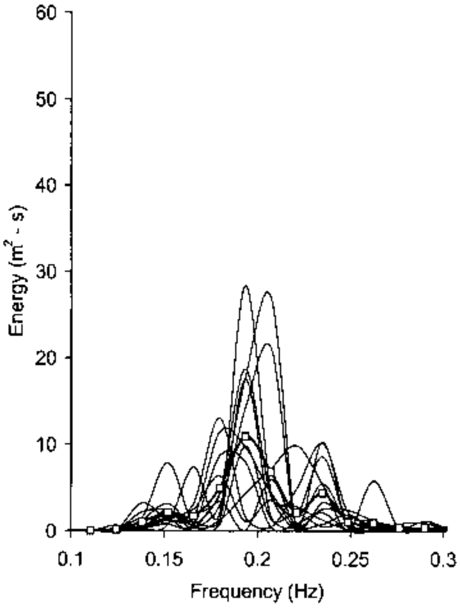

Figure D11
(Significant Wave Height = 2.62m)

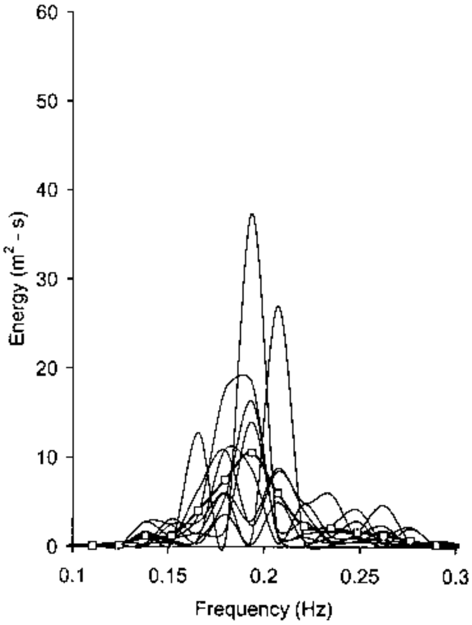

Figure D12
(Significant Wave Height = 2.70m)

—□— Average Spectrum

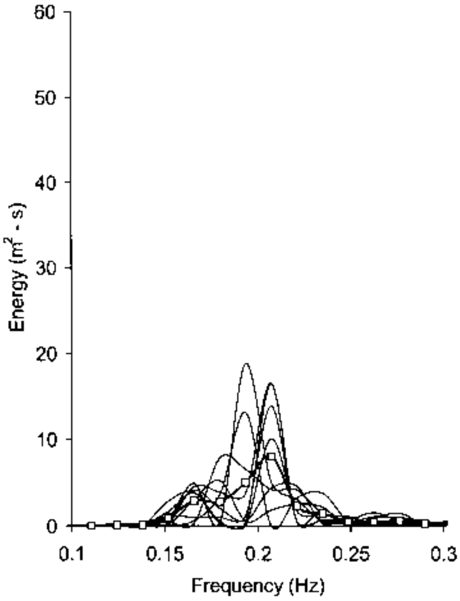

Figure D13
(Significant Wave Height = 2.19m)

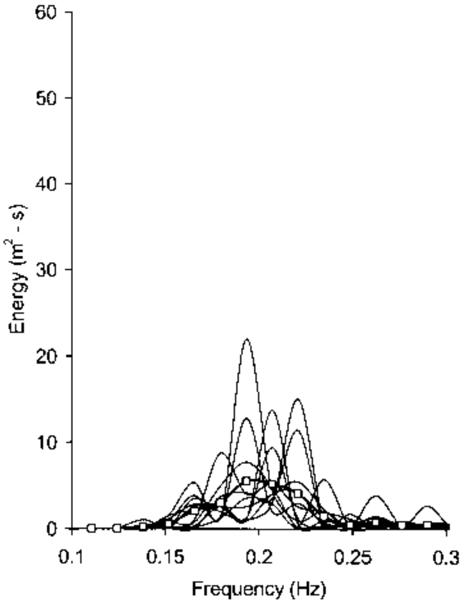

Figure D14
(Significant Wave Height = 2.14m)

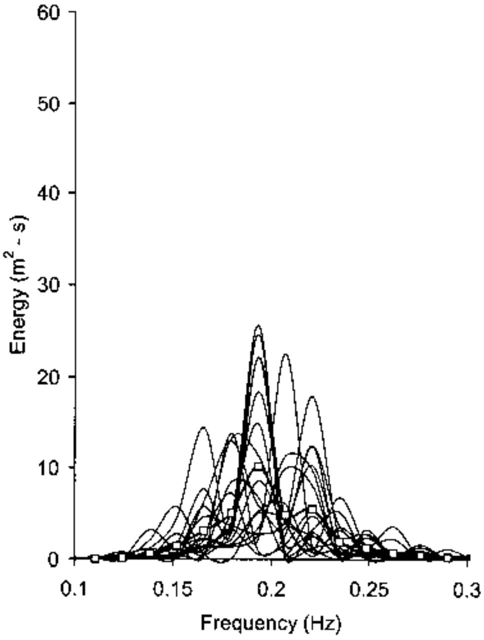

Figure D15
(Significant Wave Height = 2.60m)

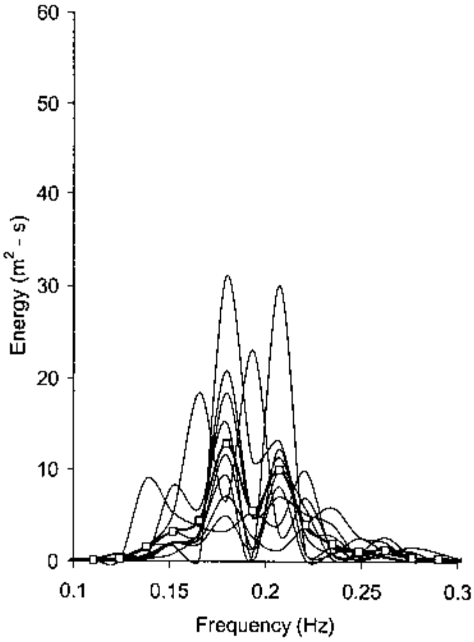

Figure D16
(Significant Wave Height = 3.06m)

—□— Average Spectrum

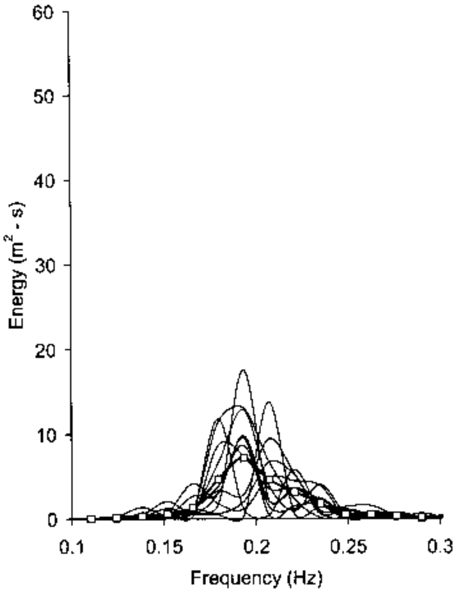

Figure D17
(Significant Wave Height = 2.23m)

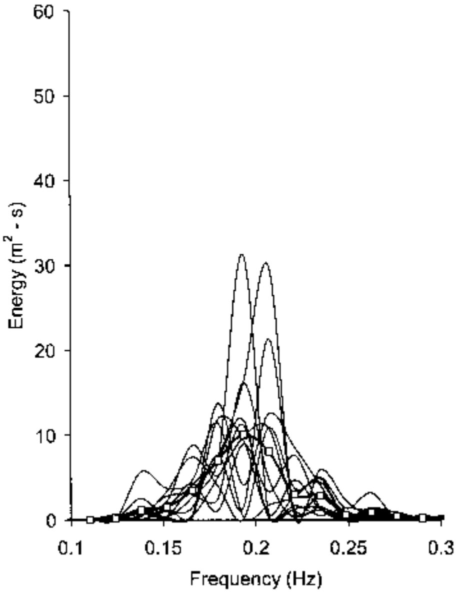

Figure D18
(Significant Wave Height = 2.73m)

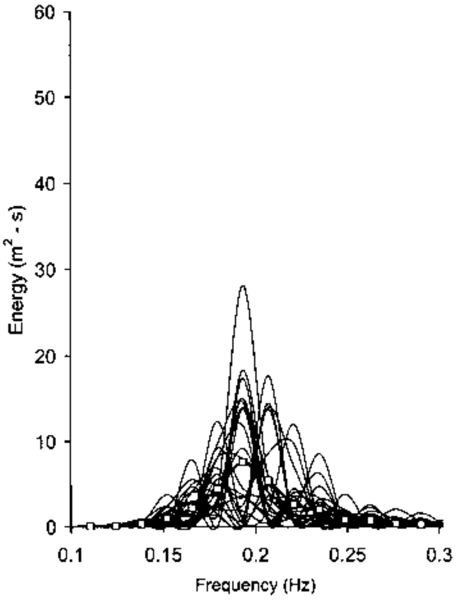

Figure D19
(Significant Wave Height = 2.18m)

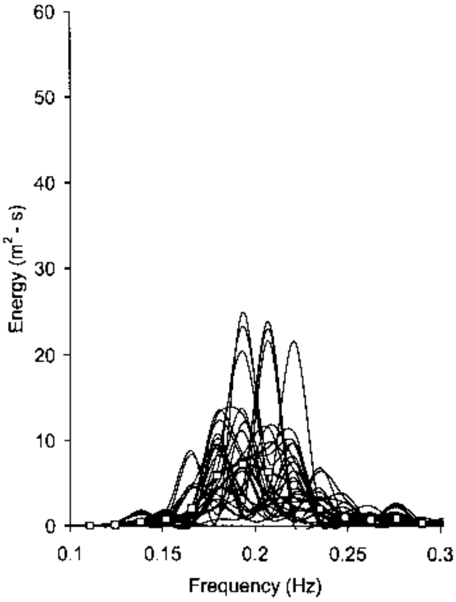

Figure D20
(Significant Wave Height = 2.49m)

—□— Average Spectrum

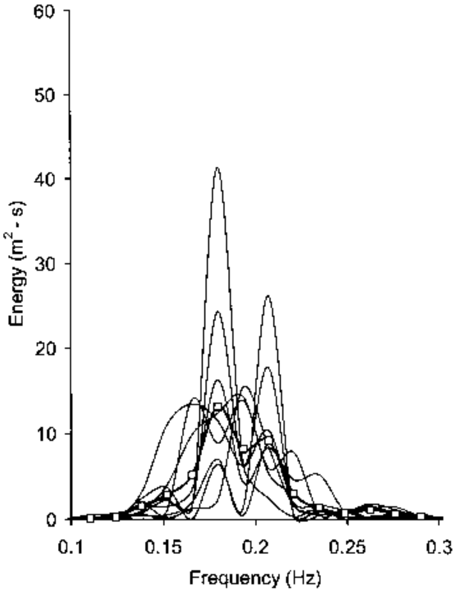

Figure D21
(Significant Wave Height = 3.06m)

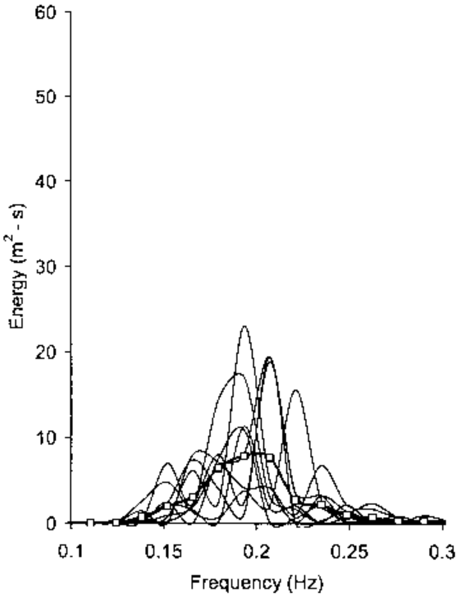

Figure D22
(Significant Wave Height = 2.65m)

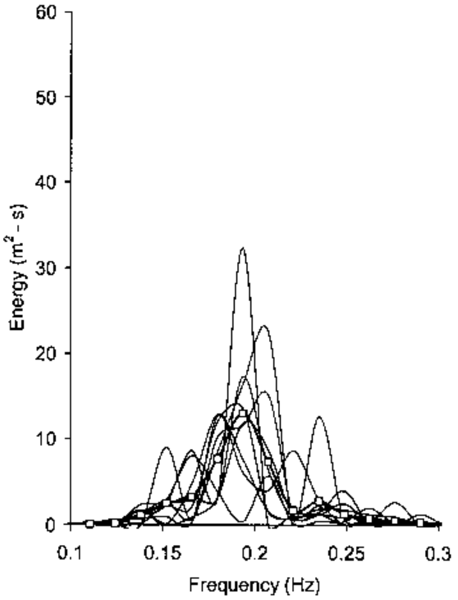

Figure D23
(Significant Wave Height = 2.83m)

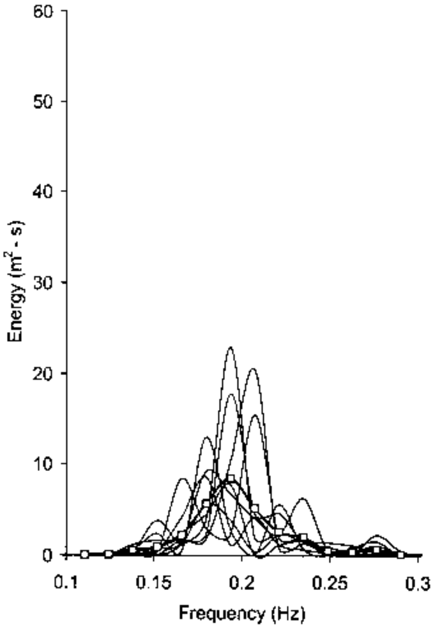

Figure D24
(Significant Wave Height = 2.36m)

—□— Average Spectrum

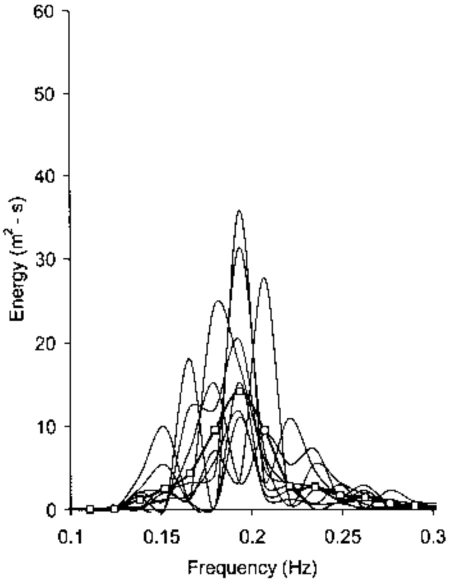

Figure D25
(Significant Wave Height = 3.12m)

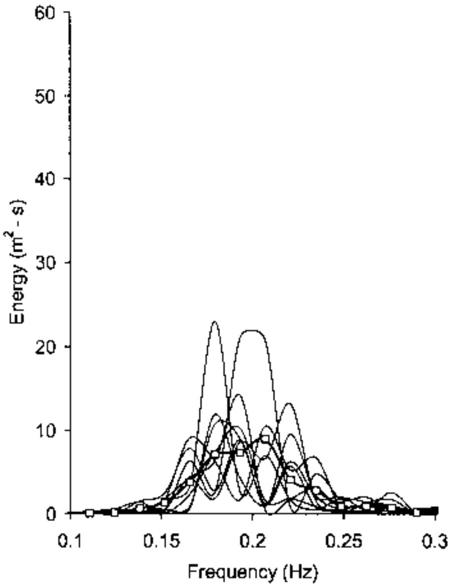

Figure D26
(Significant Wave Height = 2.75m)

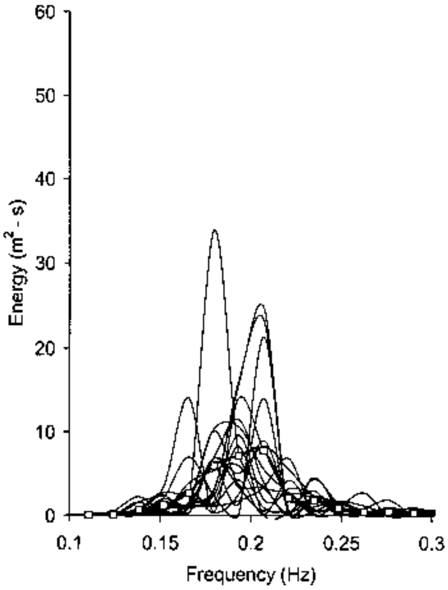

Figure D27
(Significant Wave Height = 2.42m)

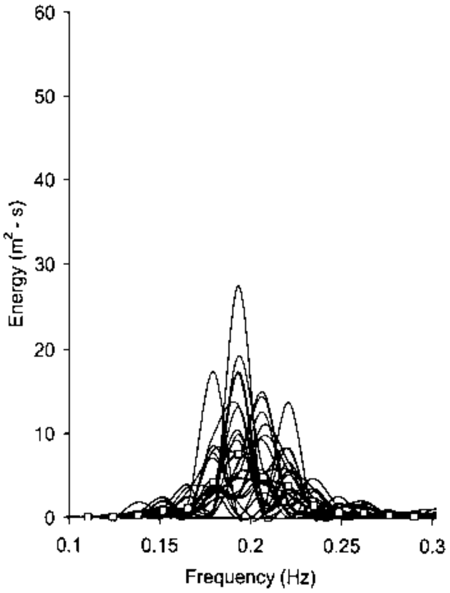

Figure D28
(Significant Wave Height = 2.25m)

—□— Average Spectrum

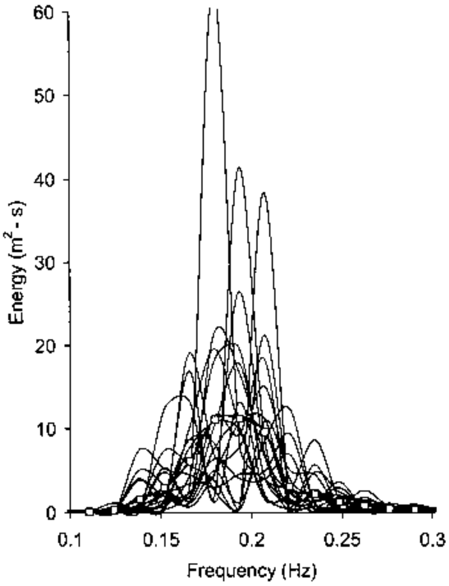

Figure D29
(Significant Wave Height = 3.09m)

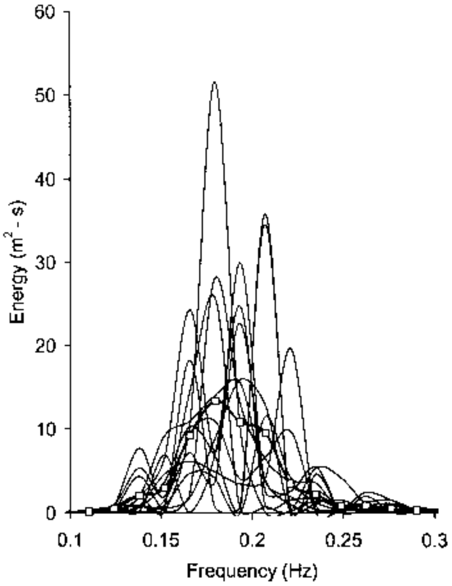

Figure D30
(Significant Wave Height = 3.27m)

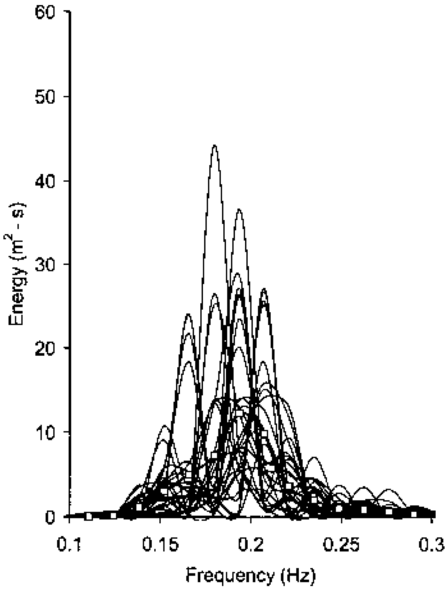

Figure D31
(Significant Wave Height = 2.96m)

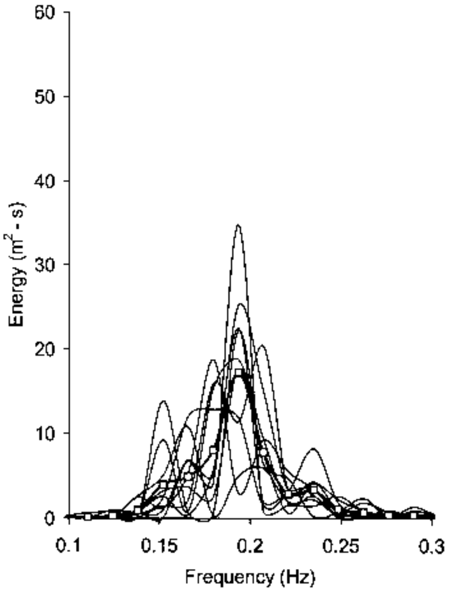

Figure D32
(Significant Wave Height = 3.12m)

—□— Average Spectrum

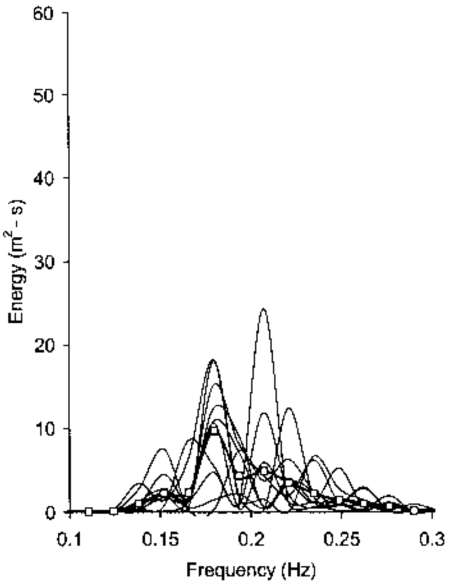

Figure D33
(Significant Wave Height = 2.53m)

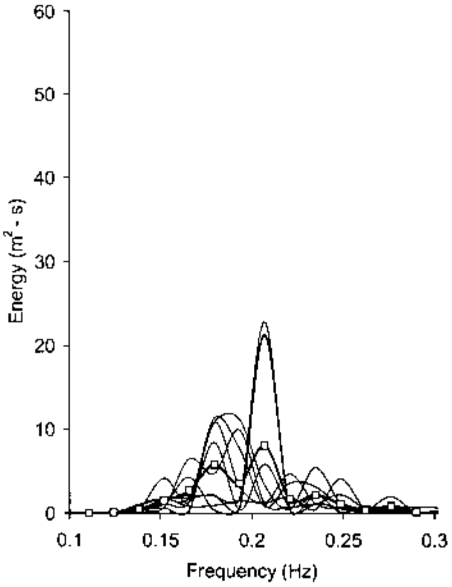

Figure D34
(Significant Wave Height = 2.36m)

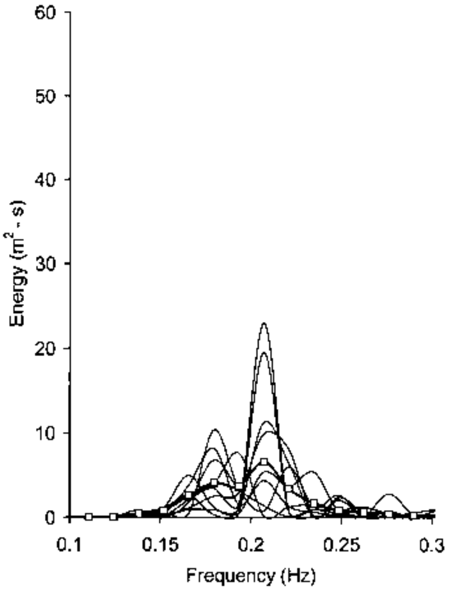

Figure D35
(Significant Wave Height = 2.24m)

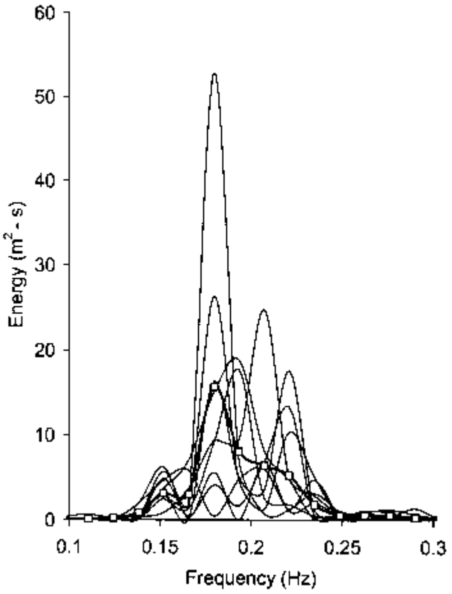

Figure D36
(Significant Wave Height = 2.99m)

—□— Average Spectrum

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APPENDIX E

INDIVIDUAL SELF-RIGHTING TIMES

A Wholly Owned Subsidiary of the Australian Maritime College

Appendix E Individual self-righting times

Condition A			
LPS = 119 degrees			
H 1/3	Time for self righting	H 1/3	Time for self righting
(Full scale)	(Sec full scale)	(Full scale)	(Sec full scale)
2.66	38.89	2.69	91.92
2.66	314.66	2.69	14.14
2.66	1096.02	2.43	81.32
2.66	45.96	2.43	364.16
2.66	148.49	2.43	42.43
2.66	268.70	2.43	1474.32
2.66	742.46	2.43	565.69
2.66	275.77	2.43	731.86
2.66	738.93	2.43	38.89
2.66	296.98	2.43	742.46
2.73	49.50	2.43	342.95
2.73	374.77	2.43	77.78
2.73	385.37	2.70	49.50
2.73	17.68	2.70	106.07
2.73	42.43	2.70	3.54
2.73	2467.80	2.70	98.99
2.73	3.54	2.70	141.42
2.73	3.54	2.70	325.27
2.73	212.13	2.70	35.36
2.73	127.28	2.70	339.41
3.17	10.61	2.70	38.89
3.17	551.54	2.70	7.07
3.17	328.80	2.19	152.03
3.17	463.15	2.19	74.25
3.17	236.88	2.19	42.43
3.17	70.71	2.19	53.03
3.17	3.54	2.19	254.56
3.17	307.59	2.19	654.07
3.17	339.41	2.19	852.06
3.17	215.67	2.19	141.42
3.37	17.68	2.19	152.03
3.37	53.03	2.19	109.60
3.37	49.50	2.14	289.91
3.37	35.36	2.14	1771.30
3.37	98.99	2.14	424.26
3.37	381.84	2.14	63.64
3.37	194.45	2.14	116.67
3.37	187.38	2.14	169.71
3.37	35.36	2.14	98.99
3.37	74.25	2.14	63.64
2.69	81.32	2.14	1141.98
2.69	180.31	2.14	84.85
2.69	293.45		
2.69	10.61		
2.69	152.03		
2.69	282.84		
2.69	60.10		
2.69	109.60		

Condition B	
LPS = 115 degrees	
H 1/3	**Time for self righting**
(Full scale)	**(Sec full scale)**
3.03	38.89
3.03	67.18
3.03	91.92
3.03	70.71
3.03	7.07
3.03	219.20
3.03	445.48
3.03	17.68
3.03	3.54
3.03	113.14
2.13	1028.84
2.13	38.89
2.13	35.36
2.13	777.82
2.13	2312.24
2.13	35.36
2.13	2595.08
2.13	205.06
2.13	3549.68
2.13	1580.38
2.53	45.96
2.53	360.62
2.53	116.67
2.53	799.03
2.53	735.39
2.53	254.56
2.53	10.61
2.53	813.17
2.53	31.82
2.53	682.36
2.91	38.89
2.91	183.85
2.91	7.07
2.91	95.46
2.91	350.02
2.91	7.07
2.91	215.67
2.91	3.54
2.91	3.54
2.91	247.49
2.62	42.43
2.62	77.78
2.62	1025.30
2.62	81.32
2.62	307.59
2.62	233.35
2.62	70.71
2.62	364.16
2.62	342.95
2.62	3.54

Condition C	
LPS = 110 degrees	
H 1/3	**Time for self righting**
(Full scale)	**(Sec full scale)**
2.60	77.78
2.60	102.53
2.60	233.35
2.60	335.88
2.60	417.19
2.60	661.14
2.60	1233.90
2.60	707.11
2.60	1092.48
2.60	2241.53
3.06	314.66
3.06	42.43
3.06	74.25
3.06	81.32
3.06	346.48
3.06	251.02
3.06	67.18
3.06	318.20
3.06	254.56
3.06	21.21
2.23	88.39
2.23	533.87
2.23	1580.38
2.23	2322.85
2.23	42.43
2.23	77.78
2.23	1541.49
2.23	795.50
2.23	31.82
2.23	1251.58
2.73	63.64
2.73	14.14
2.73	109.60
2.73	102.53
2.73	159.10
2.73	304.06
2.73	102.53
2.73	127.28
2.73	367.70
2.73	378.30
2.73	109.60
2.73	360.62
2.18	781.35
2.18	243.95
2.18	2496.09
2.18	989.95
2.18	1672.31
2.18	1064.20
2.18	544.47
2.18	958.13
2.18	8683.27
2.18	2768.32

Condition D	
LPS = 104.7 degrees	
H 1/3	Time for self righting
(Full scale)	(Sec full scale)
3.03	53.03
3.03	197.99
3.03	127.28
3.03	81.32
3.03	1035.91
3.03	91.92
3.03	654.07
3.03	526.79
3.03	194.45
3.03	395.98
2.31	91.92
2.31	2481.94
2.31	4451.24
2.31	5048.74
2.31	958.13
2.68	81.32
2.68	350.02
2.68	194.45
2.68	265.17
2.68	2347.59
2.68	625.79
2.68	618.72
2.68	820.24
2.68	721.25
2.68	933.38
2.49	636.40
2.49	2315.77
2.49	650.54
2.49	1244.51
2.49	1856.16
2.49	2796.61
2.49	3729.99
2.49	703.57
2.49	360.62
2.49	3355.22
3.06	77.78
3.06	84.85
3.06	31.82
3.06	505.58
3.06	1152.58
3.06	470.23
3.06	81.32
3.06	38.89
3.06	215.67
3.06	346.48

Condition E	
LPS = 104.7 degrees	
H 1/3	**Time for self righting**
(Full scale)	**(Sec full scale)**
3.12	77.78
3.12	180.31
3.12	3.54
3.12	731.86
3.12	339.41
3.12	74.25
3.12	296.98
3.12	675.29
3.12	367.70
3.12	176.78
2.75	42.43
2.75	523.26
2.75	731.86
2.75	1382.39
2.75	650.54
2.75	14.14
2.75	31.82
2.75	738.93
2.75	197.99
2.75	35.36
2.42	562.15
2.42	1785.44
2.42	576.29
2.42	710.64
2.42	7.07
2.42	28.28
2.42	700.04
2.42	2252.14
2.42	1962.22
2.42	173.24
2.25	3616.85
2.25	3334.01
2.25	6989.75
2.25	3882.02
2.25	982.88

Condition F	
LPS = 118 degrees (with 4t of water added)	
H 1/3	Time for self righting
(Full scale)	(Sec full scale)
3.12	84.85
3.12	17.68
3.12	21.21
3.12	88.39
3.12	304.06
3.12	261.63
3.12	21.21
3.12	120.21
3.12	88.39
3.12	24.75
2.53	77.78
2.53	180.31
2.53	77.78
2.53	10.61
2.53	586.90
2.53	21.21
2.53	929.85
2.53	403.05
2.53	618.72
2.53	24.75
2.36	77.78
2.36	364.16
2.36	31.82
2.36	615.18
2.36	21.21
2.36	205.06
2.36	608.11
2.36	226.27
2.36	42.43
2.36	434.87
2.24	636.40
2.24	31.82
2.24	1887.98
2.24	1212.69
2.24	24.75
2.24	678.82
2.24	208.60
2.24	813.17
2.24	841.46
2.24	190.92
2.99	88.39
2.99	300.52
2.99	169.71
2.99	498.51
2.99	187.38
2.99	35.36
2.99	781.35
2.99	35.36
2.99	296.98
2.99	898.03

Condition G	
LPS = 104.7 degrees (4t of water added)	
H 1/3	**Time for self righting**
(Full scale)	**(Sec full scale)**
3.09	77.78
3.09	134.35
3.09	10.61
3.09	1484.92
3.09	625.79
3.09	1948.08
3.09	1269.26
3.09	346.48
3.09	1117.23
3.09	1085.41
3.27	296.98
3.27	10.61
3.27	77.78
3.27	1237.44
3.27	608.11
3.27	102.53
3.27	661.14
3.27	1159.66
3.27	123.74
3.27	187.38
2.96	2725.90
2.96	24.75
2.96	3701.70
2.96	2633.97
2.96	38.89
2.96	4797.72
2.96	2379.41
2.96	77.78
2.96	661.14
2.96	1339.97

APPENDIX F

PHOTOGRAPHS

Figure F1 Single breaking wave impacting model

Figure F2 Model being capsized by single breaking wave

Figure F3 Model being capsized by single breaking wave

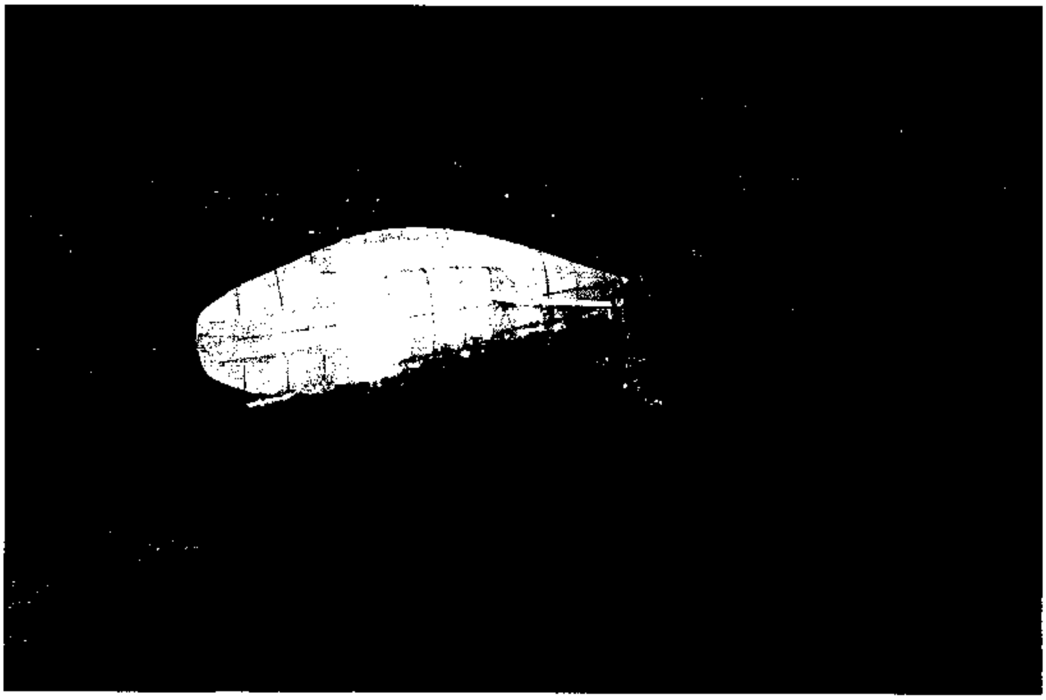

Figure F4 Model being self-righted in single breaking wave

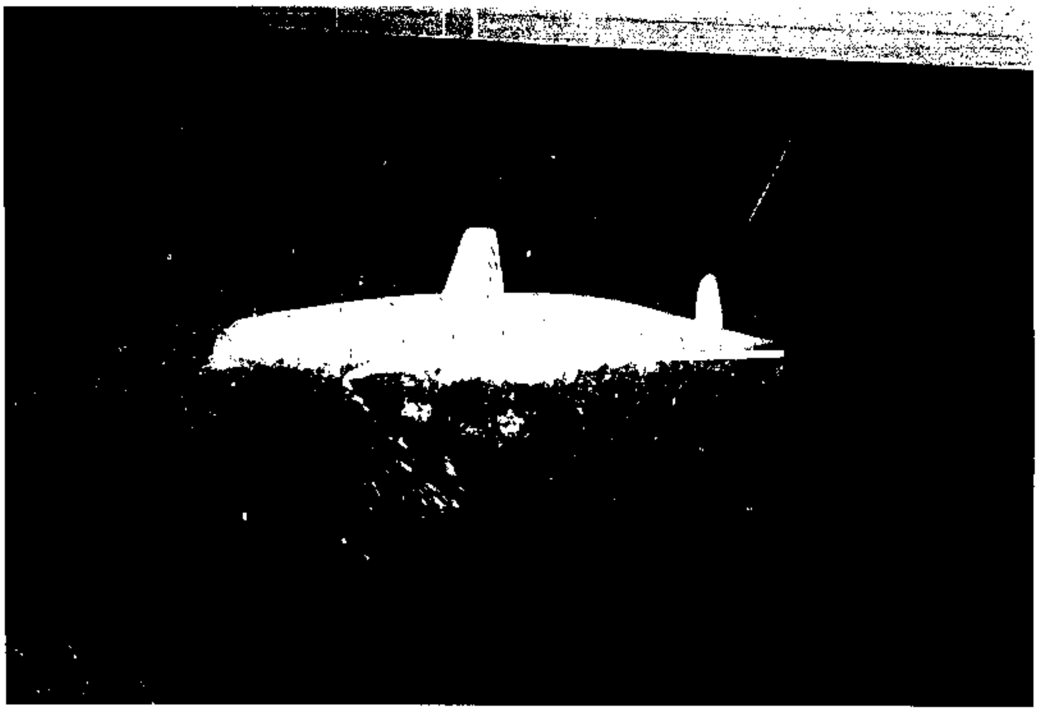

Figure F5 Model inverted in steep irregular seas

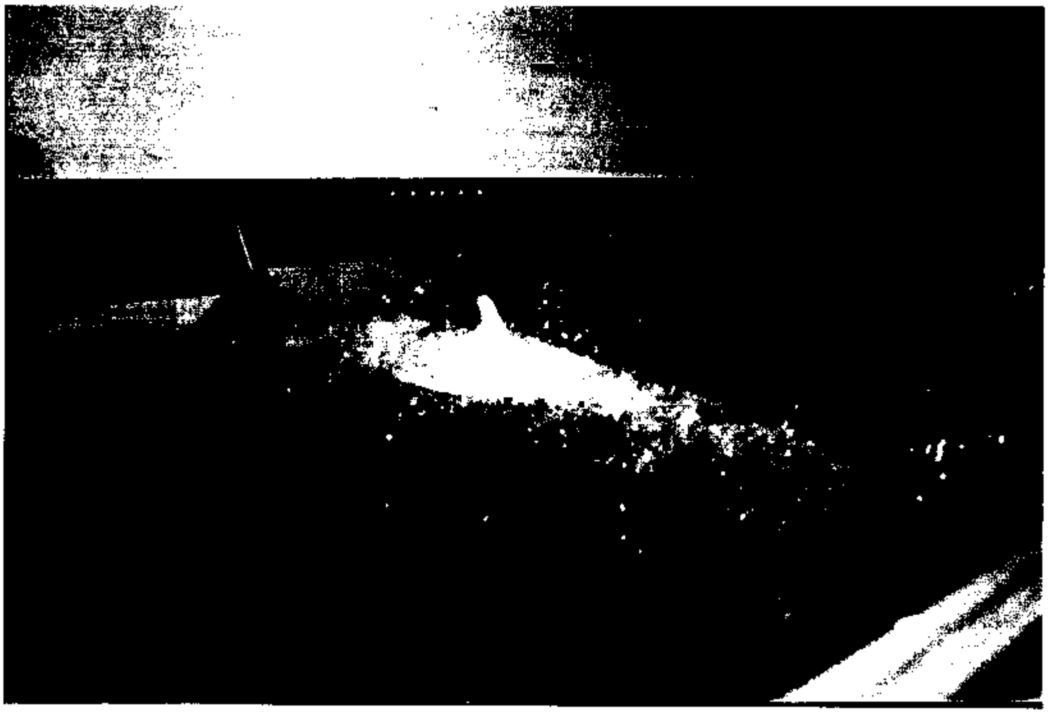

Figure F6 Inverted model being hit by steep breaking wave in irregular seas

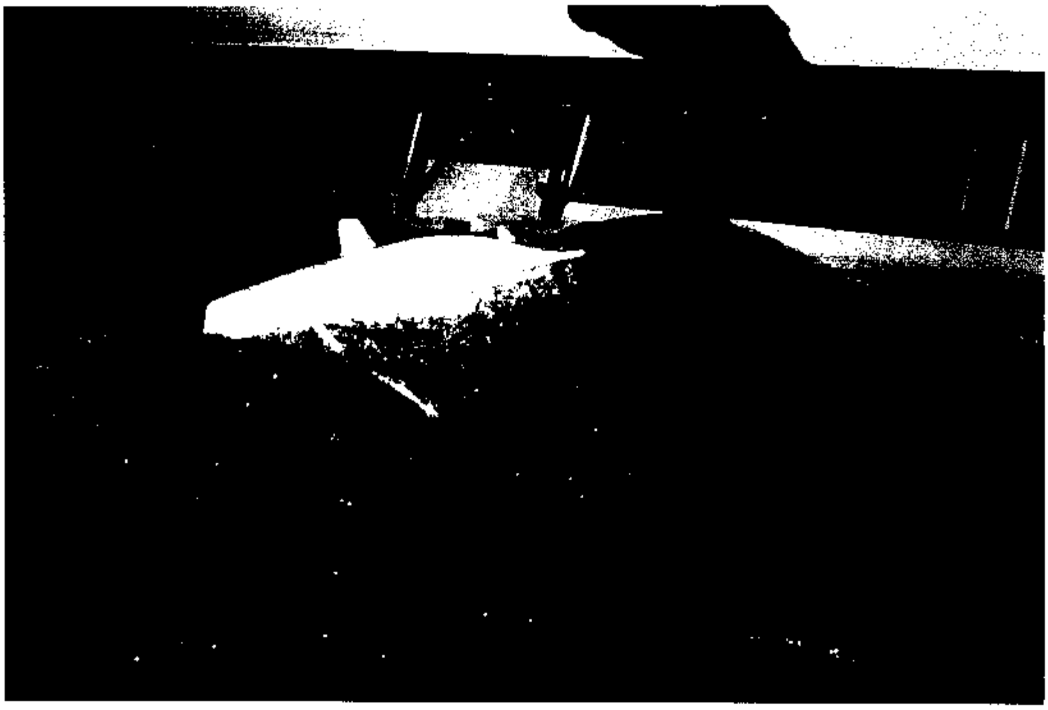

Figure F7 Model almost self-righting in irregular waves

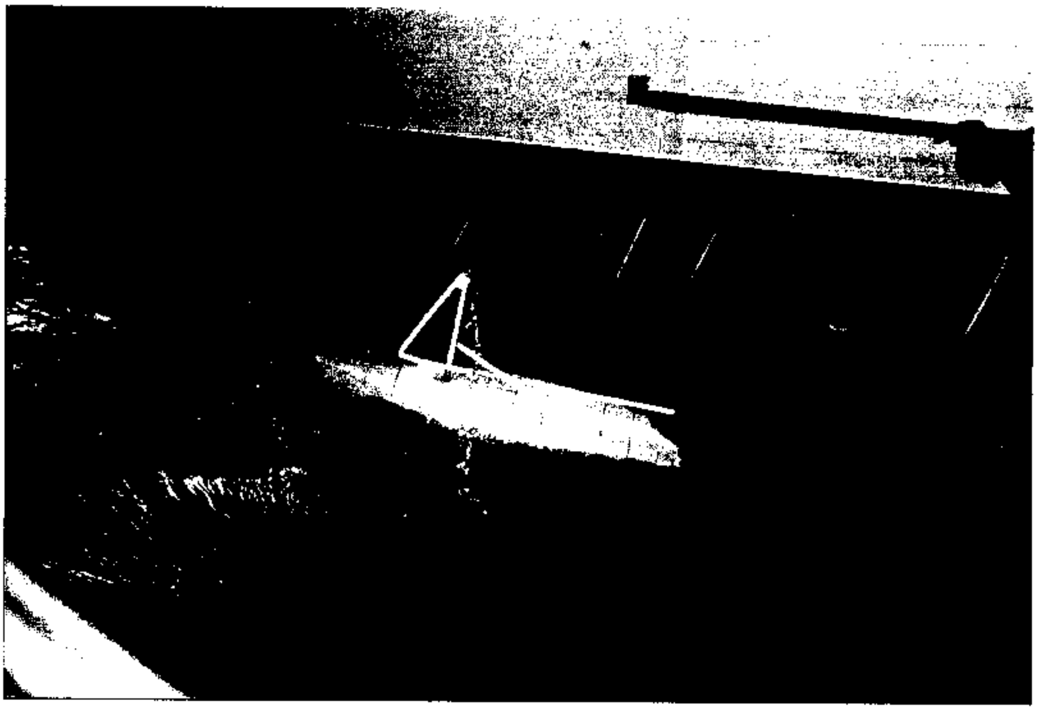

Figure F8 Model immediately after being self-righted in irregular waves