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MARITIME AND COASTGUARD AGENCY

Research Project 537 Phase II – HSC Response to Gusts

EXECUTIVE SUMMARY

This report describes Phase II of Research Project 537, to study the response of high speed craft to gusts and the manner in which this effect is incorporated within the weather criteria for the HSC code.

The work comprised the commissioning of a gust test facility in the R.J.Mitchell wind Tunnel at the University of Southampton, followed by wind tunnel tests on models of two types of catamaran HSC. Both models were built in a manner to allow a range of beam to height ratios to be tested. The steady wind speed, size and type of gust were all varied, with the dynamic wind pressure and vessel heel angle recorded.

The equilibrium heel angle results in a steady wind have been compared to the data from Phase I of Research Project 537 and the proposed HSC code formulae. The results are favourable, with a number of possible reasons stated for some inconsistencies between the data.

The dynamic effect upon the heel angle of the gust, manifest in an overshooting of the equilibrium angle, is only pronounced at angles below 5 degrees of heel. However at such angles experimental scatter does not allow a clear trend to be identified.

Suggestions for the modification of the size of the wind heeling lever in a gust are made, and the tests have provided further confidence in the proposed method of estimating the wind heeling moments. The experimental data indicates little requirement to alter the theoretical methodology for the dynamic response of multihull HSC to wind gusts.

1 INTRODUCTION

This report describes the work conducted and the findings of Research Project 537, Wind Heeling Moment Methodology Phase II, to study the wind heeling of multihull high speed craft (HSC). The research project broadly followed the programme outlined in Wolfson Unit proposal no. 2655BD, dated 3rd February 2004. The contract was issued by the MCA on 20th February 2004.

Previous studies of the wind heeling moment of multihull HSC, MCA Research Projects 503 and 537 Phase I described in Wolfson Unit Reports 1698 and 1755 respectively [3][4],, resulted in proposals for revising the method of calculating the wind heeling moments in a steady wind. There was a lack of data on response to gusts, however, and it was considered that dynamic tests were required to provide a greater understanding of the subject. Phase II was undertaken to address this dynamic response to wind heeling in a gust.

2 BACKGROUND

2.1 IMO 2000 High Speed Craft Code

The 2000 HSC Code incorporates a formula for the calculation of the wind heeling moment for multihulls. This takes the form:

$$HL_1 = \frac{PAZ}{9800\Delta}$$

Where: HL_1 is the heeling lever (m)
P is the wind pressure (N/m^2)
A is the projected lateral, or profile, area above the waterline (m^2)
Z is the vertical distance from the centre of A to half the draught (m)
Δ is the displacement (tonnes)

For intact monohull and multihull craft the wind pressure is defined as $P = 500\ (V_w/26)^2$ where V_w is the wind speed (m/s) corresponding to the worst intended service conditions. A gust wind heeling lever (HL_2) of 1.5 times HL_1 is assumed.

A reduced pressure is used in the assessment when damaged, the constant 500 being reduced to 120. This represents a reduction to half the wind speed, but the assumptions otherwise remain the same.

The HSC code states in relation to multihull HSC, "The effect of rolling in a seaway upon the craft's stability shall be demonstrated mathematically. In doing so, the residual area under the GZ curve, i.e. beyond the angle of heel θ_h, shall be at least equal to 0.028 m.rad up to the angle of roll θ_r. In the absence of model tests or other data, θ_r shall be taken as 15° or an angle of $(\theta_d-\theta_h)$, whichever is less." θ_d is defined as the angle of downflooding, and θ_h is the angle of heel due to the steady wind, passenger crowding and turning moments.

The heeling lever due to steady wind and gusting, HL_2, should not induce a heeling angle of greater than 10° when the vessel is intact (Annex 7, 3.2.1 of HSC code). Unlike the rules governing monohulls, no explicit considerations of dynamic effects are detailed. The wind heeling lever for the damaged case, HL_3, should not induce an angle of heel more that 15°, including the angle of equilibrium due to damage.

2.2 Implications of HSC code

For the intact stability criteria, there are five basic assumptions inherent in the method:

1. The constants in these formulae imply a heeling moment coefficient of 1.2.
2. The moment remains constant at all heel angles.
3. A gust is considered to contain 1.5 times more energy than the steady wind.
4. When struck by a gust the response of the vessel is as for a static equilibrium case.
5. A minimum area under the GZ curve is required to prevent capsize in wind and waves

The pressure assumed for the steady wind heeling lever, HL_1, relates to the wind speed in the worst intended service conditions. For the purposes of this study a nominal value of 50 knots is assumed, corresponding to Beaufort scale 10 'storm', and this is the value used by IMO for unrestricted shipping and also taken to be typical of the operational limits for large HSC. The gust heeling lever, HL_2, corresponds to an increase in pressure of 50% and an increase in wind speed of 22%, in our case from 50 to 61 knots. For the damage stability assessment a lower wind heeling lever is used. This is 24% of the pressure, or 49% of the wind speed used for the intact assessment. In our case this relates to a wind speed of 24.5 knots, classified as Beaufort force 6 'strong breeze'.

Data presented by Smith and Chandler [5] state that a maximum gust velocity factor of 1.3 to 1.5 is typical for a Beaufort scale 9 'strong gale' (41-47 knots) over the sea. This corresponds to a velocity increase of 15 to 25 knots in a mean wind speed of 50 knots. The gust pressure factor of 1.5 as used in the HSC Code represents a velocity factor of 1.22 and is substantially lower than the possible range of gust strengths that might be experienced at sea. A gust pressure factor of 2.0, not 1.5, to determine HL_2 would more accurately cover the realistic size of gust encountered, as it represents a velocity factor of 1.41.

Also evident from Smith and Chandler [5] is that, whilst a gust velocity factor of 1.5 is only typical of a gust of very short duration, in the order of one second, gust factors of 1.3 to 1.4 (relating to wind speed fluctuations of 15 and 20 knots in a wind speed of 50 knots) are typically up to 10 seconds in duration. A velocity factor of 1.41 therefore represents an event duration to which a vessel is able to respond.

Because the only requirement for resistance to wind heeling in the intact state is that the vessel cannot heel more than 10° when subjected to HL_2, there is an implication that no dynamic effects are considered.

The only consideration of dynamic effects and reserve righting moment is when the vessel is rolling in waves, and the minimum residual area must be maintained. It is implied by the text of the Code that this GZ area criterion is intended to provide a margin against wave induced moments rather than to address the balance of heeling energy in the gust against the righting energy of the vessel.

It should be noted that if the gust factor in HL2 was increased to 2.0 from 1.5 for multihull HSC then there would be a discrepancy with the monohull HSC which currently use a factor of 1.5 as well. Because the data upon which this alternative value is based [5] is independent of vessel type then the alternative value could be applied to monohull vessels with equal justification.

3 PREVIOUS TESTS AND DATA

There is a lack of published data detailing the effect of gusts upon water borne craft, and the dynamic effects of wind heeling moments in general.

The only published reference that could be found was Wolfson Unit report 908 [2]. This, however, dealt with monohull sailing vessels, which can have substantial aerodynamic roll damping due to the sails. The study concluded that dynamic effects were minimal for these vessels, except in light winds when the heel angles due to the wind were small, or when very little sail was set and aerodynamic damping was of little significance. Sailing vessel safety is determined by the behaviour at large heel angles where the dynamic response was found to be negligible. Furthermore, severe gusts have a finite rise time, typically similar to the time taken for a vessel to roll from upright to an extreme angle, that is a quarter of the natural roll period. A sailing vessel therefore is able to respond in a quasi-static manner as the wind speed increases in a gust. The method adopted for the stability assessment of UK sailing vessels is based on the assumption that the response of the vessel to a gust is equal to the static response to the gust wind speed.

MCA Research Projects 503 and 537 Phase I [3][4], considered purely the static wind heeling moment at given heel angles. The main conclusions were that the upright wind heeling moment is strongly dependent upon the vessel's beam to height ratio, and that the wind heeling moment varies with the vessel's heel angle.

The following formulae were suggested to determine the upright and heeled wind heeling lever –

$$P = \left(450 + 50(B/H)^2\right)(V_w/26)^2 \qquad \textbf{Formula 1}$$

$$HL_\theta = HL_0\left\{1 + \left[\left(B/H\right)^2 - 2.5\right]\theta/100\right\} \qquad \textbf{Formula 2}$$

Where P is the wind pressure
B is the vessel beam
H is the vessel mean height above DWL
HL_θ is the heeling lever at θ degrees of heel
HL_0 is the heeling lever upright, = HL_1 of the 2000 HSC code.

4 TEST FACILITY

The tests were conducted at the University of Southampton R.J.Mitchell Wind Tunnel, which has working section dimensions 3.5m wide, 2.6m wide and 10.5m long. The facility, and the axial fan powering it, was not designed for impulse loading nor short rise times in wind speed, but instead as an aeronautical wind tunnel with uniform wind. A gust test facility therefore had to be commissioned, which consisted of three main components:

1. Tunnel partitioning
2. Gust vanes
3. Water tank

The procedure used for the facility was to run the fan at constant speed, and alter the wind speed in the gust working section by opening and closing a set of vanes, thus diverting the flow through the remainder of the section. Figure 12-1 presents a general arrangement of the facility. Above the horizontal division the wind was free to flow continually but in the lower section the flow could be regulated from zero to full speed by opening and closing the six wooden vanes, as shown in Figure 12-2 to Figure 12-4. These gust vanes were operated together manually from underneath the tunnel floor using a simple pushrod arrangement.

The horizontal partition was supported at the tunnel walls and by a vertical partition that was attached to the tunnel ceiling. This resulted in the working section being split longitudinally into three subsections; two upper and one lower sections, as shown in Figure 12-5.

The gust vanes were housed in a rectangular frame formed from the horizontal partition, the wind tunnel floor and three plywood vertical supports. Either side of this frame the space between the outer panel and the wind tunnel corner fillet was closed using plywood. Transverse rods were used to support the vanes and to provide each with a pivot.

The tank was constructed as a plywood box with dimensions 2260 x 2260 x 400mm deep, and with its upper edge just above the tunnel floor level. A waterproof liner was placed inside the box and it was filled with water to the tunnel floor level.

5 FLOW CONDITIONS

The facility is an aeronautical wind tunnel rather than a boundary layer wind tunnel, hence the wind gradient and large scale turbulence properties of the atmospheric boundary layer were not modelled. The tunnel boundary layer was small in relation to the model height.

To monitor the actual air flow past the model a pitot static tube was placed 1m upstream of the water tank, approximately 300mm below the horizontal partition. It was connected via short tubes to an adjacent micromanometer, ensuring that measurement of the gust characteristics was not affected by damping in the measurement system.

6 MODEL SET-UP

Because these tests involved the dynamic response of floating models, Froude scaling was used throughout. Each model was ballasted to a known displacement and centre of gravity, and its stability characteristics calculated.

The model was fitted with a roll gyro to record heel angle. This was connected to the data acquisition system by an umbilical cable, which was suspended from the horizontal partition so as to minimise its influence upon the model motion. The model was initially moored by a bridle system until the wind speed was constant, after which the bridle was released and the model was free to move in all six degrees of freedom.

In some cases the models tended to move ahead or astern in the wind, and needed to be restrained because of the restricted scope available in the tank. Taut wires were fixed longitudinally at water level in the tank, just aft of the stern and forward of the bow of the model, with the model tethered to a small ring that was free to travel along each wire. This restricted fore and aft movement without restraint in sway or roll.

By moving the attachment point of the bridle vertically on the model, the model could be induced to have an initial heel to windward if desired.

The data acquisition system recorded dynamic wind pressure simultaneously with the heel angle in order to cross correlate the data. All test runs were also recorded on digital video tape by two cameras; one upstream and one to the side of the water tank.

Nominal wind pressures (as recorded in the free stream section of the wind tunnel) of 100Pa and 150Pa were utilised, which corresponded to wind speeds of 12m/s and 15m/s. At full scale these speeds are in the region of 54m/s (105 knots) and above, but were used in order to obtain heel angles that could be measured with sufficient accuracy.

7 MODEL CONFIGURATIONS

7.1 Model 1 – Conventional catamaran

A 1:20 scale model of a typical 33 metre conventional catamaran HSC was constructed, with a simple superstructure similar to that tested in the wind tunnel for Phase I of the project. The superstructure was built in such a manner as to allow an extra 'block' of superstructure to be added, thus increasing the profile area. No appendages were fitted. Photographs of the model in these two conditions are presented in Figure 12-6 and Figure 12-7. Appendix 1 details the principal dimensions of the model.

7.2 Model 2 – Wave Piercing catamaran

A 1:40 scale model of a typical 71 metre wave piercing catamaran HSC was constructed with a simple superstructure, as shown in Figure 12-8. As with the conventional catamaran an extra deck of superstructure was built, to investigate the influence of altering the H/B ratio. No appendages were fitted. Appendix 1 details the principal dimensions of the model.

8 TEST RESULTS

In total 100 tests were conducted with varying models, gust size and length, as well as different overall wind speeds. A number of runs had to be discarded due to the model being restricted by the tank sides and where the results recorded were not readily identifiable within experimental error. Those models that exhibited the more reliable behaviour and gave clear results were used in a greater number of the tests.

Figure 12-9 and Figure 12-10 present time histories of both the wind pressure and the heel angle for the conventional catamaran with the smaller B/H ratio (i.e. taller) in two cases – the first where the vessel was initially held heeled to windward and then released in constant wind, and the second where the vessel was released then hit by a gust.

Figure 12-11 presents time histories of the wind pressure and the vessel heel for the wave piercing catamaran subjected to a gust.

Figure 12-12 shows the ratio of the overshoot angle to the equilibrium angle of heel against the equilibrium angle for all the models tested. The results denoted as "released from initial heel angle of .." were held at a set angle then released in the steady wind. The overshoot angle for these data points was the maximum heel angle recorded in this steady wind. The other data points, denoted by non-filled symbols, were free to heel in a steady wind and then subjected to a gust. The overshoot angle in these cases was the heel angle induced by the gust with respect to the steady state heel for a wind of the same strength.

The relationship between the predicted equilibrium heel angle and the heel angle recorded during the tests is presented in Figure 12-13. The predicted value was calculated using Formula 1and Formula 2, the wind velocity measured in the tests, and the appropriate coefficient of heeling moment from Phase I. A perfect correlation would result in all the data points lying on the indicated linear trend line.

Figure 12-14 presents the plot of vessel righting moment and calculated wind heeling moments against heel angle for the tall conventional catamaran when released from an initial windward heel angle. The wind heeling moments detailed are those according to the IMO 2000 HSC code and by formulae 1 and 2, as derived in Research Project 503. Steady heel angles recorded in this and other tests, and the assumed wind heeling moment derived using the steady heel angle and formula 2, are also shown. The steady heel angle points (denoted by shaded circles) are defined from the measured heel angle and the wind speed recorded during the gust tests used in conjunction with the wind heeling moment measured in Phase I.

Figure 12-15 presents a plot of vessel righting moment and calculated wind heeling moments against heel angle for the tall conventional catamaran when hit by a gust. The wind heeling moments shown were derived in the same way as in Figure 12-14.

Table 11-1 compares the equilibrium heel angle calculated by the HSC code with the formulae derived from Research Project 503, and with the heel angle recorded in the equivalent tests. The overshoot angle and the energy balance, between the steady state heel angle and the overshoot angle, are also presented. The energy imparted to the system by the gust, and the righting energy of the vessel, have been calculated from the area between the wind heeling moment and the vessel righting moment curves. These tabulated data correspond to the results presented in Figure 12-15.

Table 11-2 details the energy balance for the tall conventional catamaran model when initially heeled to windward, as well as the equilibrium angle of heel and the maximum overshoot angle recorded. These tabulated data correspond to the results presented in Figure 12-14.

9 DISCUSSION OF RESULTS

9.1 Uncertainty of experimental process

In any experimental process there will be some scatter in the data due to uncontrollable influences and inaccuracies in the measurement system. The control and limitation of this scatter leads to a lower level of uncertainty in a set of experimental data, while the knowledge of sources of error, as well as their relative level of importance, provides improved confidence in the level of uncertainty present.

Figure 12-13 shows that the predicted heel for angles below 5° is poorer than that of higher angles, with a significant scatter of data points. In general the prediction method tends to over predict the equilibrium heel angle across the range of heel angles investigated. The 'calculated' data points, using a wind heeling coefficient from Phase I of the tests, combined with the recorded wind speed, produce a consistent scatter of 2-3°, both under and over prediction, across the range of heel angles investigated. This variance between the calculated heel angle and the recorded heel angle provides an indication of the uncertainty in the experiment, while the variance between the predicted heel angle and the recorded heel angle is a combination of the experimental error and the inaccuracies, or inherent conservatism, of the formulae.

A significant source of uncertainty in the experimental procedure was the nominal wind velocity. The Pitot static tube was fully calibrated to a control measurement upstream of the gust section, but it was not in the same spatial position as the model. It is known from the utilisation of several mounting positions for the pitot static tube during initial commissioning of the facility that there was some variation in the flow with spatial position, and a degree of recirculation was present in the flow, particularly when the gust vanes were closed. In addition to this non-uniformity to the flow, the model was allowed to drift downstream in the water tank, thus the apparent wind on the model would have been slightly less than the wind recorded by the pitot static tube.

With small scale models, of vessels with relatively small profile area, inaccuracies in modelling or measurements of area result in a significant percentage error in the overall area. The previous tests conducted by the Wolfson Unit on gust response [2] were for larger scale models (1:9 and 1:25) and for sailing vessels with much greater profile areas, hence lowering the error from model inaccuracies.

It is worth re-iterating from Figure 12-13 that the scatter of calculated results to measured results is uniform throughout the range tested, hence giving the tests at higher heel angles a much better accuracy in percentage terms than those of small heel angles.

9.2 Implications of results

In these tests the magnitude of the gusts ranged from 29% to 110% above the initial pressure. The assumed gust in the IMO 2000 HSC code is 50% above the steady wind pressure. The experimental data thus cover the range of interest, and in many cases are more onerous on the vessel than the code. The rise times of the gusts ranged from 2 seconds to 7 seconds when scaled to full size. Such rise times are realistic for gusts of 50% to 100% of the initial pressure.

Figure 12-12 shows that, as the angle of equilibrium heel increases, there is a decreasing dynamic influence upon the overshoot angle recorded. The ratio of maximum to final equilibrium heel angle approaches a value of 2 at very small equilibrium heel angles which, when combined with the linear nature of the vessel righting moment curve for such angles, indicates very little or no damping occurring.

Table 11-1 indicates a high level of damping occurring because the righting energy required to oppose that imparted by the gust is 60% of the gust energy. A non-damped system would require a 100% energy balance.

The steady wind data points presented in Figure 12-14 and Figure 12-15 promote a high level of confidence in the wind heeling moments measured during Phase I, the variation of these points from the vessel righting moment curve being within acceptable experimental scatter. The wind heeling curves presented in these Figures and in Table 11-1 indicate a degree of over-prediction in both the HSC Code and the Phase I wind heeling moment prediction method. However it should be kept in mind that the results presented are for a vessel with a relatively low B/H ratio of 1.38, and Formula 1 and Formula 2 were written to better model the effects of wind on vessels with a large beam to height ratio.

The initial windward heel tests, such as the example presented in Figure 12-12, have a relatively high maximum to equilibrium angle ratio of 2.0, but when the data in Table 11-2 are considered it can be seen that there is a high level of damping. The righting energy required to oppose that imparted by the wind was only 18% of the wind energy. Indeed, if there were no damping present in the system the vessel would have capsized due to the low level of reserve righting energy. It should be noted that the scale wind speeds required to heel the vessel to such angles are well outside the operating limits of such craft.

The trends presented in the Figures and Tables of this report are very similar to those of the sailing vessels presented in Wolfson Unit Report 908 [2], with dynamic effects rapidly diminishing as the equilibrium heel angle increases. One of the greatest dangers to sailing vessels is being knocked down by a strong gust to the angle of downflooding or capsize, and so angles of heel in excess of 40 degrees are of most interest. For multihull HSC, capsize by wind force alone is beyond the scope of even the most severe anticipated operating conditions, and consideration of heel angles close to the angle of windward hull emergence is not considered to be necessary for normal forms. It is the effect of the combination of wind heeling and other moments, such as passenger crowding, on the attitude of the vessel with regard to passenger safety and downflooding that is of most interest. Typically, the wind heeling moment alone will induce angles of heel less than 5 degrees, and it is these low angles that are of most relevance to assessment by the Code. Figure 12-12 shows that at angles below 5° overshoot angles of 1.5 times the equilibrium angle in the gust wind speed are possible. However such overshoot angle ratios must be considered in conjunction with experimental scatter and uncertainty of 2° to 3°, as discussed in Section 9.2. A peak overshoot angle to steady heel angle ratio of 2.0 at 2° is 2° itself, within the experimental scatter region. This is not to say that an increased overshoot angle ratio does not occur at smaller angles, it is just more difficult to quantify.

Large gusts typically have rise times of a second or more. If the rise time of a gust is greater than the time required for the vessel to roll naturally to the steady heel angle in the gust, the vessel is able to respond in a quasi-static way as the wind speed increases. Thus a rise time greater than one quarter of the natural roll period of the vessel will be sufficient to enable a quasi-static response. Natural roll periods of multihulls tend to be low and so this consideration suggests that dynamic effects are likely to be limited.

10 CONCLUSIONS

A series of models, typical of HSC vessels, were constructed and subjected to dynamic wind loading. The wind speeds and corresponding heel angles were recorded for a variety of wind strengths and gust types. Significant dynamic effects were found to occur at heel angles below 5° of heel, but damping reduces the effects significantly as the equilibrium heel angle increases.

All of the conclusions of Phase I of Research Project 537 [4], remain valid.

10.1 Wind Heeling Moment

Formula 1 and Formula 2, as defined in Research Projects 503 and 537 Phase I [3][4], have proven to give reasonable predictions of the angle of heel of a range of catamaran forms. Inaccuracies in the heel angles calculated have generally been over predictions, thereby erring on the side of safety.

$$P = \left(450 + 50(B/H)^2\right)(V_w/26)^2 \qquad \textbf{Formula 1}$$

$$HL_0 = HL_0\left\{1 + \left[\left(B/H\right)^2 - 2.5\right]\theta/100\right\} \qquad \textbf{Formula 2}$$

10.2 Gust Factor

The increase in the wind pressure due to a gust is larger than that specified in the 2000 HSC code if the steady wind is 50 knots, a wind speed typically used for operational limits. It is suggested that the gust heeling lever, HL_2, should be 2 times the normal wind heeling lever, not 1.5 as currently assumed –

$$HL_2 = 2HL_1 \qquad \textbf{Formula 3}$$

As with the existing code, the angle induced by this lever can be compared to a set value, such as 10°.

10.3 Dynamic Response

The experimental results presented in this report show that there is significant overshooting of the equilibrium heel angle when subjected to a gust if the equilibrium angle in the gust is below 5°. At larger angles there is significant damping of the vessels movement and the gust rise times are comparable with the vessels roll period, thereby removing the need to consider dynamic effects at such angles.

Figure 12-12 shows that the dynamic overshoot can be significant for the angles under consideration by the HSC code, but Figure 12-13 indicates the experimental uncertainty is too great at such angle to provide a clear and definitive relationship. Figure 12-13 also indicates a general over-prediction of the heel angle in this range by Formula 1 and Formula 2. Hence it is suggested that no extra factor to compensate for dynamic effects is applied beyond that defined in Formula 3 above.

The experimental results presented, and their analysis, indicate that what dynamic effect is present is small enough to be neglected in the criteria of the HSC code. That is, the methodology currently utilised by the code models the behaviour of such vessels sufficiently accurately. The numerical bounds of the heeling moment and resultant heel angle generated have, however, been shown to vary from those stated in the code, while Formula 1, Formula 2 and Formula 3 presented in this report have a greater degree of accuracy.

11 TABLES

Table 11-1 Comparison of IMO HSC 2000 code guidelines and experimental results for tall conventional catamaran

Run 74
Full scale initial wind speed = 77 knots
Full scale gust wind speed = 116 knots.
Size of gust = 1.506 by wind speed, 2.27 by wind pressure
Full scale gust rise time = 3.6 seconds

	Equilibrium heel angle in steady wind	Equilibrium heel angle in gust	Maximum heel angle	Area between wind heeling moment and vessel righting moment curves (Nm.rad)	
				From steady wind equilibrium to gust equilibrium	From gust equilibrium to max overshoot
IMO HSC 2000	7.1	15.9	-	-	-
Formulae 1& 2	7.4	15.7	-	-	-
Experimental	5.3	14.0	16.3	0.309	0.185

Note – The data presented in this table are also presented in Figure 12-15.

Table 11-2 Comparison of energy balance for tall conventional catamaran subjected to initial windward heel

Run 84
Initial heel = -14°
Full scale wind speed = 95 knots

Method of analysis	Equilibrium heel angle	Max heel angle	Area between wind heeling moment and vessel righting moment curves (Nm.rad)		
			From initial heel to equilibrium	Between equilibrium and max heel	Reserve beyond max heel
Experimental and Formula 2	13	26	5.539	0.962	0.436

Note – The data presented in this table is also presented in Figure 12-14.

12 FIGURES

Figure 12-1 General arrangement of the gust test facility

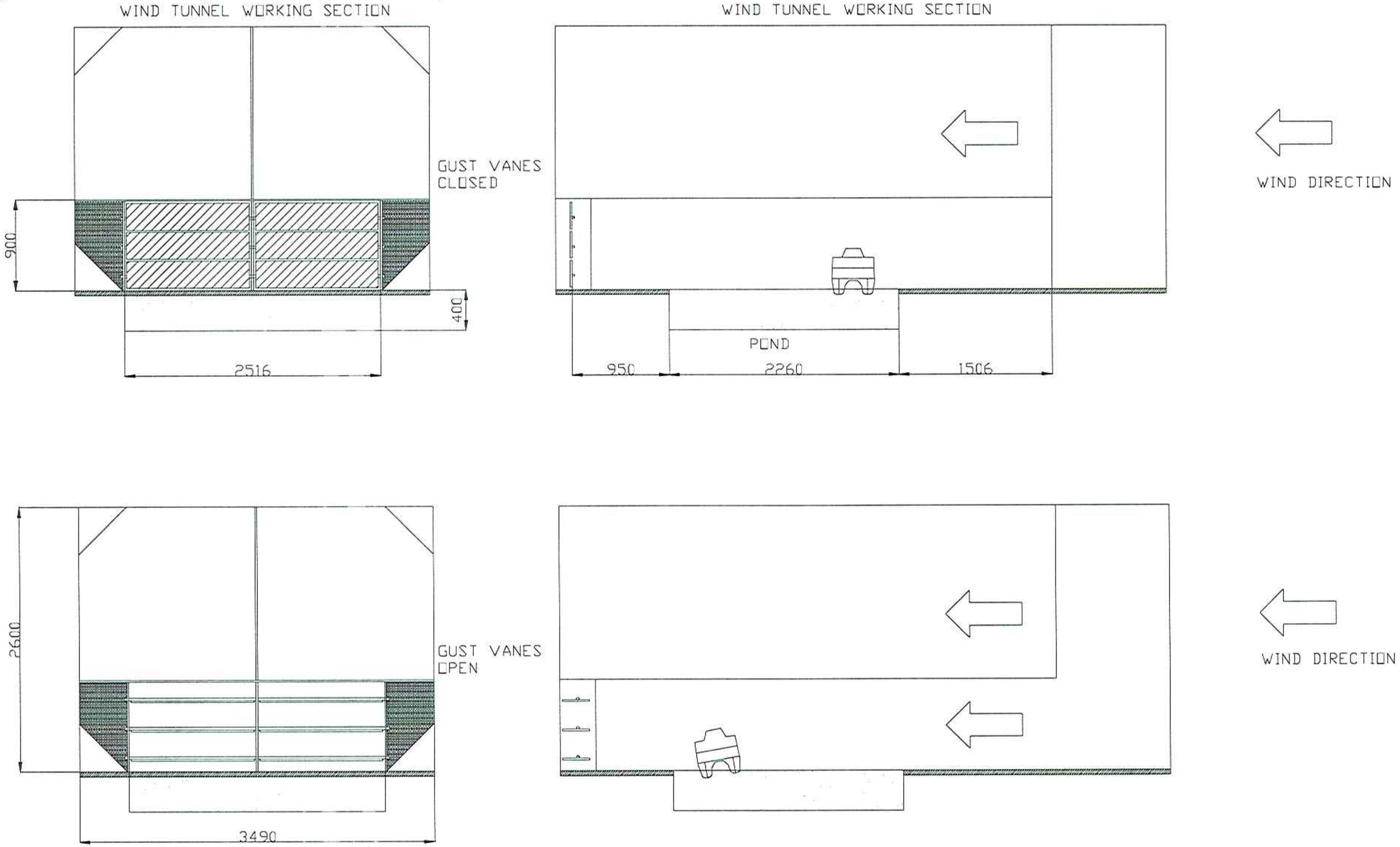


Figure 12-2 Vanes fully closed

Figure 12-3 Vanes half open

Figure 12-4 Vanes fully open

Figure 12-5 Overall view of gust test facility, looking downstream

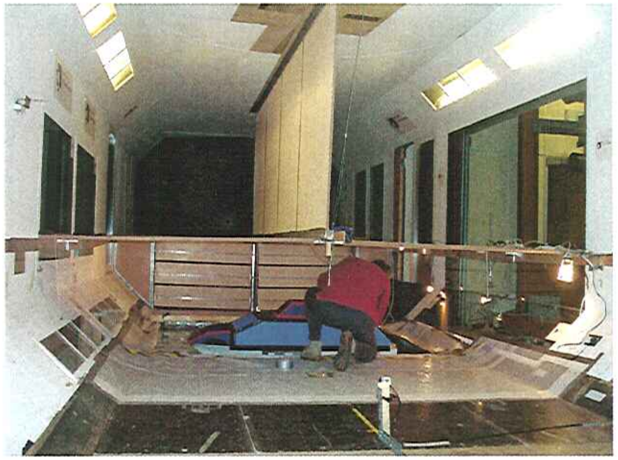


Figure 12-6 Model of conventional catamaran with standard superstructure, responding to a gust

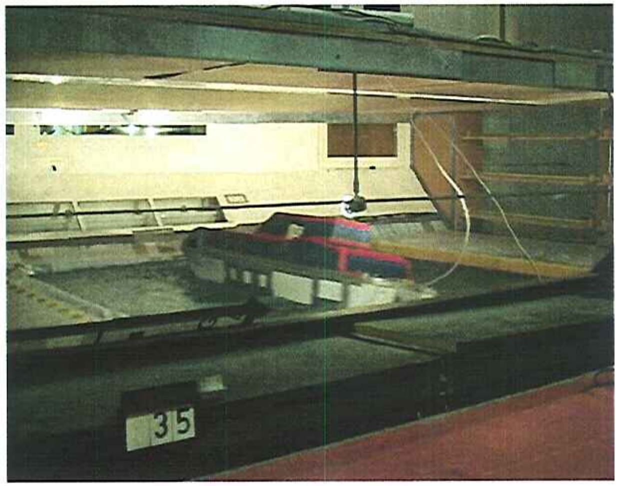


Figure 12-7 Conventional catamaran model with high superstructure

Figure 12-8 Wave piercing catamaran model

Figure 12-9 Time history of wind pressure and vessel heel for conventional catamaran with extra superstructure in a constant wind, when released from an initial windward heel

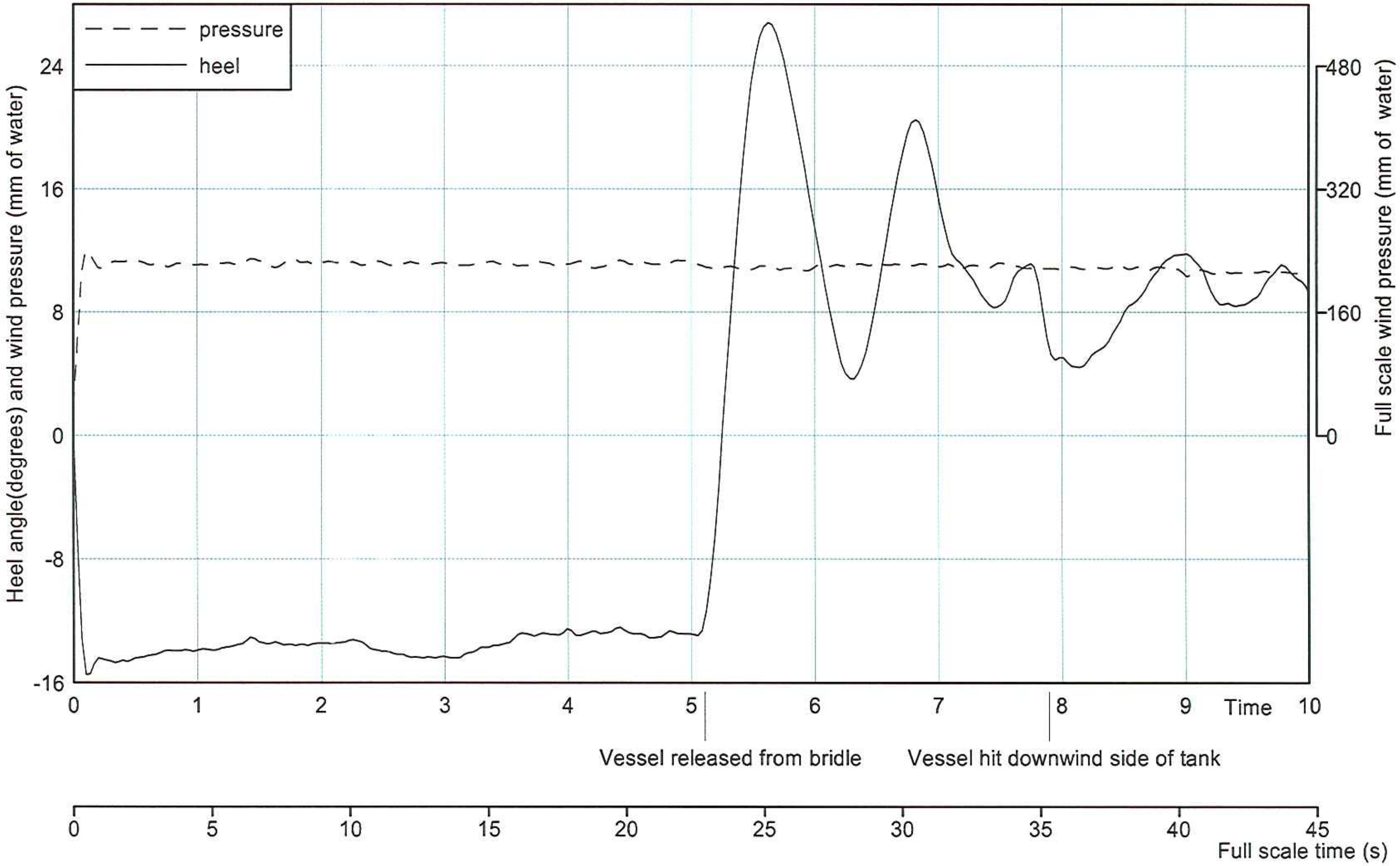


Figure 12-10 Time history of wind pressure and vessel heel for conventional catamaran with extra superstructure in a gust

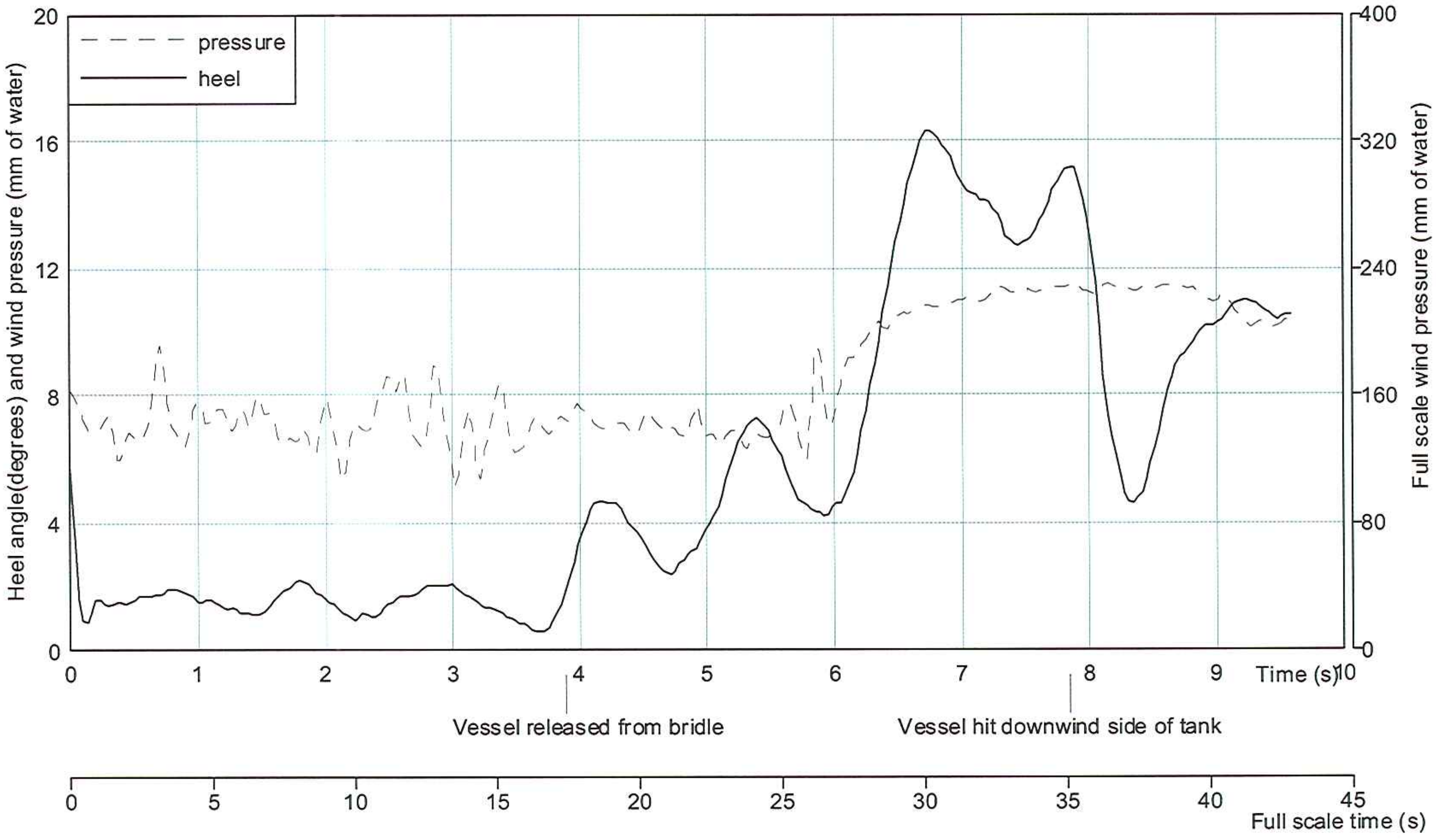


Figure 12-11 Time history of wind pressure and vessel heel for the standard wave piercing catamaran model

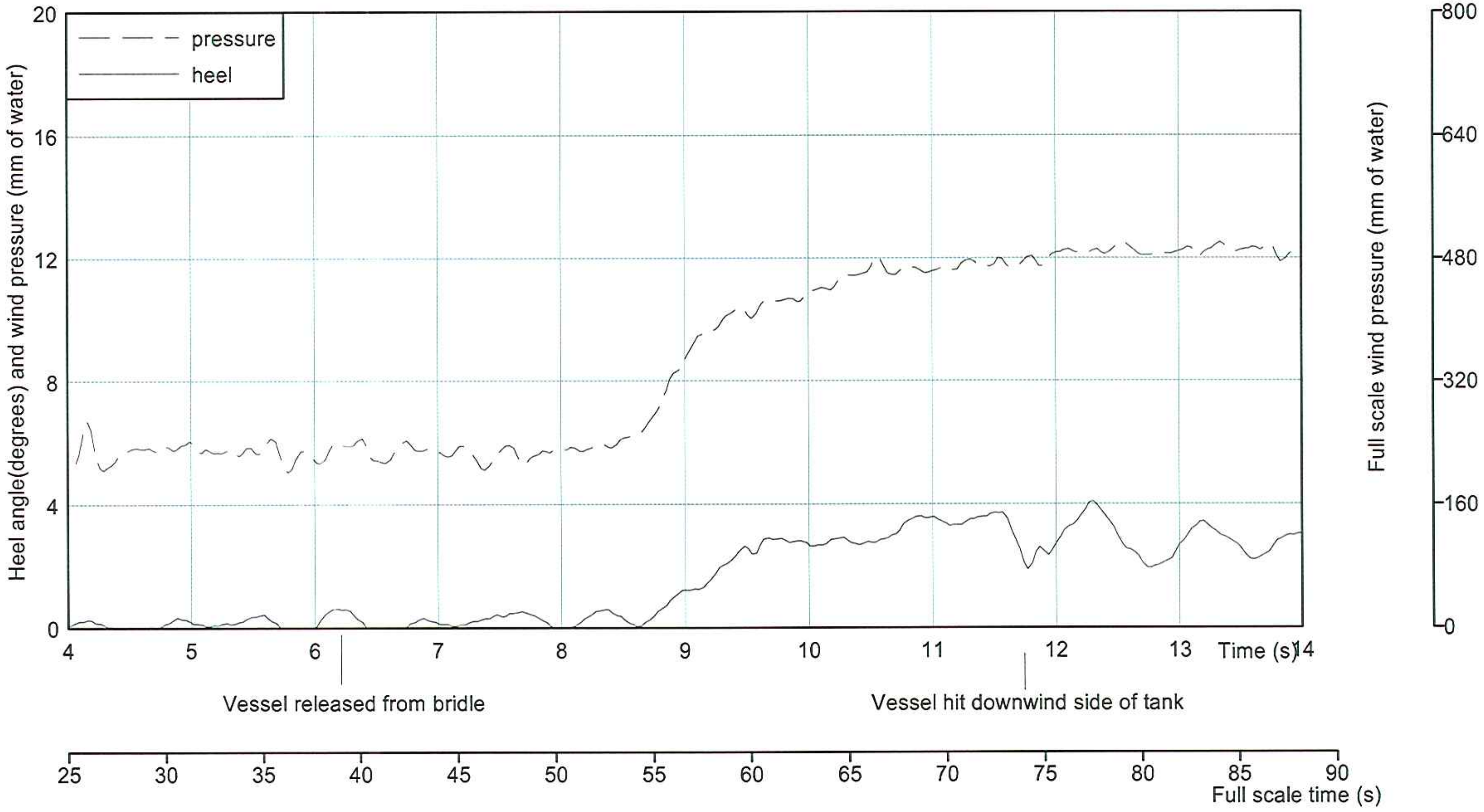


Figure 12-12 Ratio of overshoot angle to final heel angle against final heel angle for all HSC configurations tested

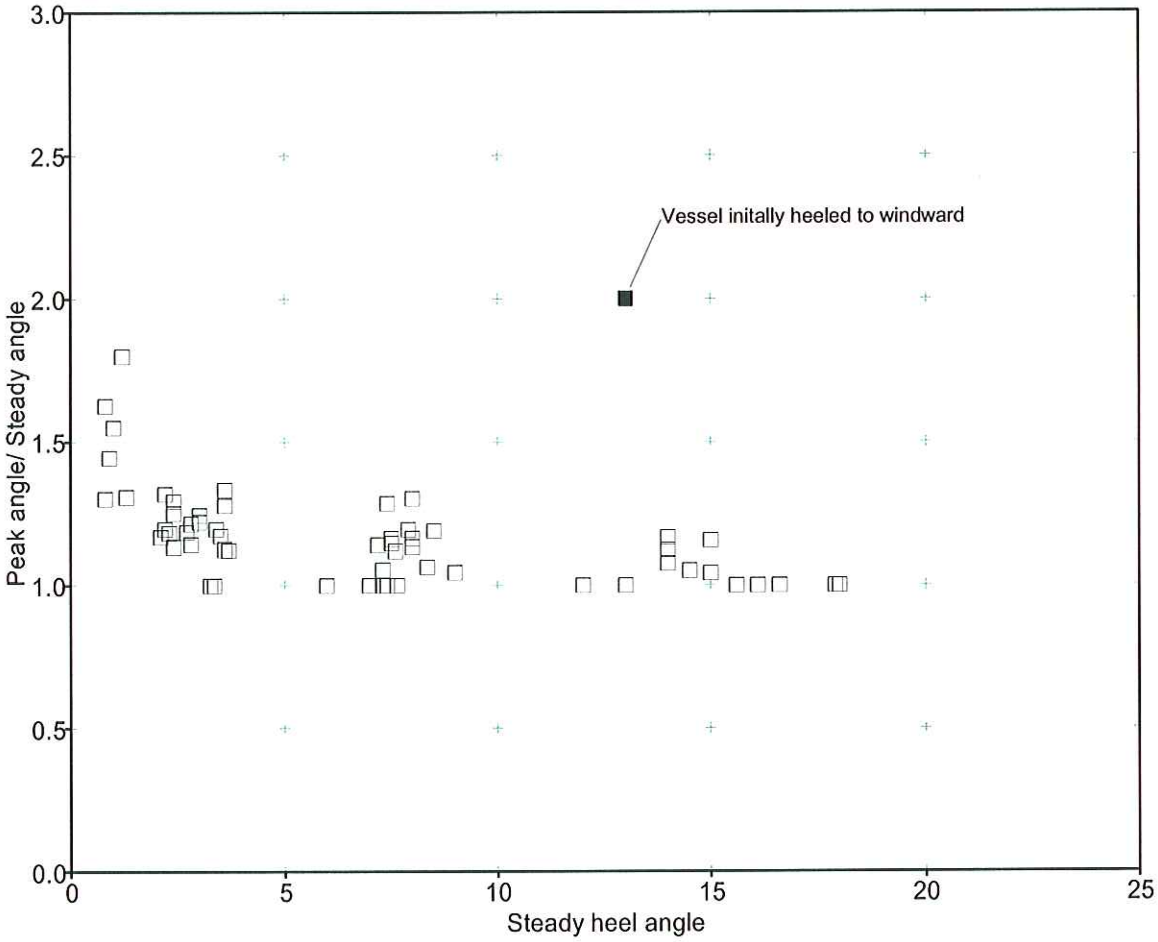


Figure 12-13 Comparison of predicted and measured equilibrium heel angle

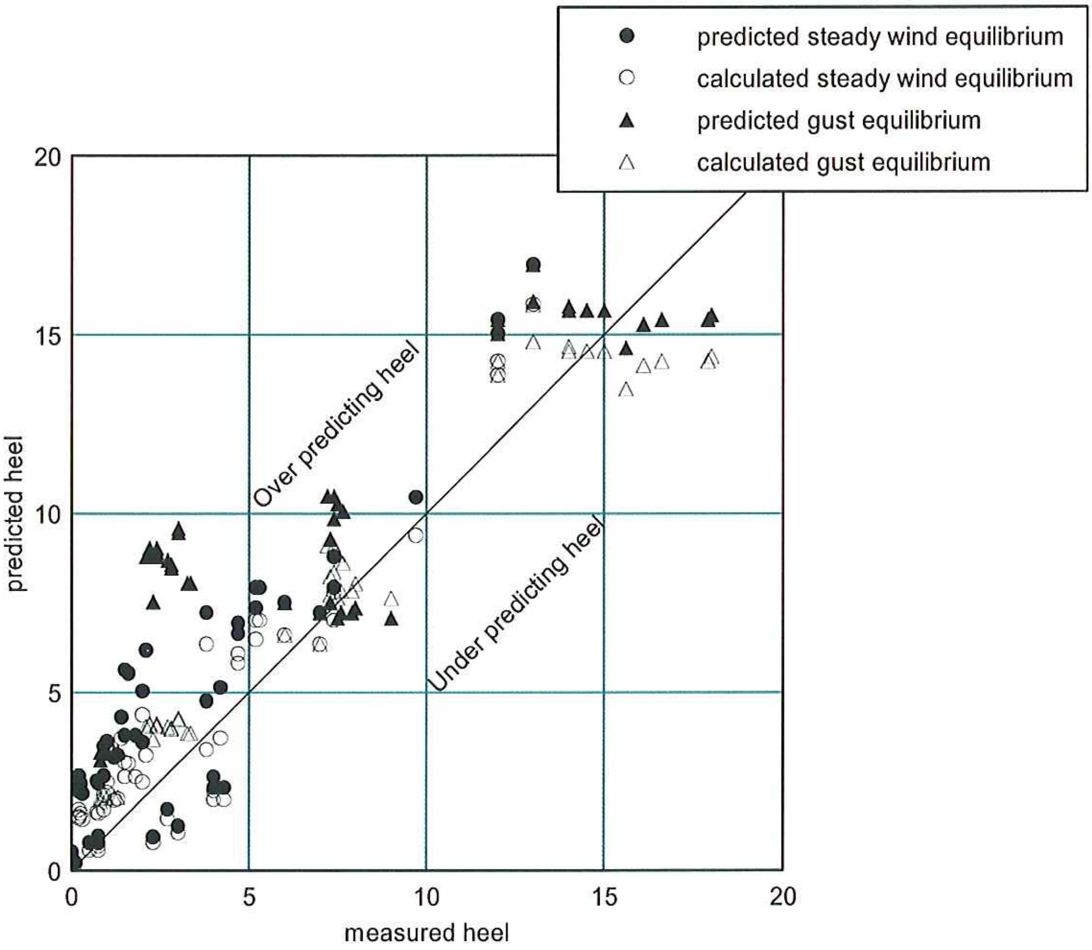


Figure 12-14 Heeling moment and righting moment variation with heel angle for conventional catamaran when vessel subjected to an initial windward heel

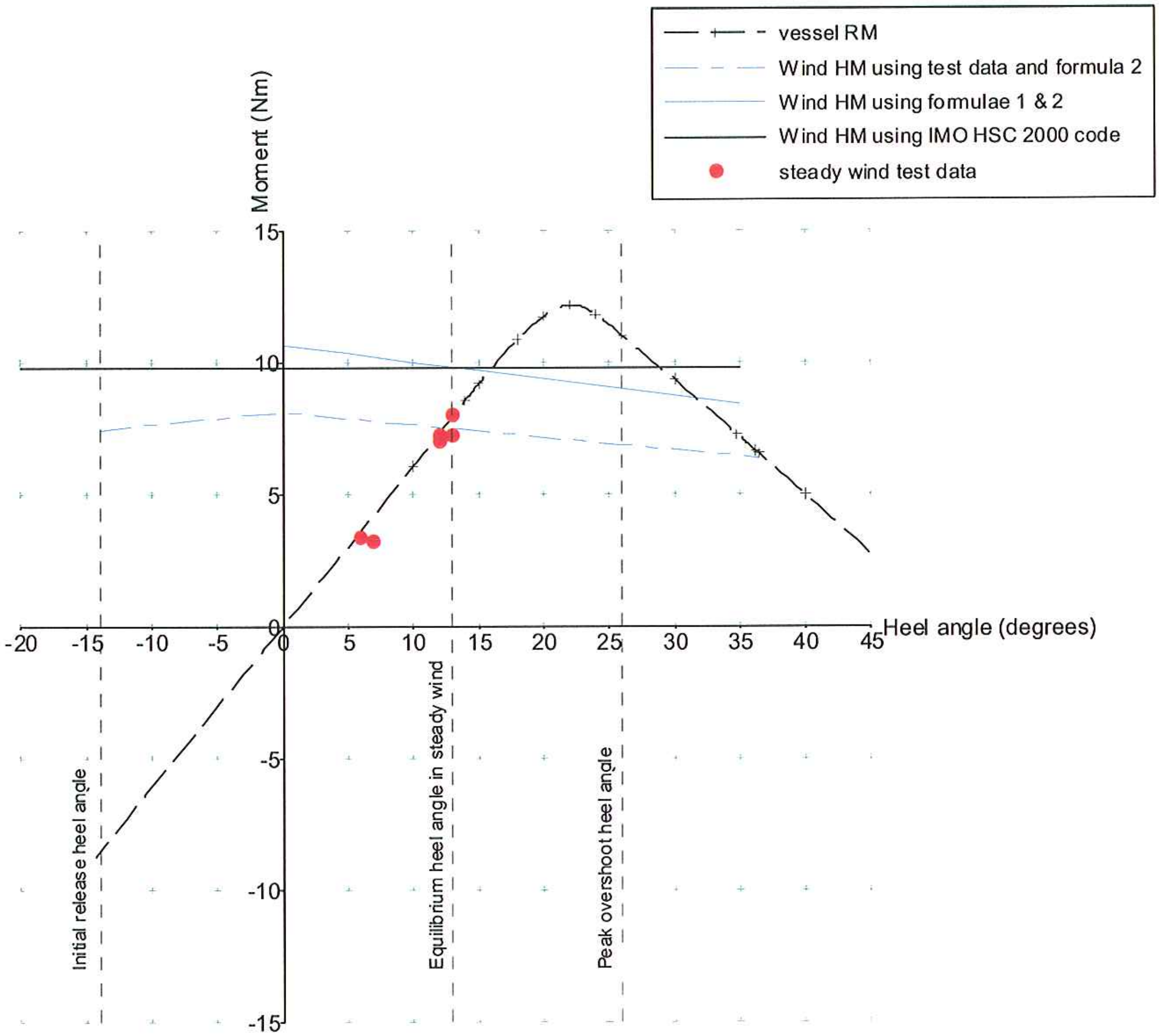
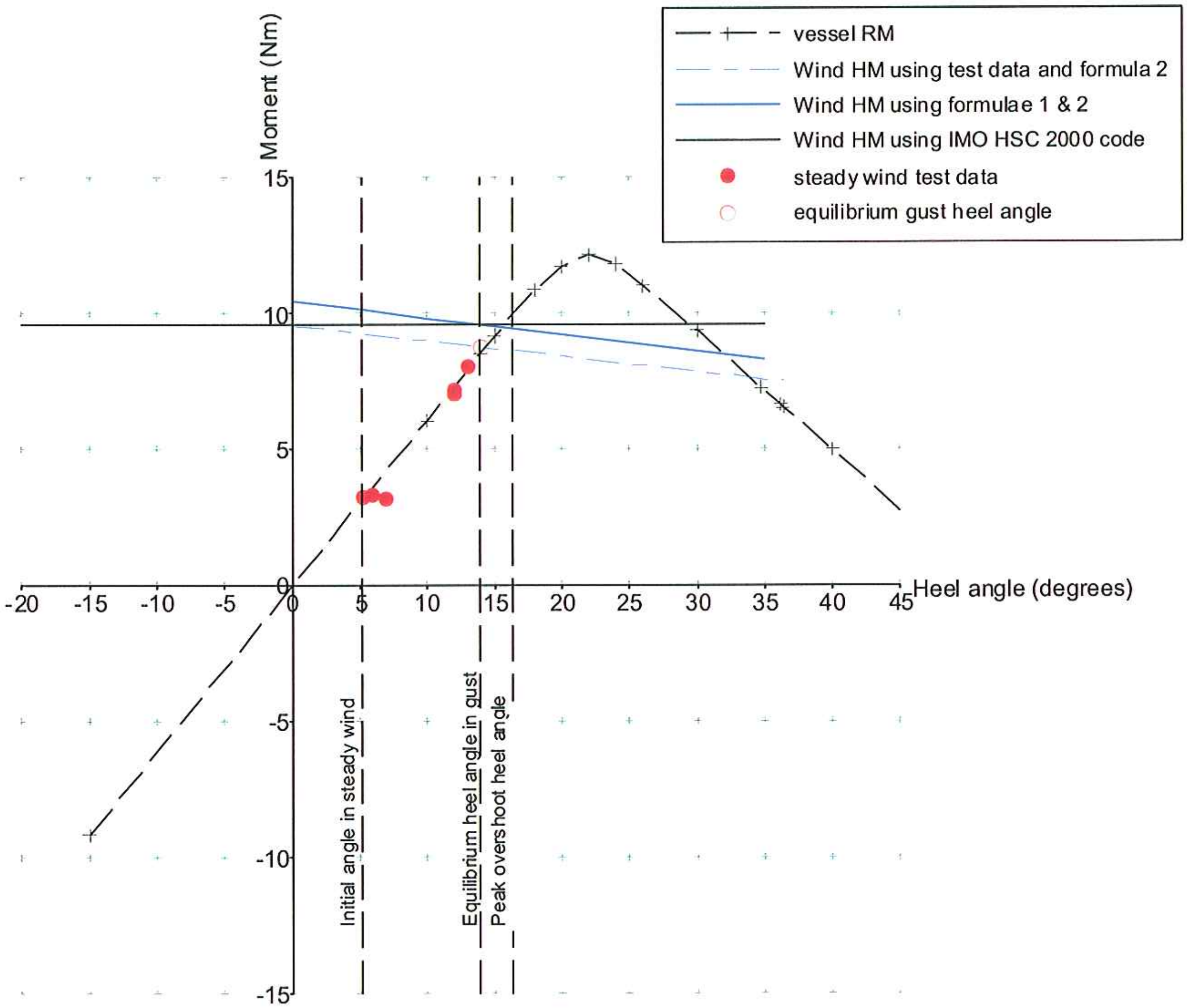


Figure 12-15 Heeling moment and righting moment variation with heel angle for conventional catamaran when vessel subjected to a gust



APPENDIX 1 – MODEL CHARACTERISTICS

Model	Conventional Catamaran - Std	Conventional Catamaran - Tall	Wavepiercer - Std	Wavepiercer - Tall
Scale	20	20	40	40
Weight (kg)	13.30	14.54	17.45	19.65
VCG above baseline (m)	0.170	0.201	0.172	0.211
LCG fwd of stern (m)	0.656	0.622	0.688	0.692
Kyy (m)	0.184	0.180	0.202	0.217
Profile Area s/s (m^2)	0.234	0.356	0.290	0.540
Profile Area hull (m^2)	0.140	0.135	0.132	0.121
Total profile area (above waterline) (m^2)	0.374	0.491	0.422	0.661
Height Centroid s/s (above shearline) (m)	0.098	0.151	0.087	0.172
Height Centroid total (above baseline) (m)	0.200	0.253	0.214	0.300
Total plan area (m^2)	0.644	0.644	0.923	0.923
length (m)	1.629	1.629	1.775	1.775
beam (m)	0.416	0.416	0.620	0.620
height (m)	0.230	0.301	0.270	0.455
B/H	1.81	1.38	2.30	1.36

APPENDIX 2 – BIBLIOGRAPHY

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