The Windward Performance of Yachts in Rough Water

Jonathan R. Binns, Australian Maritime Engineering Cooperative Research Centre Ltd. (AME CRC)
Bruce McRae, Australian Maritime Engineering Cooperative Research Centre Ltd. (AME CRC)
Giles Thomas, Australian Maritime Engineering Cooperative Research Centre Ltd. (AME CRC)

ABSTRACT

A 5 year research program to investigate the effect of realistic hull form parameters on the added resistance of a yacht in waves is nearing completion. Model experiments and theoretical predictions were carried out and the results are discussed in this paper.

Five hull form parameters have been investigated so far, they are: 1. stern overhang; 2. LCB-LCF separation; 3. prismatic coefficient, 4. displacement length ratio and 5. beam draft ratio.

NOTATION

C_P	Prismatic coefficient
Cts	Total resistance coefficient, for calm water
LCB	Longitudinal Centre of Buoyancy
LCF	Longitudinal Centre of Flotation
Lwl	Length, waterline
RAO	Response Amplitude Operator
V	Yacht velocity, (m/s)
VPP	Velocity Prediction Program

INTRODUCTION

The aim of this joint Australian Maritime Engineering Cooperative Research Centre (AME CRC) and Murray, Burns & Dovell (MBD) project was to develop a VPP module which calculates the added resistance of a yacht in waves from theoretical predictions and towing tank experiments. The RAO of the added resistance is obtained by dividing the added resistance of the yacht in waves by the square of wave amplitude.

The International Measurement System (IMS) handicapping system relies on a VPP, originally developed by Kerwin, 1978, to predict the performance of a yacht for a given hull shape and rig geometry. The predicted yacht velocities are used to determine, for different wind velocities, a handicap time allowance for the particular yacht in seconds per mile. This handicapping system therefore endeavours to allow the only variables between yacht performances to be the sailing abilities of the crew. The IMS VPP is available to yacht designers to use during the design procedure, however it has certain drawbacks, for example, inability to incorporate tank test results into its calculations. To rectify this a VPP has been developed by MBD, that has the facility to include calm water resistance data obtained from tank tests, thus giving a more accurate indication of the yacht's calm water performance compared to using the regression based resistance algorithms. This enables the designer to determine how a yacht will perform in relation to its handicap, by comparing results from the AME CRC VPP with the IMS VPP.

Gerritsma conducted a set of theoretical predictions on the Delft Systematic Yacht Hull Series using a strip theory seakeeping code. This enabled them to produce a polynomial expression for added resistance based upon the main yacht parameters: length, displacement, beam, draught and prismatic coefficient, see Gerritsma et al., 1993, pp 239-245. Using this polynomial expression it is possible to calculate the added resistance, as a function of wave amplitude, of a yacht for a given wave direction, wave frequency and Froude number. The research described in this paper was conducted to investigate further the parameters tested by Gerritsma.

MODEL DETAILS

A standard yacht series was designed by MBD and tested by AME CRC. The parent hull form in the AME CRC series, 004a, is an IMS type yacht based on the Delft Series 2 yacht form. A body plan of the yacht is shown in Fig. 1.

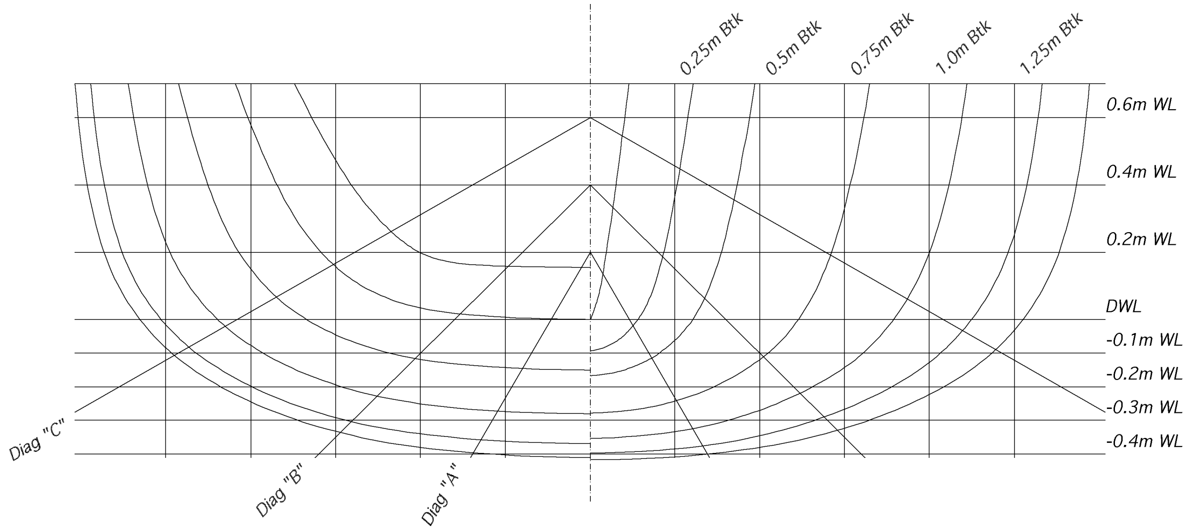

Fig. 2 Body Plan of AMECRC 004a

The following five hull form parameters were investigated in calm and rough water:

1. stern overhang length
2. LCF-LCB separation
3. C_p.
4. Length displacement ratio
5. Beam draft ratio

Stern overhang effects on added resistance in waves were examined by constructing an additional stern section to be added to AMECRC 004a. The section is 1500 mm long (full scale) and simply extends the lines in a straight line from the existing transom. This additional section was attached using nuts and bolts, with the joint faired by modelling plasticine. The resulting new model with the additional stern section is named AMECRC 004b.

To examine the effect of LCB-LCF separation two further models were designed. AMECRC 005 with the LCB position moved aft, reducing the LCB-LCF separation, and AMECRC 006 which had the LCB position moved forward increasing the LCB-LCF separation.

The effect of prismatic variations was investigated by designing two new models with prismatic coefficient (C_p) values greater than and less than the values for AMECRC 004a. The two new models were AMECRC 007 (C_p lower than AMECRC 004a) and AMECRC 008 (C_p greater than AMECRC 004a).

Length displacement ratio was varied whilst maintaining other hull and sail non-dimensional parameters, details of this variation can be found in McRae, et al. (1998) p 4. It is important to maintain sail non-dimensional parameters because changes in displacement require changes in stability, which in turn effects the amount od drive forces available for the yacht. Two new models were constructed to suit the two new displacements, models AMECRC 009 and AMECRC 010.

Beam draft ratio variation was achieved by varying the turn of the bilge. This approach yielded models AMECRC 011 and AMECRC 012, which had constant displacement and righting moment whilst varying B/T.

The first models tested, models 005 and 006, included a crew weight component. It was subsequently discovered that this procedure was not adopted by Delft University researchers. It was decided to conduct all future AME CRC tests at the same tested displacement used at Delft, to allow better comparisons of the two standard series.

The parameters of the yacht hull forms are shown in Table 1, all for the full scale prototype in measurement trim. The parameters used for these models are considered to represent realistic yacht designs.

	004a	004b	005	006	007	008
Length O.A.	11.3 m	11.45 m	11.3 m	11.3 m	11.3 m	11.3 m
Length W.L.	10.0 m	10.0 m	10.0 m	10.0 m	10.0 m	10.0 m
Beam W.L.	2.654 m	2.654 m	2.655 m	2.650 m	2.681 m	2.624 m
Draft	0.417 m	0.417 m	0.417 m	0.417 m	0.423 m	0.416 m
Displacement	5100 kg	5100 kg	5280 kg	5280 kg	5100 kg	5100 kg
Prismatic Coeff.	0.535	0.535	0.532	0.534	0.513	0.554
LCB, from bow	-5.418 m	-5.418 m	-5.595 m	-5.235 m	-5.417 m	-5.385 m
LCF, from bow	-5.593 m	-5.593 m	-5.665 m	-5.540 m	-5.612 m	-5.600 m
LCB-LCF separation	0.180 m	0.180 m	0.07 m	0.305 m	0.200 m	0.210 m
Gyradius	2.25 m	2.25 m	2.25 m	2.25 m	2.25 m	2.25 m
Model Scale	1 : 5	1 : 5	1 : 5	1 : 5	1 : 5	1 : 5

	009	010	011	012
Length O.A.	11.3 m	11.3 m	11.3 m	11.3 m
Length W.L.	10.0 m	10.0 m	10.0 m	10.0 m
Beam W.L.	2.498 m	2.785 m	2.622 m	2.669 m
Draft	0.343 m	0.486 m	0.363 m	0.480 m
Displacement	4100 kg	6100 kg	5100 kg	5100 kg
Prismatic Coeff.	0.534	0.535	0.533	0.536
LCB, from bow	-5.416 m	-5.419 m	-5.415 m	-5.396 m
LCF, from bow	-5.599 m	-5.596 m	-5.626 m	-5.592 m
LCB-LCF separation	0.180 m	0.180 m	0.180 m	0.200 m
Gyradius	2.25 m	2.25 m	2.25 m	2.25 m
Model Scale	1 : 5	1 : 5	1 : 5	1 : 5

Table 2 AMECRC yacht series parameters, full scale

The same keel and rudder were used for all models. In order to stimulate turbulent flow, studs were attached to the hull at stations 1 and 2 (station spacing equal to 200 mm). Each stud had a cross sectional area of 8 mm^2, and they were fitted at a spacing of 25 mm. Studs were also fitted to the keel and rudder at one third of the chord from the leading edge. These studs had a cross sectional area of 2 mm^2, and they were fitted at a spacing of 15 mm.

EXPERIMENTAL PROGRAM

Experimental Setup

The experiments were carried out in the AME CRC towing tank based in the Australian Maritime College, Launceston, Tasmania. The tank has a constant rectangular cross section with the principal dimensions shown in Table 3.

Overall Length	60 m
Width	3.5 m
Depth	1.5 m

Table 4 Test tank parameters

Situated at one end of the tank is a single flap, flat plate, hydraulically driven wavemaker. At the other end is a wet dock used for ballasting models.

A steel carriage running on rails along the walls of the tank, with a maximum speed of 4.5 m/s, is used to tow the models.

The model was connected to the carriage using a single post yacht dynamometer, and was free to pitch and heave, but constrained in surge, sway, yaw and roll. The dynamometer comprises: two flexures arranged orthogonally to enable lift and drag measurements; a torsion cell for measuring yaw moment; a strain gauge for measuring roll moment; a rotary potentiometer for determining pitch and a linear potentiometer for measuring heave. This dynamometer is identical to that used by the Wolfson unit used at Southampton University in the UK.

In order to measure the wave height and also determine the motion phase relationships, a capacitance wave probe was fixed to the carriage, clear of any wave disturbance from the model.

The data from the dynamometer and wave probe were processed using an analog to digital converter and then recorded by an IBM-PC mounted on the carriage, recording at a rate of 20 Hz.

Model Ballasting

Each model was ballasted to its required displacement and trim. This weight was then distributed along the model to achieve a full scale gyradius of 2.25 m about the LCB. The bifilar method, which assumes that the pitch gyradius is equal to the yaw gyradius, was used for estimating the pitch radius of gyration.

Since the tank tests were conducted with the models at constrained angles of heel and yaw, weights were shifted laterally to heel the model to the required angle, thus minimising the stress on the dynamometer. The models were additionally ballasted to account for the pitch moment and vertical force applied by the sails.

Experimental Conditions

For each model a complete set of calm water resistance tests were conducted, between the speeds 4.5 knots and 11.0 knots (full scale), at varying angles of heel and yaw. The heel angles tested were 0°, 10°, 20° and 25° degrees, whilst the yaw angles were 0°, 3° and 5°. Such a comprehensive set of calm water tests is required to establish a VPP resistance matrix.

All the rough water tests were conducted at the design windward speed of 6.5 knots (full scale) in regular head seas. The models were constrained at a heel angle of 20° and a yaw angle of 3° (the rudder angle relative to the yacht centreline was set to the same as the yaw angle). The tests were carried out for a range of wave periods between 2.0 s and 5.0 s (full scale), at a constant wave slope.

Repeat Experiments

For each wave height and frequency three runs were conducted to increase the test data recorded and provide a check on repeatability. An example of the spread of the added resistance RAO between these three runs can be seen in Fig. 3.

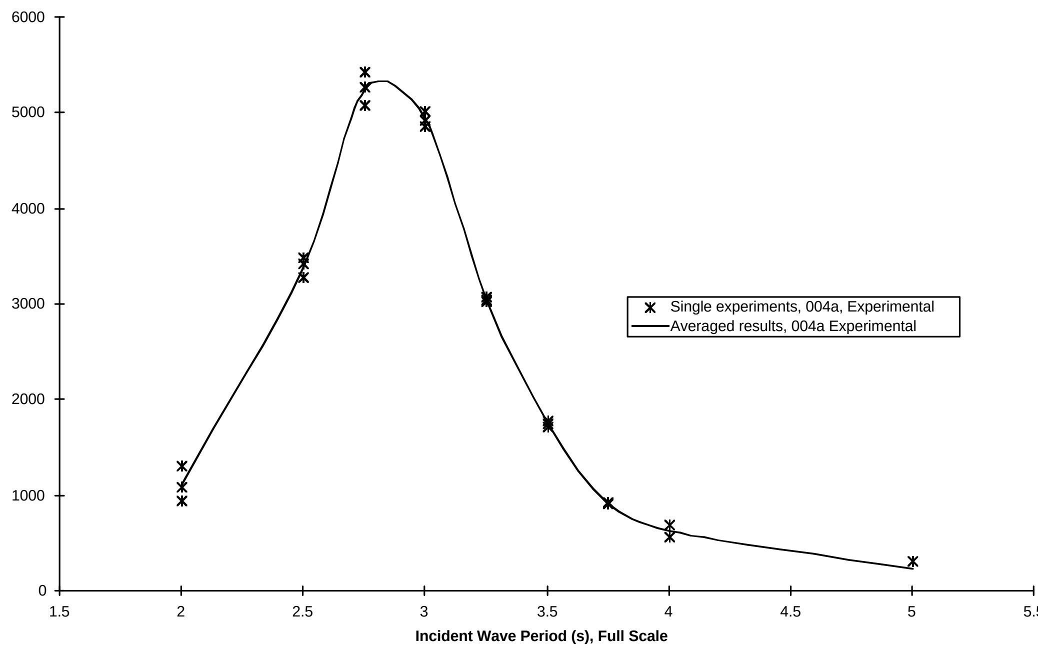

Fig. 4 Example of repeated test for model 004a

CALM WATER EXPERIMENTS

A full calm water matrix of test runs was completed for each of the models, this allowed the results to be used in a velocity prediction program. An example of such results and their uses have been detailed in McRae et al. (1998). An example of the calm water resistance is shown in Fig. 5.

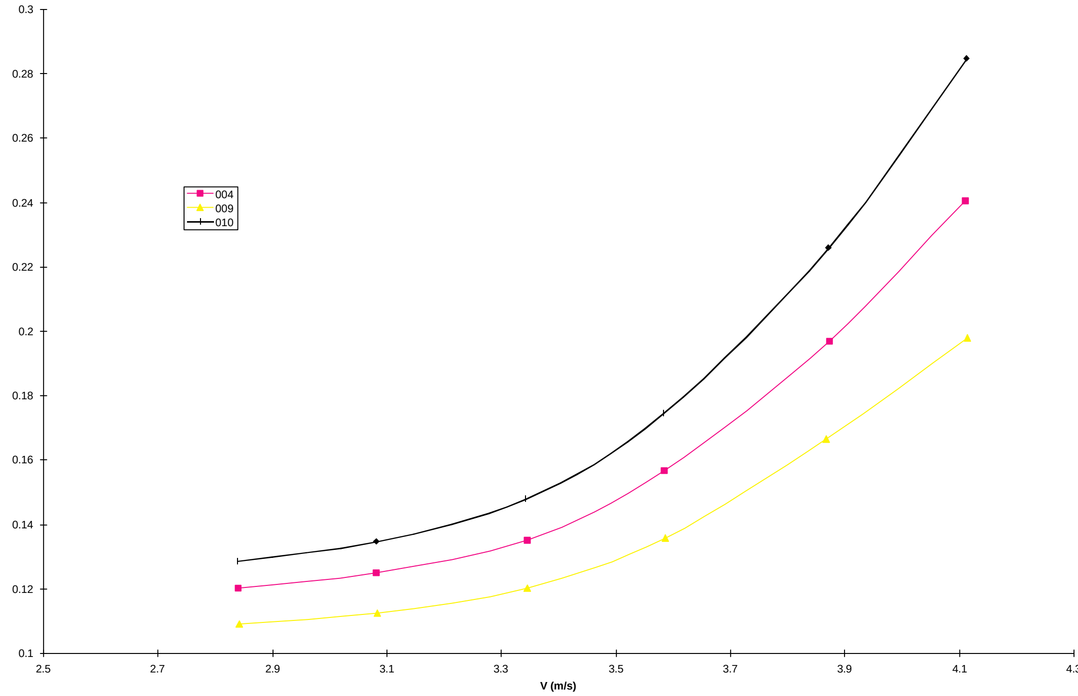

Fig. 6 Calm water Cts vs full scale speed, for 20° heel, 3° yaw

In Fig. 7 the total resistance coefficient was calculated using a full scale reference area of 1 m^2 and a form factor of zero.

THEORETICAL PREDICTIONS

A computer program that predicts the motions, loads and added resistance experienced by vessels in a seaway has been developed by AMECRC (Sutherland, 1987). It is based upon strip theory (see Salvesen, Tuck and Faltinsen, 1970), where the yacht is divided into a series of transverse strips. The yacht is modelled as a two degrees of freedom spring, mass and damper system undergoing sinusoidal motion due to an exciting force from regular waves. The method proposed by Gerritsma and Beukelman (Gerritsma and Beukelman, 1972) is used to calculate the added resistance of the yacht.

Certain non-linear effects have subsequently been incorporated into this program 'SEALAM' (Boyd, Klaka and Thomas, 1995). The hydrodynamic coefficients are calculated from the true 'local waterline' position along the hull rather than assuming a continuous flat waterline as in conventional strip theory programs. Effects such as the Kelvin wave pattern, immersion and emergence of bow and stern sections, the profile of the incident wave and the amplitude and phasing of the resultant motions are therefore considered.

SEALAM was used to investigate the influence of hull form parameters on yacht motions and added resistance in waves.

EXPERIMENTAL AND THEORETICAL RESULTS

Stern Overhang

The added resistance RAOs for the two models used to test stern overhang are shown in. Fig. 8 for both experimental and theoretical predictions.

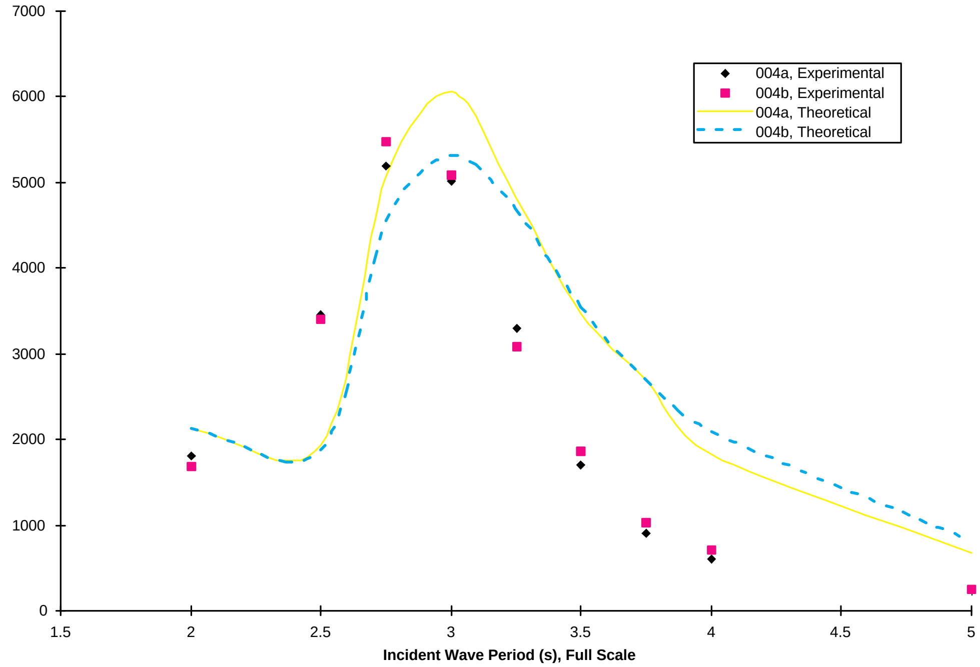

Fig. 9 Added resistance RAO for stern overhang investigation

LCB-LCF Separation

The added resistance RAOs for the three models used to test LCB-LCF separation are shown in Fig. 10.

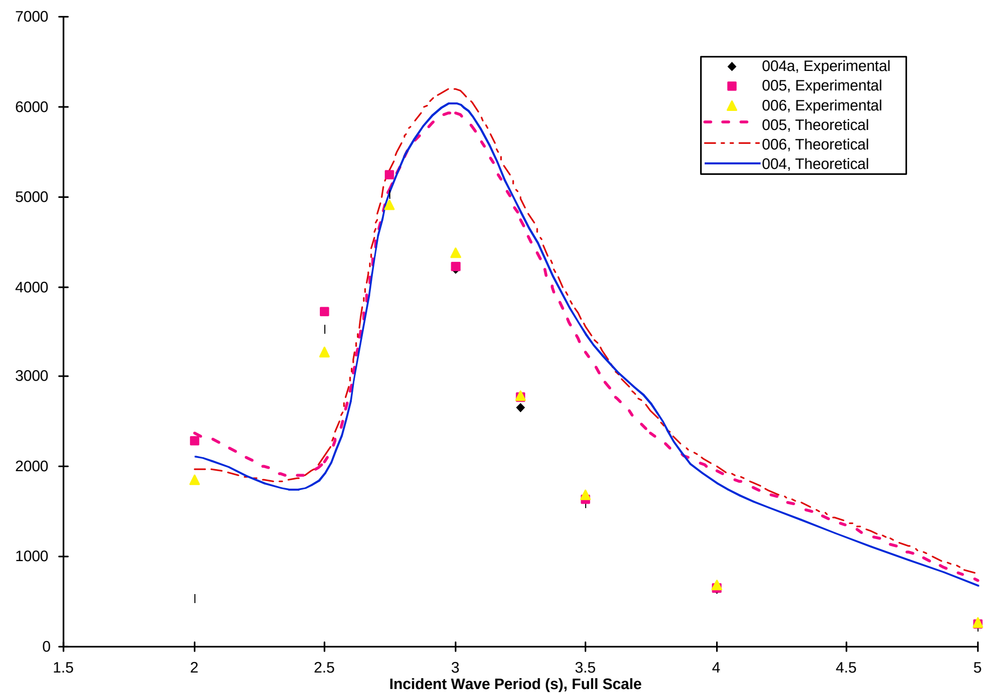

Fig. 11 Added resistance RAO for LCB-LCF separation investigation

Prismatic Coefficient

The added resistance RAOs for the three models used to test the effects of test prismatic coefficient on added resistance are shown in Fig. 12.

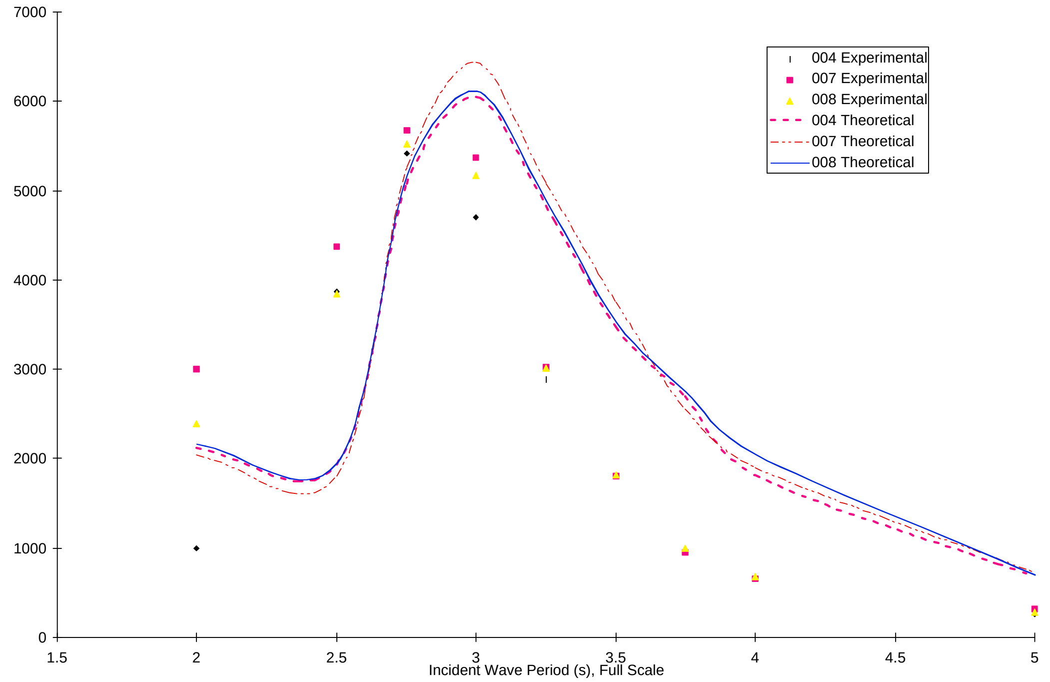

Fig. 13 Added resistance RAO for prismatic coefficient investigation

Displacement Length Ratio

The added resistance RAO for the three models used to test the affects of displacement length ratio on added resistance are shown in Fig. 14.

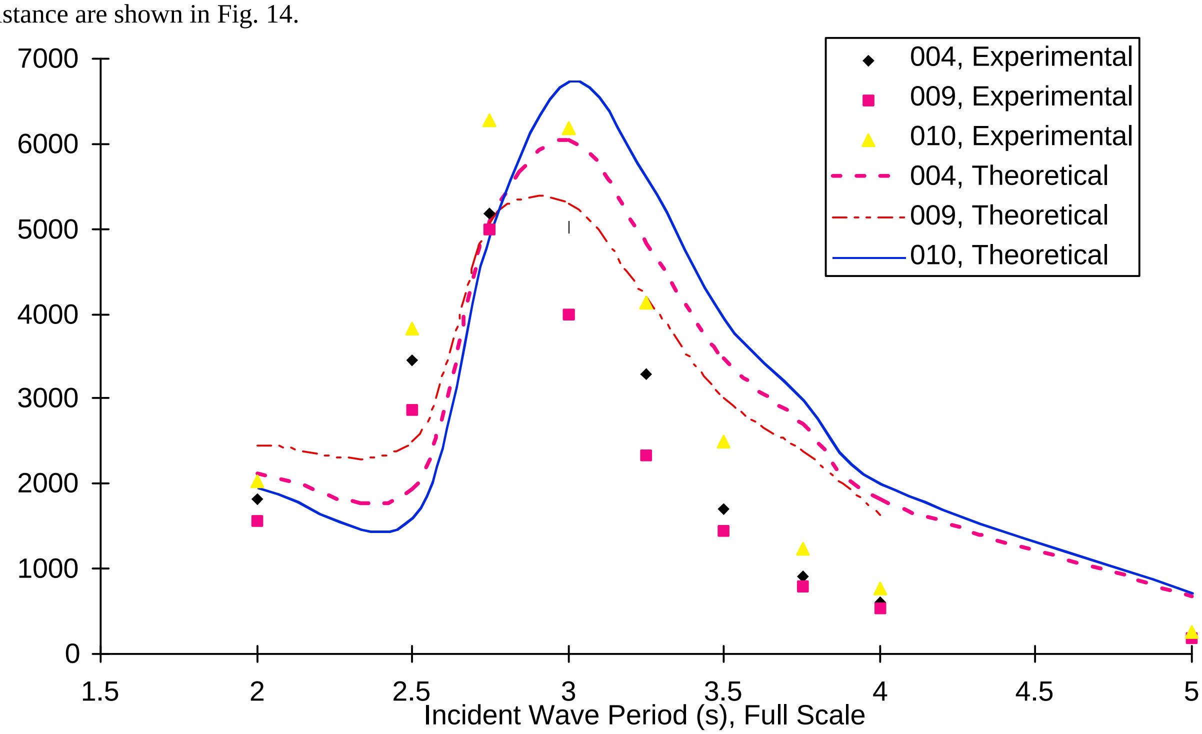

Fig. 15 Added resistance RAO for displacement length ratio investigation

Beam Draft Ratio

The added resistance RAOs for the three models used to test the effects of beam draft ratio on added resistance are shown in Fig. 16.

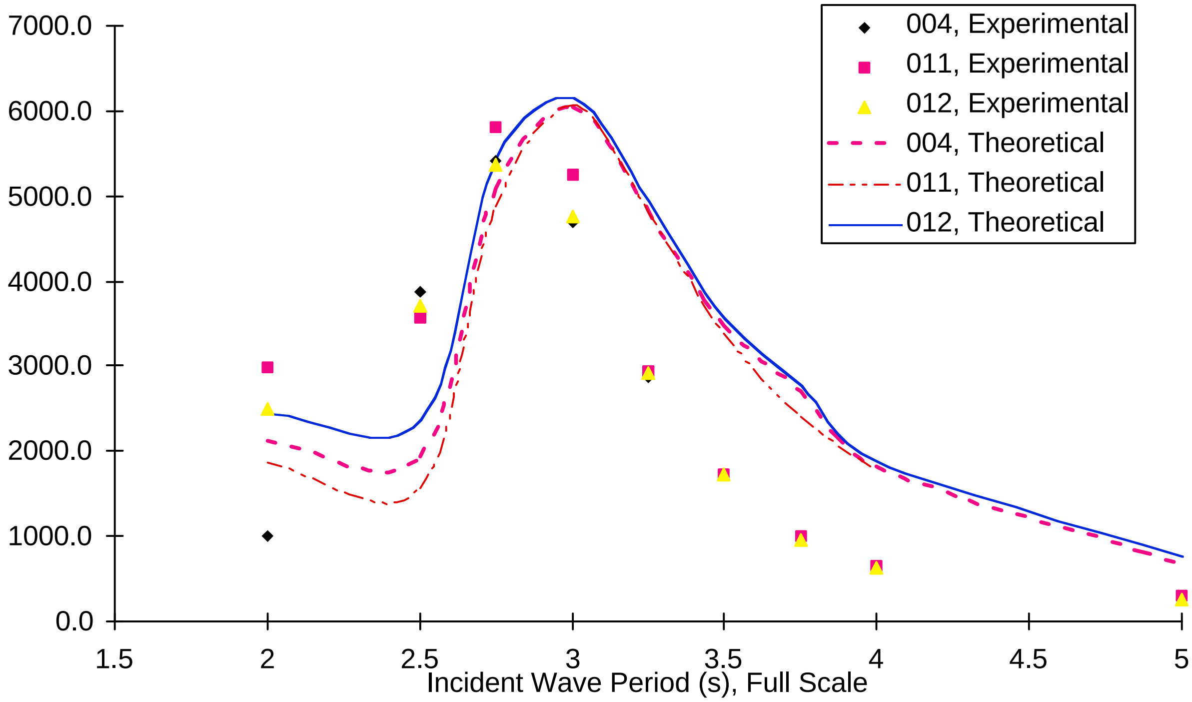

Fig. 17 Added resistance RAO for beam draft ratio investigation

DISCUSSION OF RESULTS

Stern Overhang

The effect of the stern overhang extension was quite small on the added resistance. Fig. 18 shows that these affects appear to vary with frequency. The theoretical predictions also show a dependence on frequency, however, the predictions and the experiments do not agree in the nature of the variation with frequency. The effect of overhang on the predicted results is a highly non-linear one. This was also concluded in previous research, for example Kuhn and Schlageter, 1993, p 261. In the research by Kuhn and Schlageter the predictions followed the same trends as those presented in Fig. 19. It is believed that the non-linearities present in these test conditions have not been modelled correctly in the SEALAM predictions.

LCB-LCF Separation

The effect of centroid separation would appear to be heavily dependant on wave period, as shown by Fig. 20 . Therefore the effect on performance depends on the wave spectrum encountered. This is a somewhat different conclusion to that of Sclavounos and Nakos, 1993, in which it was calculated that added resistance was reduced for LCF moving aft, and increased for LCB moving aft. One possible reason for the trends not being as clearly defined across the frequency spectrum in the results presented here is that the models used in this research were 53% lighter than the models used in Sclavounos. It is therefore likely that this difference in displacement is the dominating parameter in comparing these results to those obtained by Sclavounos.

Prismatic Coefficient

The effect of C_P on the RAO of the added resistance is small in comparison with other parameters investigated. In Fig. 21 this is shown in both the experimental results and the theoretical predictions. This conclusion is generally not suppported by experience on the race course, which tends to suggest that a yacht with a large C_P will not perform well. Differences suggesting this conclusion can be drawn when results are processed using the VPP and utilising a fully developed sea-state, which will tend to bias the higher period wave performance, for which there is a very slight advantage to the smaller C_P yacht.

Length Displacement Ratio

The effect of length displacement ratio is quite clear for both theory and prediction, that is an increase in length displacement ratio will result in an increase in added resistance in head seas. However, a shift in the cross over point and the resonant frequency could result in slightly different answers being calculated if theoretical predictions were used to replace experimental results. This situation arises when sea spectra with resonant frequencies located around yacht resonant frequencies are used. Therefore when using these results for performance predictions consideration should be given to this fact by conducting sensitivity studies on the sea spectra used.

Beam Draft Ratio

The trends predicted by theory and experment in this case vary considerably in magnitude and direction. From the experimental results it can be seen that yachts with a low to moderate B/T (models 004 and 012) are reasonably equal in terms of added resistance in waves. The experiments also show fairly clearly that a high B/T yacht (model 011) exhibits a very poor performance in waves, with a considerable increase in added resistance in waves.

The theoretical predictions show quite a different story however. It would appear that all yachts are extremely close in terms of added resistance in waves, however a small trend showing a small B/T ratio to perform worse in waves can be seen from the theoretical predictions.

The differences between theory and experiment here are thought to be due to the bias placed by theory on the characteristics of the water plane. These three yachts have almost identical water planes, and so theory cannot discenr the difference at all well. However, the underwater sectional shapes of these yachts vary considerably and so the experimental results vary accordingly.

INTEGRATION OF RESULTS INTO THE AME VPP

Given the results above and a sea spectrum it is possible to calculate an average added resistance for that sea condtion.

Sea Spectrum Definition

Firstly, the problem is simplified by assuming the sea state is long crested, that is it has no spreading function. Secondly a relationship between wind speed and wave spectra needs to be decided upon. This may be done by using a sea spectrum which is dependant on wind speed, such as the Pierson-Moskowitz, or by using wave data gathered simultaneuously with wind data. Next a relationship between wind direction and wave direction needs to be determined, for all of the studies conducted during this project the wind direction was assumed to equal the wave direction.

Finally a relatoinship between wave frequency and wave amplitude energy density needs to be calculated. Again this may be done by either using a standard wave spectrum definition or by using actual wave data. If actual wave data is used a Fourier transform can be performed on the time series to produce an actual wave spectrum.

Modification to RAOs

The experimental and theoretical RAOs for added resistance in waves are for head seas cases, however sailing yachts rarely encounter head seas. The restrictions imposed by assumptions made in the theoretical predictions and by tank dimensions in the experimental results have precluded this project from making an accurate assessment as to the exact nature of this variation. Therefore the problem was simplified greatly by assuming that the added resistance for a head seas case would be a maximum and it would be zero for a beam seas case, all angles in between have been calculated by a simple linear interpolation.

Calculation of Average Added Resistance

The average added resistance of a yacht may be calculated from Equation (1), given below

$$\overline{Raw} = 2\int_0^\infty RAO\ Se(\omega e)d\omega e\,. \qquad (1)$$

In Equation (2) RAO is the response amplitude operator, ωe is the encounter frequency and $Se(\omega e)$ is the wave energy specturm.

CONCLUSIONS

Test tank results for a heeled, yawed yacht and theoretical predictions for an upright, zero-leeway yacht in regular seas are presented.

A non-linear strip theory code has provided valuable results on the effect of above- and below-waterline hull variations on added resistance. Although the trends around the peak of the added resistance have not been well predicted, the trends toward the higher wave periods are well predicted.

The effect of stern overhang is large with respect to the other parameters investigated and would appear to depend on the incident wave period, in an inherently non-linear manner.

The effect of LCB-LCF separation on added resistance is dependant on wave period. These effects have not mirrored the results of previous research, however the displacement used in this series of experiments was substantially less than that used in previous research.

The effect of of the change in C_P investigated is small in comparison with the other parameters.

The effects of displacement to length ratio are shown to be large, and extremely well predicted by theory.

The effects of beam draft ratio have been very badly predicted by theory, and perhaps demonstrate a case where theory should not be used at all.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of the Australian Maritime Engineering CRC Ltd. in providing support and funding for the research presented in this paper.

The authors would also like to thank the staff of the Australian Maritime College, Launceston, for their help during experiments..

REFERENCES

Boyd, J., Klaka, K. and Thomas, G., “Analysis of Non-Linear Motions: Experiments and Predictions”, *RINA Intl. Conf. Seakeeping and Weather*, London, 1995

Couser, P., “Prediction of Aerodynamic Sail Forces for Upwind Yacht Velocity Prediction Programs”, *1st Australian Sailing Science Conference*, 1997

Gerritsma, J. and Beukelman, W., “Analysis of the Resistance Increase in Waves of a Fast Cargo Ship”, *International Shipbuilding Progress*, 1972

Gerritsma, J., Keuning, J.A., and Versluis, A., “Sailing Yacht Performance in Calm Water and Waves”, *The 11th Chesapeake Sailing Yacht Symposium*, 1993, pp 233-245

Kuhn, J.C. and Schlageter, E.C., “The Effects of Flare and Overhang on the Motions of a Yacht in Head Seas”, *11th Chesapeake Sailing Yacht Symposium*, 1993, pp 261-276

McRae, B., Binns, J.R., Klaka, K. and Dovell, A., “Windward Performance of the AMECRC Systematic Yacht Series”, *International Conference on the Modern Yacht*, 1998

Salvesen, N., Tuck, E.O. and Faltinsen, O., “Ship Motions and Sea Loads”, *Transactions SNAME*, 1970

Sclavounos, P.D., and Nakos, D.E., “Seakeeping and Added Resistance of IACC Yachts by a Three-Dimensional Panel Method”, *11th Chesapeake Sailing Yacht Symposium*, 1993, pp 247-260

Sutherland, I.W., *Prediction of Hull Responses to Waves*, MAppSc Thesis, Curtin University of Technology, 1987

Thomas, G., Klaka, K. and Dovell, A., “Project 1.5.2 Development of a Velocity Prediction Program for Yacht Windward Performance in Waves, Report 1”, *AMECRC IR* 95/8, 1995

Thomas, G., Klaka, K. and Dovell, A., “The Effect of Stern Overhangs on the Added Resistance of Yachts in Waves”, *AMECRC IR* 95/16, 1995