Towards Predicting the Behaviour of Yachts in Following Seas

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ABSTRACT

This paper reports on work conducted to date towards the development of a numerical simulation of yacht's behaviour whilst sailing downwind in waves. Numerical models for the resistance, wave force and sail force have been incorporated into a longitudinal time domain simulation. The resistance and wave force components have been compared with experiments, conducted at the Australian Maritime Colleges' Ship Hydrodynamics Centre. The experiments used a series of IMS style yacht models designed by industry participants Murray Burns and Dovell. The effects of hull form parameters, appendages, encounter frequency and wave conditions on the wave force experienced by a yacht have been investigated and the results presented.

1. INTRODUCTION

Past investigations into the behaviour of yachts in waves have primarily focussed on their upwind performance, and in particular their added resistance when sailing in head seas. This research has usually been incorporated into Velocity Prediction Programs (VPPs), Oliver et. al. (1995), which may be utilised as a design tool or a handicapping system such as the International Measurement System (IMS). Capsizing of yachts in beam seas has been the other principle research area, particularly following the Fastnet Race tragedy of 1979, Claughton et. al. (1984). Consequently little work has been carried out to date into the performance and controlability of yachts sailing downwind in large following seas, Kuening et. al. (1993).

Yachts racing in many of today's high profile yacht races eg. Volvo Race around the World, Around Alone and The Millenium Race will spend the majority of their time sailing downwind in following seas. The ability of a yacht to sail fast in severe following seas and stay in control will therefore have a major influence on its ability to win such a race, and its ability to survive the harsh conditions they experience. At present, designers have no tools for the systematic comparison of different designs in order to ascertain their downwind performance and controlability in following seas. The objective of this project is to develop a computer program that may be utilised in the design, design selection and optimisation of yachts, by modelling their downwind performance in following seas.

Work done by two of the authors (Thomas and Renilson, 1991) and others (Grim, 1962, Du Cane et. al., 1962, Umeda, 1984) has shown that the surging behaviour of powered vessels in following seas can be modelled mathematically. This surging behaviour is caused by the longitudinal force imposed on the vessel by the wave, which is a function of the vessel's position in the wave. The surging can cause the vessel to travel at a mean speed greater than that in calm water, whilst if the vessel accelerates to wave phase velocity the vessel is said to be 'surf-riding'.

The vessels utilised in following sea studies to date have predominantly been propeller driven, traditionally shaped craft with large displacement to length ratios. In comparison, racing yachts generally have small displacement to length ratios, have a large amount of shape above the calm waterline ie. flare and bow and stern overhangs and are powered by sails, whose thrust varies significantly with apparent wind speed and hence vessel velocity.

This paper reports on the work to date in developing the tools to predict the performance and controlability of yachts sailing downwind in following seas. A numerical simulation has been developed to model the longitudinal motion of a yacht and two of the three individual components of this simulation have been validated through towing tank experiments.

2. NUMERICAL MODEL

To predict the performance of a yacht operating in following waves a numerical model of the yacht's response to external forces and moments is being developed. Due to the highly non-linear nature of the response of a vessel operating in a following seaway the numerical model is solved in the time domain.

The present model takes into account forces induced by the sails, hull and waves. These are resolved to obtain a total force which is then applied over a specified time interval; the resultant acceleration is used to determine the new velocity, position in wave and relative wind velocities.

Fig.1 indicates the coordinate system being employed:

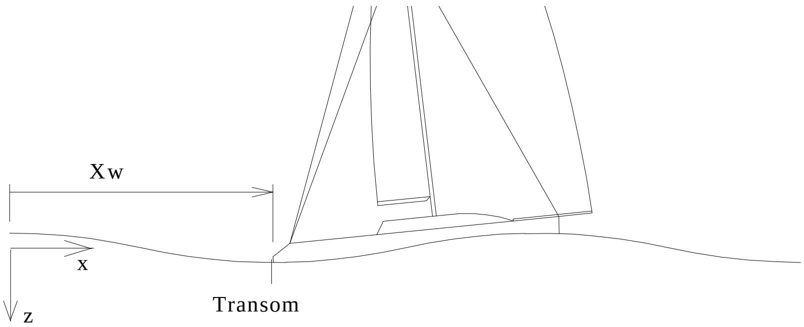

Figure 1. Notation

The longitudinal equation of motion adopted for the numerical model is shown below:

$$m\dot{u} = X_x(x) + R(u) + T(V_{wa})$$

where m is the mass of the vessel (physical mass + added mass); X_ξ is the longitudinal wave force which is dependent on the yacht's non-dimensional position in the wave, ξ; R is the resistance force and is dependent on the yacht velocity, u; and T is the thrust provided by the sails and is dependent on the apparent wind velocity, V_{wa}.

The method for calculating the upright calm water resistance is based on the extensive experimental and theoretical study undertaken at the Delft University of Technology (Kuening et. al. 1999). This research was mainly conducted with a view to windward performance prediction of typical IMS style yachts, with the range of Froude numbers tested being 0.1-0.6. However in surf-riding conditions it is not uncommon for yachts to experience speeds in excess of this range. Therefore the model proposed by Gerritsma et. al. (1993) for calm water resistance prediction is utilised in the speed range Fn 0.6-0.75.

Wave induced forces and moments on a yacht in following waves are extremely complex, due to the number of non-linear forces involved. To simplify the problem only the longitudinal case is investigated, and a quasi-static assumption made producing forces as a function of the yacht's position in the wave only. This is deemed appropriate as yachts operating in a following seaway predominantly have a velocity at, or close to, wave phase velocity.

The predominant longitudinal force induced by the wave is the Froude-Krylov force. Due to the very low encounter frequency diffraction forces may be ignored. The Froude-Krylov forces arise from the undisturbed pressure field acting on the submerged surface of the hull, given by (Umeda, 1990):

$$X(x) = -rgzk\int_{AP}^{FP} e^{-kd(x)} S(x)\sin(2px + kx_w)dx$$

where $S(x)$ is the sectional area at a distance x_w along the vessel (measured from the transom). Using linear seakeeping theory, the wave pressure is assumed to act up to the calm water free surface position as the wave height is assumed to be small.

A sail force model proposed by Hazen (1980) is used in the initial sail force computer code. This model is used as a basis in many VPPs, for example the IMS handicap system.

When sailing directly downwind all thrust provided from the sail is purely from drag. Hence the sail thrust is given by:

$$T(V_{wa}) = 0.5 \cdot r_a \cdot V_{wa}^{\ 2} \cdot C_D$$

where V_{wa} is the apparent wind velocity and r_a is the air density.

With all the forces effectively accounted for it is possible to construct a numerical simulation. The results from two simulations shown in Fig.2 illustrate the yacht's behaviour under two different wave conditions. Both simulations begin with the same true wind velocity and at the same position in the wave, ξ=0 (transom on wave crest).

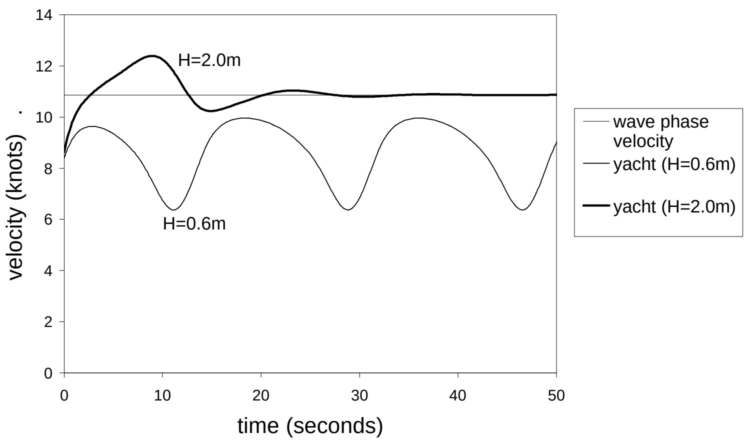

Figure 2. Example Simulation; AME 004, LWL=10.0m, λ=20.0m, V_w=15 knots.

The velocity of the yacht in the wave height of 0.6m fluctuates periodically as it moves through different positions in the wave. In this case the wave is overtaking the yacht; when the yacht is travelling fastest it will be closest to wave celerity and will hence spend more time in this section of the wave. In this instance, although the yacht is not surf-riding, the average velocity is slightly greater than it would be in flat water under the same wind conditions. When the wave height is increased (2.0m) the wave force is increased sufficiently to accelerate the yacht's velocity to wave celerity. In this instance the yacht's longitudinal position in the wave reaches a stable equilibrium, and the yacht is surf-riding. The yacht's velocity is significantly increased over its flat water velocity under the same wind conditions.

Simulation results of non-linear systems are sensitive to the simulation initial conditions. Therefore, when comparing different simulations care must be exercised to ensure that the initial conditions are identical. It is possible to generate phase plane plots from the simulation output. Such a plot illustrates the mathematical model's sensitivity to initial conditions, Fig. 3:

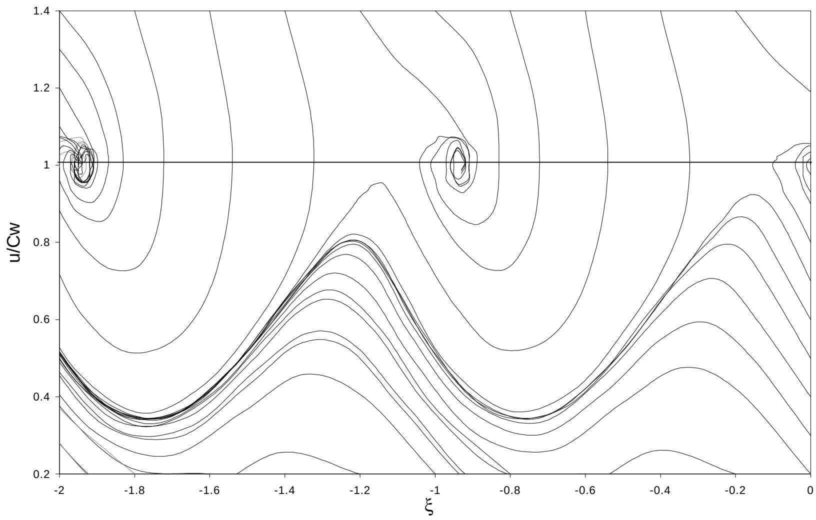

Figure 3. Phase plane portrait. AME004, l=20.0m, H=1.0m, true wind velocity=7.0m/s

From this phase plane portrait it may be seen that for vessels with the same initial position of ξ=0 the resulting average velocity may be considerably different depending on whether the vessel converges on a stable attractor (U/Cw=1), which in physical terms represents surf-riding, or oscillates periodically as the vessel surges with each passing wave. The initial conditions leading to surf-riding can be determined by calculating trajectories from an unstable equilibrium as shown in Umeda (1990).

3. EXPERIMENTS

Experiments were conducted to validate the wave force and resistance force models used in the numerical model for several wave conditions and hull forms. The experiments were conducted in the towing tank at the Ship Hydrodynamics Centre of the Australian Maritime College. The towing tank is 60m long, 3.5m wide and 1.5m deep. It was decided to conduct a series of experiments similar to those conducted by Thomas and Renilson(1991). The experiments conducted were semi-captive using a dual post system with the model free to heave and pitch while being constrained in surge, sway, yaw and roll. Measurements of heave, pitch, surge force and sway force were taken. A wave probe was positioned one wave length in front of the transom to determine the model's position relative to the wave, and a stationary wave probe was used to measure the wave profile. The data was recorded on a PC at a sampling frequency of 100 Hz for 10 seconds.

The parent hull, model 004, of the AME CRC systematic yacht hull series, was used for the experiments investigating the influence of wave conditions on the longitudinal wave force, Fig .4.

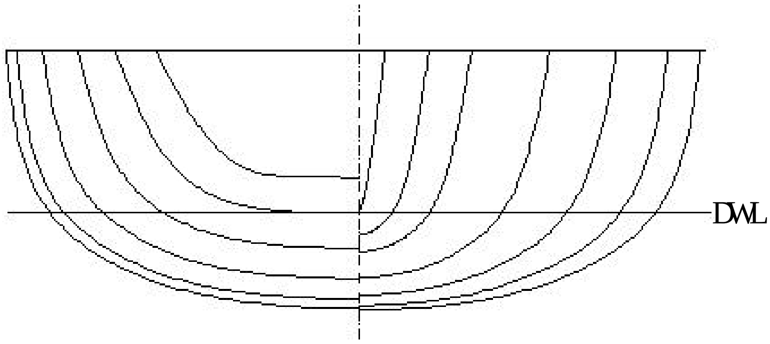

Figure 4. Body plan AME 004.

In order to investigate the effect on wave force of a change in length-displacement ratio the displacement of model AME 004 was both increased, to give AME 004X, and reduced, to give AME 004Y. Experiments were also conducted on two further models to investigate the influence of hull form parameters on the wave induced surge force. These experiments were used to determine whether the numerical model is sensitive enough to predict the change in wave force due to a subtle, yet realistic, change in hull form. The hull form differences between 004 (the parent hull form), 018 and 017 occur aft of amidships. Model 018 has a flat, shallow aft section and a large transom, while 017 has deeper, narrower sections with increased rocker in the aft profile leading to a smaller transom. The parent hull of the systematic series, 004, has a hull form aft which lies between 018 and 017. All the models were designed by the project industry participant Murray, Burns and Dovell. Full scale principal parameters of Models 004, 004X, 004Y, 017 and 018 of the AME systematic series are presented in Table I.

	AME 004	AME 004X	AME 004Y	AME 017	AME 018
Length W.L.	10.0m	10.6m	9.1m	10.0m	10.0m
Beam W.L.	2.654m	2.72m	2.46m	2.653m	2.654m
Draft (canoe body)	0.417m	0.5m	0.32m	0.416m	0.418m
Displacement	5100kg	6315kg	3885kg	5100kg	5100kg
Cp	0.535	0.57	0.49	0.535	0.534
Model Scale	1:6.667 & 1:5	1:6.667	1:6.667	1:5	1:5
Full Transom area	$0.840m^2$	$0.840m^2$	$0.840m^2$	$0.662m^2$	$1.048m^2$
LCB (from FP)	-5.418m	-5.42m	-5.42m	-5.414m	-5.421m
LCF (from FP)	-5.593m	-5.59m	-5.59m	-5.664m	-5.542m

Table I. Full scale hull principal parameters

The original model of AME 004 had a LWL = 2.0m which restricted the maximum wave length to vessel length ratio to 1.5; since assuming deep water wave theory the maximum wave length attainable, without distortion at a water depth of 1.5m, is 3.0m. With this restriction it was decided to construct a LWL = 1.5m scale model of AME 004 so a ship length to wave length ratio of 2.0 could be attained. This also allowed an investigation into the effect of scaling of following sea wave force measurements to be conducted. Models 017 and 018 were constructed with a 2.0m waterline length for consistency with other models in the AME systematic yacht hull series.

The influence of the appendages (keel and rudder) on the longitudinal wave force were also assessed by testing AME 004 both with and without appendages. When testing without appendages the displacement of the vessel was decreased so the hull floated at its design draft and trim.

The experimental test matrix used during experiments on the AME systematic yacht hull series is outlined in Table II.

Systematic Series Yacht Hull	**H/l**	**l/LWL**
004 (LWL=1.5m)	1/25	1.0
004 (LWL=1.5m)	1/30,1/25, 1/20	1.5
004 (LWL=1.5m)	1/25	2.0
004X (LWL=1.5m)	1/25	1.5
004Y (LWL=1.5m)	1/25	1.5
004 (LWL=2.0m, with appendages)	1/25	1.5
004 (LWL=2.0m, without appendages)	1/25	1.5
018	1/30,1/25, 1/20	1.0
018	1/30,1/25, 1/20	1.5
017	1/30,1/25, 1/20	1.0
017	1/30,1/25, 1/20	1.5

Table II Test Matrix

4. RESULTS AND DISCUSSION

The longitudinal wave force was determined by subtracting the calm water resistance from the overall drag measured:

$$X_x = X_M - R(u)$$

where X_M is the total measured force on the model and R(u) the calm water resistance at velocity u.

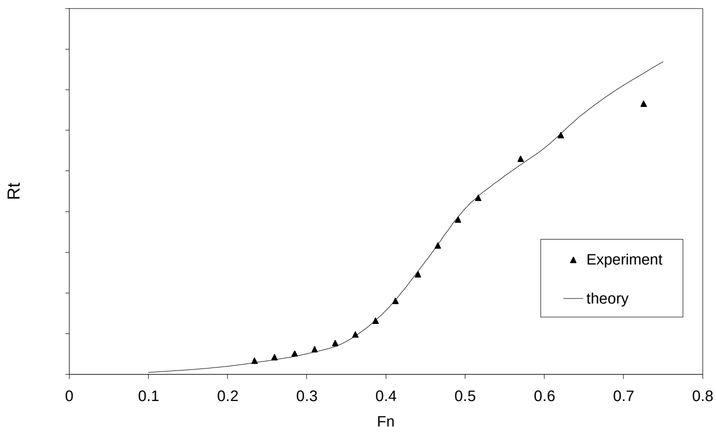

Figure 5. Resistance curve AME 004

As may be seen in Fig. 5 the calm water resistance results compared extremely well with theory up to Fn~0.65, however at the higher speeds the older regression polynomial proposed by Gerritsma et. al. (1992) does not agree as well with experiments. Initially during the following seas experiments a trimming moment was added to the model, usually utilised in model yacht tank testing to simulate the trimming moment induced by the sail force, however this led to nose diving problems. Therefore no trimming moment was applied to the model during either the wave or calm water experiments. From a practical standpoint, this may be assumed to be acceptable since when sailing downwind in large waves the crew weight would be moved aft and there may be considerable vertical lift from the spinnaker, therefore providing only a small net trimming moment.

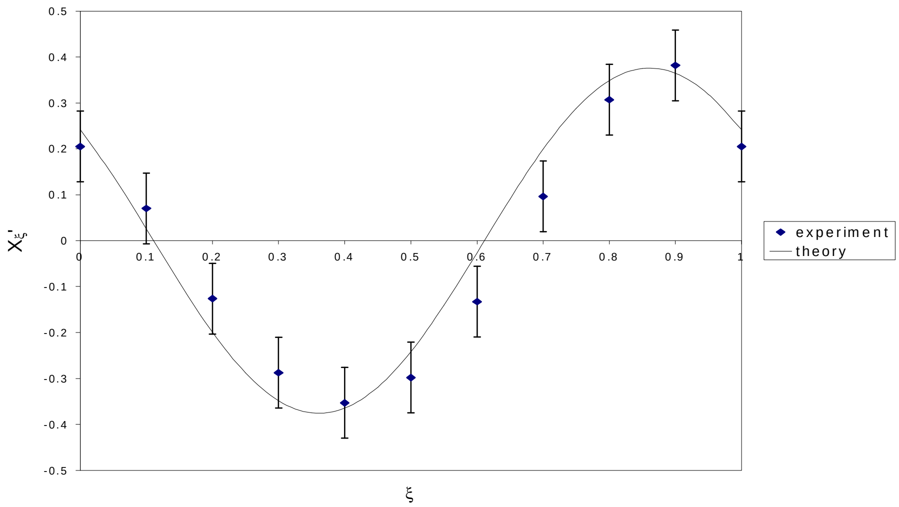

Figure 6. Wave Force vs Vessel Position in Wave. AME 004, λ/LWL=1.5, H/LWL=1/25

Fig. 6 shows the variation of wave force with vessel position in wave both experimentally and theoretically. The longitudinal wave force is periodic over the wave length and the peak force occurs when the yacht is on the front face of the wave. Correlation between the theory and experiment is satisfactory. Error bars on the graph indicate that 95% of the data points from the experiment lie within this region. The longitudinal wave induced force is periodic over the wave length and the peak force occurs when the yacht is on the front face of the wave (ξ~0.9). Error bars have been included in Figures 6, 7 and 8 as an indication of the spread of data, however they have been omitted from Fig. 9 and Fig. 10 for ease of interpretation.

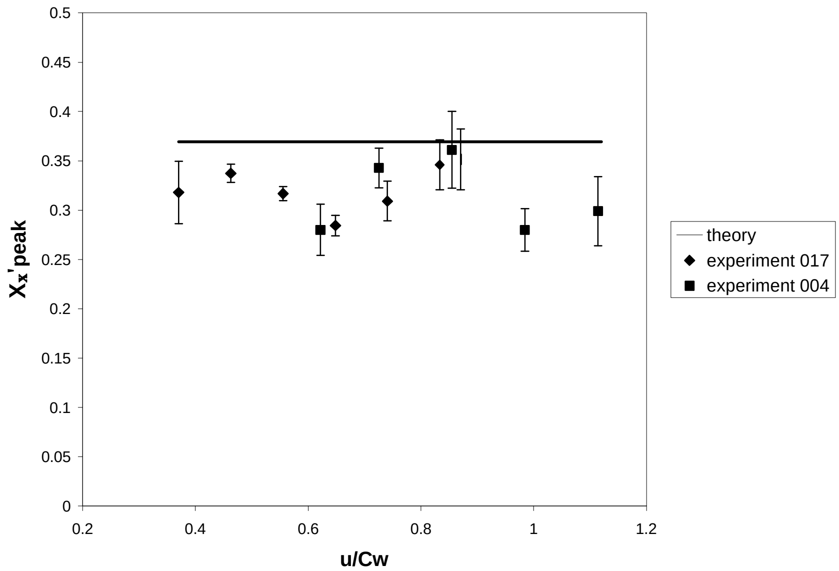

Figure 7. Peak to Peak Wave Force ($X_{\xi}'_{peak}$) vs (u/C_w). AME 017 & AME 004, λ/LWL=1.5, H/LWL=1/25.

Fig. 7 illustrates the wave force, for a single wave condition, over a range of encounter frequencies. $X_{\xi peak}$ is the difference between the maximum and minimum wave force experienced by the vessel. Experimental results are not exactly symmetric as found with theory, hence $X_{\xi peak}$ as opposed to maximum wave force has been used to present the results. The results for both models remain fairly constant over the range of encounter frequencies tested. This suggests that, although some dynamic effects appear to be present, it is valid to use the quasi-static assumption in the numerical simulation for the range of encounter frequencies tested. This result also allowed the experiments to be conducted at an encounter frequency of u/Cw = 0.87, which allowed one full wave length to overtake the model per run.

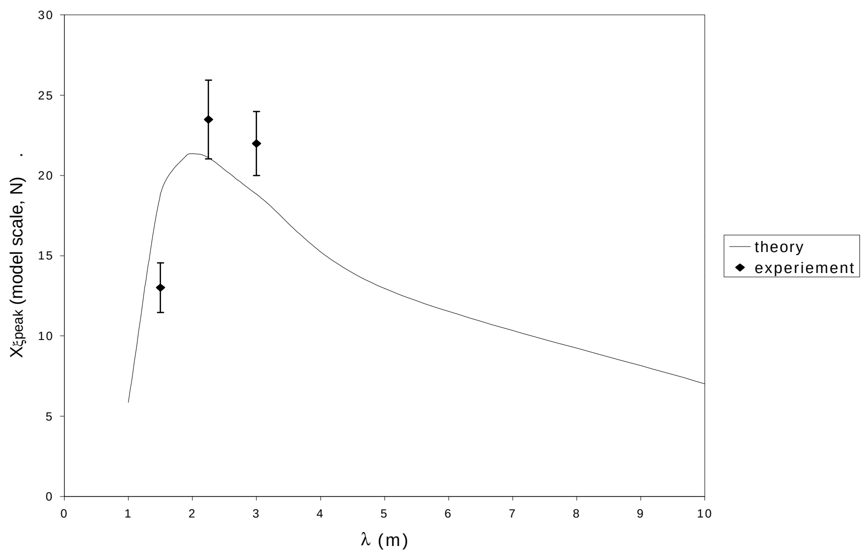

Figure 8. Wave force vs Wavelength. AME 004, LWL=1.5m, constant wave height H=0.09m.

The peak wave force as a function of wave length is illustrated in Fig.8. The wave height is constant which implies that the wave steepness varies with wave length. The graph indicates that the maximum wave force, for this particular wave height, is experienced at λ/LWL~1.5. This supports studies on the broaching-to of fishing vessels in severe following seas (Tuite and Renilson, 1997, Thomas and Renilson, 1991), where experiments and theory focussed mainly on this region.

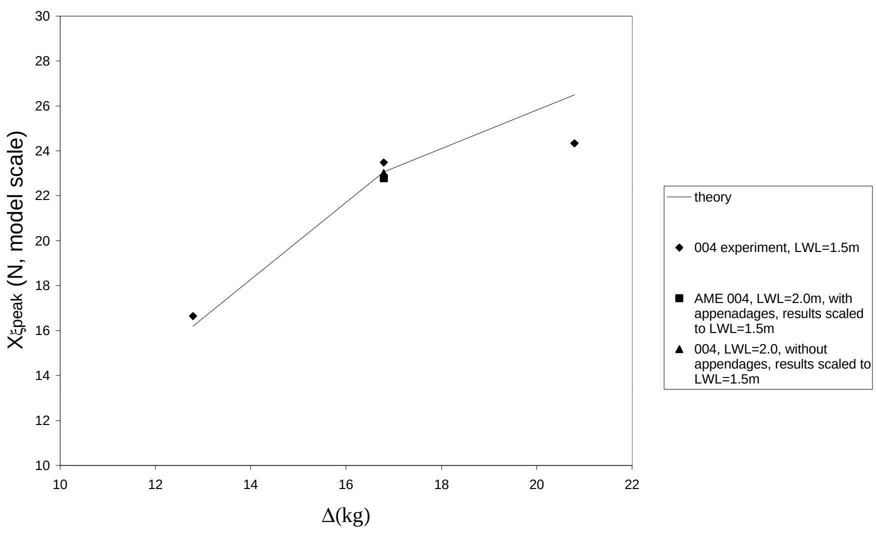

Figure 9.   Wave Force (peak to peak) vs Displacement. AME 004, λ/LWL=1.5, H/λ=1/25, u/Cp=0.85

As may been seen from Fig.9, wave force increases with displacement and the Froude-Krylov theory predicts this change in wave force relatively accurately. Also shown in this graph is the wave force from the larger AME 004 model (LWL=2.0m), both with and without appendages, scaled down using the non-dimensionalisation method outlined in the nomenclature. The three points at the design displacement agree exceptionally well which indicates that there are no scaling effect problems with utilsing the two different sized models and that the appendages' contribution to the wave force on the vessel is insignificant.

Figure 10 shows the wave force comparison for models 004, 017 and 018 for 3 wave length to vessel length ratios at varying wave steepnesses. The plot demonstrates that for each hull form the wave force increases with wave steepness, and for a constant wave steepness the wave force increases with wave length. The experimental results indicate that 017 experiences a greater longitudinal wave force than 018 in each condition, even though 017 is the model with the deeper, narrower aft sections. The parent model 004 has a wave force between the other two models for each condition except for a wave steepness of 1.5. It should be noted that the differences in wave force between the three hull forms are small when compared with the spread of experimental results. The theoretical results for the three models are too close together to be distinct lines on the plot since the underwater sectional areas of each model are very similar. Although the experimental results indicate that 017 has the largest longitudinal wave force it is necessary to run the simulation, including the calm water resistance results and sail forces, to ascertain the full downwind performance characteristics.

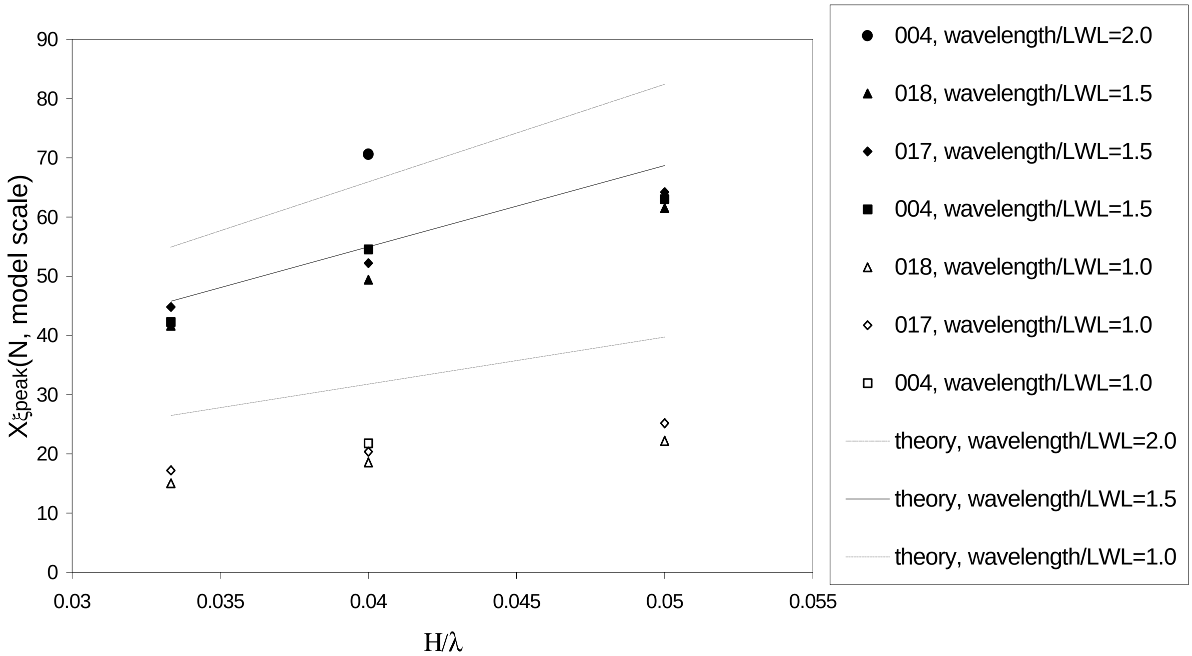

Figure 10. Wave Force vs Wave Steepness. 004, 017 and 018.

5. CONCLUSIONS

A numerical model has been developed to simulate the downwind performance of yachts in waves. The resistance and wave force components of this model have been validated through a series of towing tank experiments. For the models and wave conditions tested it can be concluded that:

1. The calm water resistance numerical model appears appropriate.

2. The longitudinal wave induced force is periodic over the wave length and the peak force occurs when the yacht is on the front face of the wave.

3. The longitudinal wave force increases with wave steepness.

4. The maximum wave force for a constant wave height occurs at a λ/LWL of approximately 1.5.

5. The wave force remains fairly constant over the range of encounter frequencies tested, implying that the quasi-steady assumption is valid.

6. The appendages' contribution to the longitudinal wave force is insignificant.

7. The longitudinal wave force results for the models of the same hull form with varying scale factor correlate well, indicating that scaling effects are negligible.

8. An increase in vessel displacement causes an increase in the wave force and correlates well with theory.

9. Model 017 experienced a slighter larger wave force than model 018 for all conditions tested. The parent hull, 004, experienced a wave force greater than 017 at λ/LWL=1.5, and a wave force between 018 and 017 for all other conditions. The wave force theory was not able to differentiate substantially between the three models.

6. NOMENCLATURE

AP	aft perpendicular
BWL	waterline beam
C_D	sail drag coefficient
C_P	prismatic coefficient
C_w	wave phase velocity
DWL	design waterline
FP	fwd perpendicular
g	gravity
H	wave height
IMS	international measurement system
k	wave number (=2π/λ)
LCB	longitudinal centre of buoyancy
LWL	waterline length
m	mass of yacht (physical mass+added mass)
R	calm water resistance
T	aerodynamic thrust provided by sails
$\dot{u}$	acceleration in x direction
u	velocity in x direction
V_{wa}	apparent wind velocity
X	surge force
X_m	surge force measure on model
X_w	distance from wave crest behind vessel to transom

x_w	distance from transom to section under consideration.
X_x	surge force as a function of wave pos.
X_{xpeak}	peak(max) to peak(min) surge force
Δ_c	canoe body displacement
r	water density
r_a	air density
x	non-d distance from wave crest to transom
λ	wave length
n	viscosity
z	wave amplitude

Non-dimensionalisation methods:

1. Wave induced surge force $$X_x' = \frac{X_x}{0.5 \cdot r \cdot BWL \cdot H \cdot C_w^{\ 2}}$$

2. Vessel velocity $$Fn = \frac{u}{\sqrt{g \cdot LWL}}$$

3. Vessel position in wave $$x = \frac{X_W}{l}$$

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