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The Effect of Mast Height and Centre of Gravity on the Re-righting of Sailing Yachts

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ABSTRACT

The effects of mast height and centre of gravity on re-righting have been investigated experimentally using free and captive models. Free model motions were measured using six degree of freedom photogrammetry. Captive model forces were measured using a six component force balance. The results have shown that a relatively small increase in mast height has a much greater effect than the increase in limit of positive stability used in the experiments. It would appear from the results that the overriding factors influencing re-righting in these experiments are the mast height and the wave height and steepness.

NOMENCLATURE

BOA	Beam overall (m)
c	Wave celerity (m/s)
C_X, C_Y, C_Z	Force coefficients
C_L, C_M, C_N	Moment coefficients
Fn	Froude number, based on *BOA*
GZ	Hydrostatic restoring arm (m)
LOA	Length overall (m)
L, M, N	Measured moments (Nm)
r_x, r_y, r_z,	Line of action vector (m)
R	Magnitude of vector **r**
V	Velocity (m/s)
X, *Y*, *Z*	Measured forces (N)
ρ	Density (kg/m^3)
ω	Wave frequency (rad/s)
ζ_0	Wave height (m)

INTRODUCTION

Stability standards of sailing yachts have all been based on hydrostatic measures. For example ISO 12217-2:2002(E) requires the calculation of a stability index (STIX) which includes as its input: area of the GZ curve; down-flooding angle; angle of vanishing stability; and righting moment at 90°, as well as numerous hull and sail geometric properties. Most of these stability parameters can be improved by lowering the centre of gravity of a yacht, none have the hydrodynamic effects of mast height included. Experiments detailed in this paper demonstrate the importance of including hydrodynamic measures of sailing yacht stability.

Experiments have been carried out to investigate the effect of varying centre of gravity and mast height. The investigations made use of a six component force balance for measuring moments and forces acting on the models in constrained testing. A six degree of freedom photogrammetric system was utilised to measure free model motions.

The free motion analysis experiments have shown that lowering the centre of gravity of a particular model in a particular condition has little effect on increasing its chances of re-righting. This effect is most likely due to the change in the centre of roll inertia with changing the centre of gravity, and appears to mirror some results quoted in Salsich and Zseleczky, 1983 (pp 61-62) for upright yacht shapes. This is not in direct agreement with conclusions presented in Ishida et al., 2000, and a reason for the differences is given.

An increase in mast height has relatively little effect on sway forces or moments on a fixed model due to waves but a large effect on forces due to sway motion. An increase in mast height also has a large effect on the induced moments due to sway motion, or the line of action of the sway force.

The impulsive nature of breaking wave forces combined with the relative motion of the yacht and mast to local velocities in the wave mean that the likelihood of re-righting is dramatically changed depending on the presence of a mast and its length.

PROJECT DIRECTION

The sailing yacht re-righting project as a whole has been active at the Australian Maritime College (AMC) since 2000. Early in the project it was realised that hydrostatic measures of stability alone would not be adequate to describe the dynamic motions of a yacht whilst re-righting, (Renilson and Binns, 2001). As such a combined experimental and theoretical project was developed. The entire project was divided up into 5 tasks as

1. re-righting experiments with the yacht unconstrained (Renilson and Binns, 2001);

2. develop prediction techniques for forces and moments on an inverted sailing yacht due to breaking waves (Binns and Brandner, 2003);

3. develop a force balance capable of statically and dynamically measuring forces and moments in six components (Binns and Brandner, 2003);

4. conduct experiments in calm water and in waves over a range of sway velocities and accelerations for a captive model and compare these with predicted results; and

5. incorporate the results of forces from experiments and/or predictions into a mathematical model to predict motions of an inverted sailing yacht in breaking waves, and compare these with results with free model experiments.

Some results from tasks 3, 4 and 5 are presented.

EXPERIMENTAL OVERVIEW

Model parameters

Experimental results from two models (00-16 and 03-08) are discussed. The body plans of the two models are shown in Figures 1 and 2.

The principal hull form parameters of the models tested are shown in Table 1 for full scale and Table 2 for model scale.

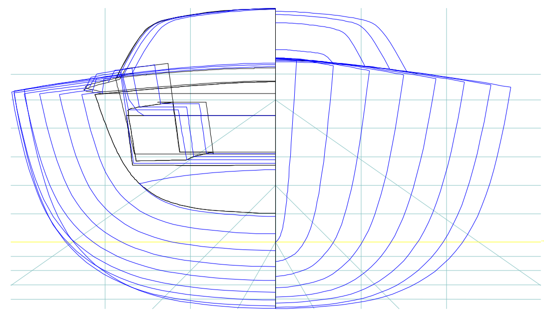

Figure 1 - Body plan for model 00-16

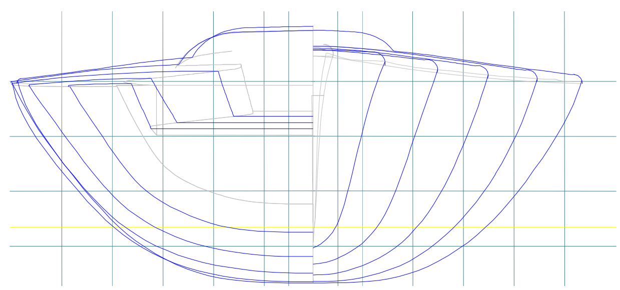

Figure 2 - Body plan for model 03-08

Design Parameter	00-16	03-08
Model scale	1:12.5	1:16
Length Overall (m)	12.5	19.4
Beam Overall (m)	3.7	5.2
LWL (m)	11.5	17.9
BWL (m)	3.0	3.6
Displacement (kg)	7353	16354
Actual *LPS* tested	138	139.7, 143.5, 146.3

Table 1 - Hull principal characteristics, full scale

Design Parameter	00-16	03-08
Model scale	1:12.5	1:16
Length Overall (m)	1.000	1.213
Beam Overall (m)	0.296	0.325
LWL (m)	0.920	1.119
BWL (m)	0.240	0.225
Displacement (kg)	3.673	3.895
Actual *LPS* tested	138	139.7, 143.5, 146.3

Table 2 - Hull principal characteristics, model scale

Photogrammetric setup

A six degree of freedom photogrammetric system consisting of three to four CCTV cameras and the software WinAnalyze v1.4 was used to measure the motions of each condition. The software uses the method developed by Tsai, 1987, to calibrate and analyse the images.

Force balance setup

The models were attached to the force balance using a two post system. Connection to the model was via two carbon fibre heave posts through a hinge and a ball joint. The hinge was oriented to permit trimming motions. The model was therefore constrained in surge, sway, heel and yaw. A further restraint was added, where noted, by clamping the model heave posts to remove heave and trim motions.

The heave posts were used as model ballast to remove the added inertia effects of counter-balances. A schematic view of the force balance and model setup is shown in Figure 3.

Constant sway velocity experiments

For the constant sway velocity experiments the sway force is non-dimensionalised using

$$C_Y = \frac{Y}{\frac{1}{2}\rho V^2 BOA\, LOA}, \qquad (1)$$

and the roll moment is non-dimensionalised using

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 BOA^2\, LOA}. \qquad (2)$$

Where Y is the measured sway force, L is the measured roll moment, V is the sway velocity, BOA is the beam overall and LOA is the length overall of the model. Froude numbers have been non-dimensionalised with respect to BOA.

Regular wave experiments

The models were attached to the towing carriage and the carriage positioned such that the model was 4 m away from the wave maker. Waves were then produced to propagate in the negative Y direction. A schematic diagram of the setup is shown in Figure 4. A view looking in the positive Y direction towards the wave maker is shown in Figure 5

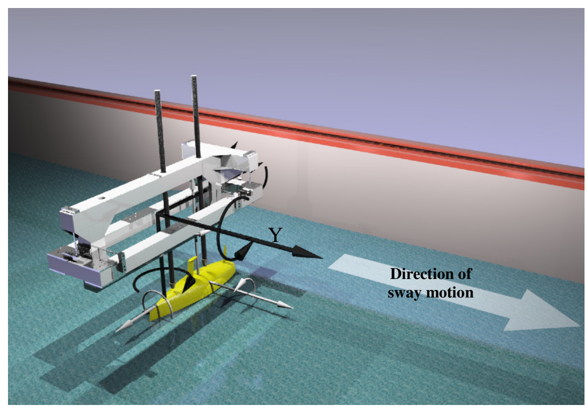

Figure 3 - Schematic of sway velocity and acceleration experiments

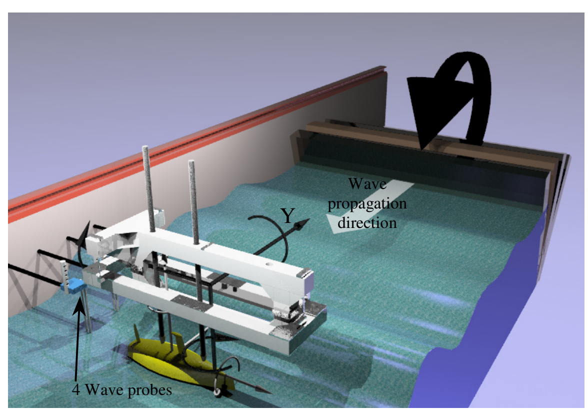

Figure 4 - Schematic diagram of captive wave experiments

Figure 5 - View from model toward wave maker

For the regular wave experiments the sway force is non-dimensionalised using

$$C_y = \frac{F_y}{\frac{1}{2}\rho c^2 LOA\, \zeta_0}, \qquad (3)$$

where F_y is the single tone amplitude of the measured sway force, ρ is the density of water, c is the wave celerity, *LOA* is the length overall of the model, ζ_0 is the wave amplitude. The wave celerity has been taken as its linear inviscid theoretical value of

$$c = \frac{g}{\omega}. \qquad (4)$$

in which g is acceleration due to gravity and ω is the linear inviscid circular frequency of the wave. The single tone analysis procedure used to measure F_y was that implemented by LabView v6i. The built-in function used a windowed frequency domain representation of the data and then found a maximum amplitude by interpolating the frequency domain data.

The input waves were measured using four resistance type wave probes located well aft of the model. The first wave probe was located in-line with the stern of the models, the other three were located closer to the wave maker at increments of 250 mm.

Solitary waves experiments

Solitary waves were passed over the model constrained by the force balance but free to heave and pitch. In this case forces and moments acting on the models are best considered in the time domain, due to the impulsive nature of the forces essentially violating the Fourier assumption, and are presented as time series data for the passing of one solitary wave.

RESULTS

Photogrammetry

The maximum heel angle achieved during the runs is plotted against wave height, as shown in Figures 6 for model 00-16, Figure 7 for model 03-08 and Figure 8 has the combined results. For the runs that re-righted a value of 180 degrees has been plotted for the lowest wave which re-righted, all other re-rights have not been plotted. The wave height was taken as the maximum wave probe value minus the minimum wave probe value prior to the maximum. The dark horizontal lines shown on Figures 6 and 7 are the angle required in flat water to re-right, that is (180° - *LPS*).

From Figures 6 to 8 it can be seen that varying the mast height has a large influence on re-righting, **much** larger than varying the centre of gravity. It can also be seen that no instance of the model rolling beyond the hydrostatic re-righting angle and remaining inverted was observed. Therefore the *LPS* angle does define a boundary, over which the yacht will re-right. Finally, the increase in wave height required to re-right a model is small compared with the range of wave heights tested.

From Figure 8 it can be seen that the difference in wave height required to re-right models of varying geometry is small compared with the difference obtained when mast height is varied. It can also be seen that it was not possible to re-right either model with the waves generated if the model had a mast height of 284 mm or less.

From these experiments varying the mast height by as little as 150 mm model scale has a much larger effect on the maximum heel angles obtained and the likelihood of re-righting than varying the actual limit of positive stability by 5°. From Figure 8 it can be seen that the size of the mast and the wave appear to be the dominant influences on the maximum heel angle and likelihood of re-righting. This can be seen by the fact that model 00-16 is quite different to model 03-08, and yet both require very similar mast heights and wave heights to re-right.

These observations are not quite in line with those by Ishida et al, 2000. Ishida concludes that the dominating influence is the *LPS* value. However, it appears that Ishida did not vary mast height, instead a full mast was always used for re-righting experiments. Also Ishida measured re-righting times of around 3 seconds, for these experiments 2 seconds would appear more accurate. Therefore, it would seem that Ishida may have had a lot more roll inertia than was used here, and a constant mast length. Under these conditions the next most important parameter could indeed be *LPS*.

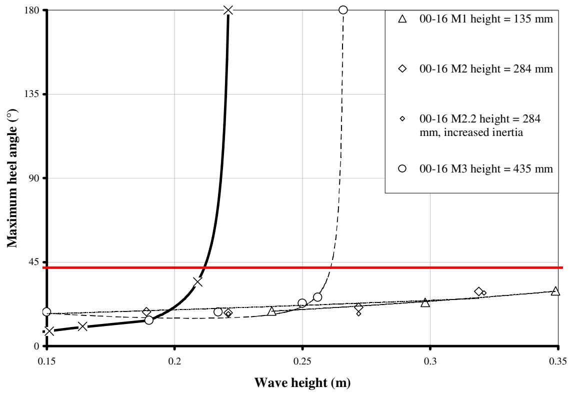

Figure 6 - Maximum heel angle for model 00-16

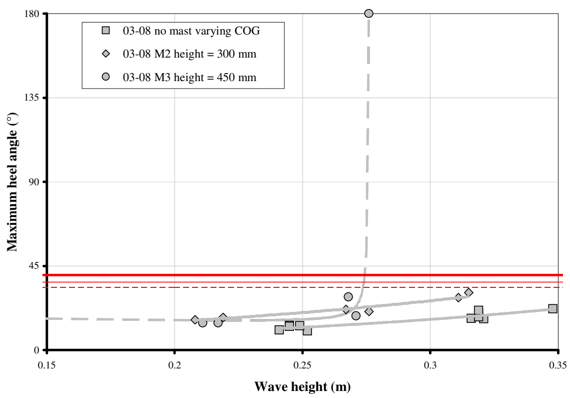

Figure 7 - Maximum heel angle for model 03-08

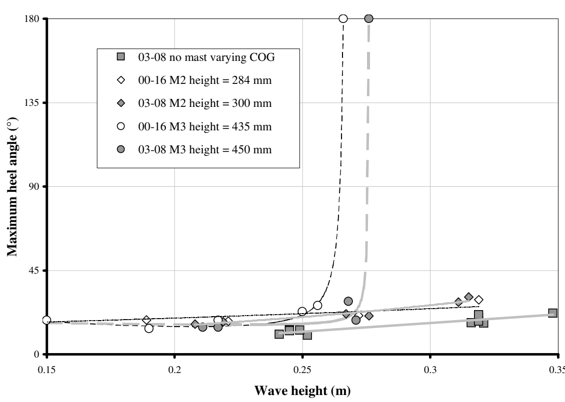

Figure 8 - Maximum heel angle for models 00-16 and 03-08

Constant sway velocity

The sway force coefficient for model 00-16 with varying mast height is shown in Figure 9 for the fixed in heave and trim condition. The roll moment coefficient about the centre of gravity for model 00-16 is shown in Figure 10 for variable mast height.

From the results it can be seen that in the coordinate system used, model 00-16 will develop a roll moment of the same sign to the sway force when placed in a uniform sway velocity field. However, when a mast is added to the model the roll moment will reverse sign, and then increase substantially with increased mast height.

In this coordinate system, a positive roll moment will result in the model "tripping". That is the model will develop a roll moment tending to turn the parts of the model above the centre of gravity into the direction of sway velocity. A negative roll moment will result in stabilising the model (rolling away from the direction of travel), the boat can be thought of as planing, inverted and sideways, with a resulting aft trimming moment. If the model undergoes any kind of surfing, it will require a tripping moment to re-right. From Figure 10, model 00-16 without a mast will develop a stabilising moment in a uniform flow field. However, the presence of any of the masts tested will convert this into a tripping moment. Increasing the mast size dramatically increases the magnitude of the tripping moment.

From Figures 9 and 10, it can be seen that the presence of a mast can dramatically change the forces experienced by an inverted sailing yacht undergoing a sway velocity. For example the addition of an 1185 mm mast at model scale (the full sailing mast is 1368 mm model scale) increases the sway force by a factor of 3.77 and multiplies the roll moment by a factor of -4.46.

When Figures 9 and 10 are examined along side Figure 6 a direct correlation between negative sway force, positive roll moment and size of wave to re-right can be seen. That is, if the roll moment experienced by a yacht when undergoing sway velocity is a tripping moment (tending to turn the higher portions of the yacht into the direction of travel), then the chance of re-righting can be seen to be increased. This correlation exists because when hit by a breaking wave, a yacht will experience significant surfing even whilst inverted. The surfing will continue long enough after the wave has passed, due to the yacht's inertia, and so the probability of re-righting will be significantly increased as the tripping moment is increased.

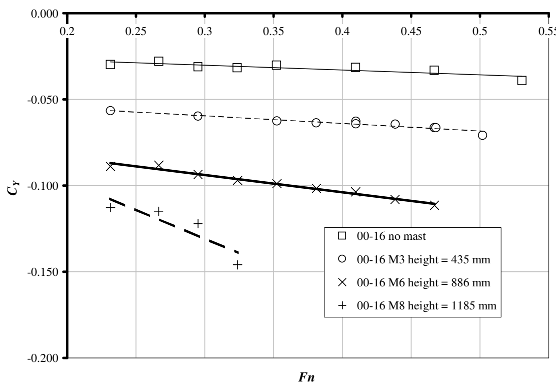

Figure 9 – Sway force coefficient variable mast height, 00-16 fixed in heave and trim

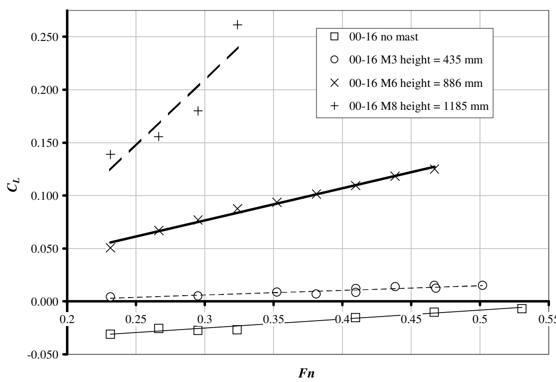

Figure 10 - Roll moment coefficient variable mast height, 00-16 fixed in heave and trim

Regular waves

The amplitude of oscillation of sway forces in regular waves was measured by taking the sway force time records from force balance measurements and applying a single tone analysis. The frequency of the input waves was measured using the time records of the in-line wave probe and applying the same single tone analysis. The single tone amplitude of the sway force has been plotted against wave input frequency in Figures 11 to 13.

From Figure 11 it can be seen that there is little difference in the excitation force in sway for either model. From Figure 12, an increase in wave slope has little effect on the sway force for either model 03-08 or model 00-16.

From Figure 13, an increase in mast height slightly reduces the excitation force in sway when the models are exposed to regular waves.

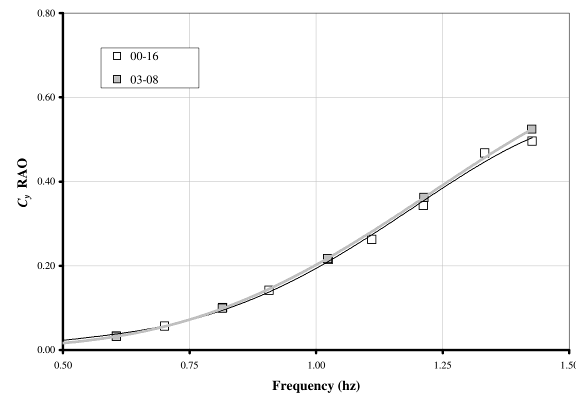

Figure 11 - Sway force coefficient, wave slope = 0.02

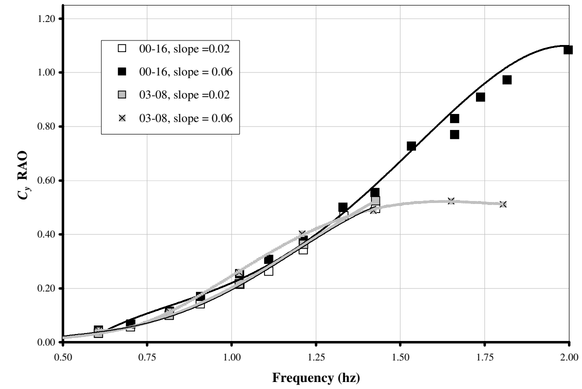

Figure 12 - Sway force coefficient, wave slope = 0.02, 0.06

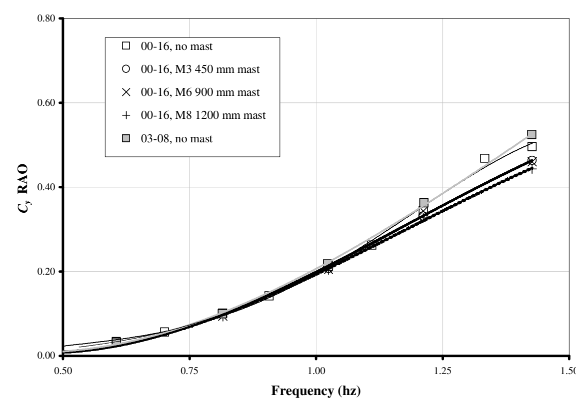

Figure 13 - Sway force coefficient, wave slope = 0.02, variable mast height

Solitary waves

Most model conditions were analysed for sway forces in solitary waves. Four are presented in Figures 14 and 15 for the sway force and roll moment about the moving centre of gravity, plotted with respect to time. The four conditions are for model 00-16 with varying mast height. From Figure 14, an increase in mast height can be seen to decrease the sway force from a breaking wave. From Figure 15 the same increase in mast height does not change the magnitude of the roll moment significantly, but does change the position in the wave that the maximum occurs.

Considering the results in Figures 13 and 14 it can be seen that the addition of a mast decreases the excitation force in sway for a model in waves. This is a minor effect in small regular waves, but is more pronounced in breaking waves. This could be due to the velocity profile vertically through the wave. From prediction of breaking waves from boundary element and finite volume techniques, the internal velocities can be shown to reverse, which would result in this reduction in sway force. From Figure 15, an increase in mast height has little effect on the total moment, apart from shifting the maximum point in the wave. This adds weight to the result being due to a reversing vertical velocity profile, that is, the same moment is produced with less force.

A reduction in excitation force in sway could result in the yacht spending more time inverted, as a smaller sway velocity would be accompanied by a corresponding smaller tripping moment. This does not correlate with the free motion experiments as models with larger masts re-right with smaller waves.

From the free motion experiments, the re-righting event occurs some time after the wave crest has passed the model. This can be seen from the heave time series of the model motion. Although the initial sway forces are lower for a model with a mast, the motion that is induced by the wave continues well after the wave has passed. It is at this point that the tripping moments, so evident from Figure 10, take over and force the model into re-righting. Also, a model with a larger mast will require significantly less sway velocity to produce the same tripping moment. All of the models tested (regardless of mast height) will therefore receive sufficient sway force to induce a large sway velocity. After the wave crest has passed the sway velocity will be converted to tripping moment, this conversion is highly dependent on mast geometry.

To summarise, a model with a mast will receive a smaller sway force from a wave (Figures 13 and 14), but equal righting moment (Figure 15). Therefore a model with a mast will attain lower sway velocities, but similar roll angles as a wave crest passes. However, a model with a mast will require much less sway velocity to create much higher tripping moments (Figure 10). As the re-righting event occurs after the wave crest has passed, it is the tripping moment that is critical in determining the probability of re-righting.

Centre of pressure

The results presented in Figures 9 and 10 for flat water and Figures 14 and 15 for a model in a breaking wave show that the presence and size of a mast significantly changes the line of action of hydrodynamic sway forces. The net effect is greater moments to force re-righting. From Figure 10 the model without a mast is seen to have a negative roll moment, essentially the moment is produced by the variable pressure distribution on the deck of the model, and could go either way. As noted above, in a re-righting scenario a boat will require a positive moment in this coordinate system. The addition of a mast can be seen in Figure 10 to change the sign of the moment, therefore counteracting the pressure distribution on the deck. Increasing the mast height then produces more tripping moment. From Figures 14 and 15 a similar phenomenon can be seen for a variable velocity distribution of a breaking wave.

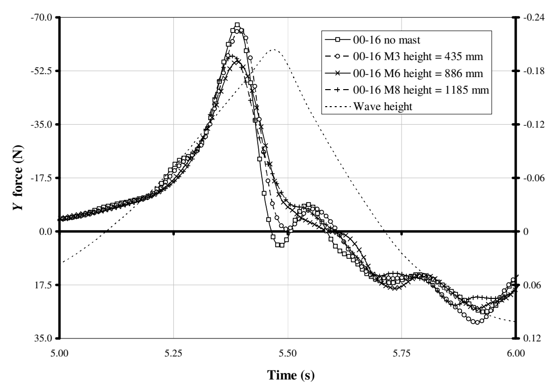

Figure 14 - Sway force from a solitary wave 00-16, varying mast height

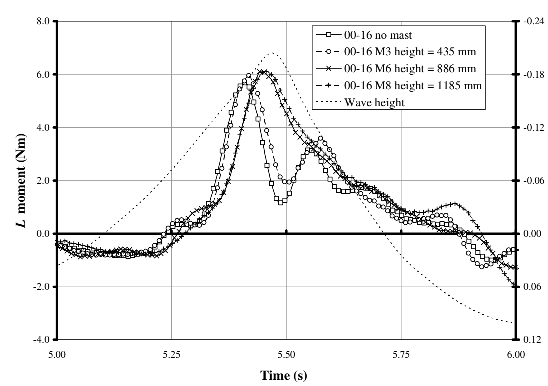

Figure 15 - Roll moment from a solitary wave 00-16, varying mast height

CONCLUSIONS

The results from the free model photogrammetric experiments clearly show that the presence and size of a mast has a dominating influence on the chance of re-righting. This influence is much larger than the effect of varying the *LPS* by as much as 5°. The large effect of a mast warrants further investigation of how the forces and moments change with varying mast heights. This was achieved through force and moment measurements on a captive model undergoing sway motions and subjected to waves.

From the sway force and roll moment measurements in calm water, model 00-16 without a mast will develop a stabilising moment. Also an increase in mast height has a dramatic effect on the tripping moment. For model 00-16, the addition of a mast has turned a stabilising moment (one which will tend to keep the model capsized) to a tripping moment (one which will tend to re-right the model). Essentially the mast acts as a sea anchor placed some distance below the hull.

The force measurements in regular and breaking waves have shown that a mast slightly decreases the excitation force in sway. This fact by itself could lead to smaller sway forces and correspondingly smaller tripping moments. This in turn could lead to more time spent inverted. However, the re-righting event does not occur at the wave crest, which is the point being examined in the wave experiments. Rather it occurs some time afterwards. Regardless of mast height, a model will receive sufficient sway force to set in train a series of flow fields and free body motions which are capable of producing a re-righting event.

ACKNOWLEDGMENTS

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