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Performance Prediction of Sailing Yachts in Waves

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1.0 SUMMARY

The response of an America's Cup yacht in waves is investigated using real-time data and tank tests. The tank results show a significant reduction of resistance and motions response for the heeled condition, whilst the effect of a wing keel configuration is negligible. Dynamic righting moment effects are small. The relationship between added resistance and wave amplitude shows considerable variation from a square law. The response curves of added resistance are applied to an ocean wave field and the results incorporated in a modified calm-water velocity-prediction program.

2.0 INTRODUCTION

In 1985 the Centre for Marine Science & Technology began a research programme for the Taskforce 87 America's Cup syndicate encompassing a wide range of technological areas. Part of this programme is the investigation of performance of yachts in realistic wave fields, to which this paper addresses itself. The work is on-going, involving the collaboration of several other research colleagues and members of the Taskforce 87 syndicate. The aims of the project are to develop a method of obtaining response curves for a yacht in waves and determine the speed loss in waves for a given ocean wave field. Three sources of response curves were originally considered:-

(a) strip theory suitably modified for yacht forms,

(b) tank test experiments , and

(c) analysis of real time data received from the Taskforce 87 America's Cup yachts.

The strip theory calculations were conducted by an associate investigator. The real-time data analysis is still in hand, the aim having been modified from obtaining response curves to determining speed loss in waves directly.

It should be noted that motions testing is more difficult for yachts than for ships because:

(a) yachts operate at large heel and leeway angles;

(b) the vortices shed by a yacht hull as a consequence of sideforce generation may influence the response;

(c) the sails influence damping and the sailforces will in turn be affected by the motions.

Strip theory calculations for yachts are also more difficult because:

(a) yachts are rarely slab-sided;

(b) length/beam and length/draught ratios are comparatively low,

(c) a heeled shape with appendages is difficult to model, and

(d) the effect of dynamic waterline is more significant.

3.0 NOTATION

B = waterline beam (m)

L = waterline length (m)

RAO_z = heave amplitude/wave amplitude

RAO_θ = pitch amplitude/maximum wave slope

R_{add} = added resistance in waves (N)

$S_{radd}(\omega_e)$ = added resistance spectral density (N s rad^{-1})

$S_\zeta(\omega_e)$ = wave amplitude spectral density (m s rad^{-1})

ρ = water density (Kg m^{-3})

σ = added resistance coefficient

$$= \frac{R_{add}}{\rho g \zeta_a^2 B^2/L}$$

ω_e = encounter frequency (rad s^{-1})

ζ_a = maximum wave amplitude (m)

4.0 PREVIOUS WORK

Facilities for testing ship models in waves have been available for some time,but the testing of yacht models has been limited by the complex physics of the sailing yacht and the comparatively expensive nature of testing in waves. A milestone in yacht research was laid by Spens et al (1967) who tackled the problem of yacht testing in oblique waves. They concluded that response in oblique waves is in general agreement with the response in head seas of corresponding frequency. They also found that change in leeway angle due to waves was, having regard for experimental accuracy, barely measurable. Experimental results by Gerritsma (1971) on a '1/2-ton' model were compared with theoretical calculations. He concluded that strip theory methods in their present form were not completely adequate for calculating yacht motions. Pedrick (1974) analysed results of yacht tests in oblique waves in a manner which enabled him to quantify the effect of waves on sideforce. Gerritsma & Beukelman (1972) determined the effect of surge constraint on ship models and found it to be generally negligible. Gerritsma & Keuning (1986) measured the motions and added resistance of different yacht-keel configurations, showing that the wing keel was slightly detrimental to added resistance as a consequence of its effect on motions.

Most previous work has assumed that yacht motions are proportional to wave amplitude. This assumption has been largely verified by Gerritsma(1971) and Spens(1967) but the equivalent assumption that added resistance is proportional to wave amplitude squared has been found true only under certain conditions.

5.0 TANK TESTING EXPERIMENTS

The original aim of the tank testing programme was to provide experimental verification of the yacht strip-theory predictions. However, as testing progressed a number of unexpected results were obtained which lent themselves to further investigation. Consequently the programme not only provided a data check for theory but also:-

(a) highlighted the important parameters to which theory should address itself and:

(b) became self-supporting as a useable data set for a first estimate of performance loss in waves .

The tests were conducted at the Australian Maritime College, Launceston using a GRP 1/6th scale America's Cup model. Two interchangeable GRP keels were made; one a conventional fin, the other a 'typical' wing keel. Both keels were virtually identical in volume and mass thus allowing tests to be conducted at constant displacement and gyradius. The shift of LCB was second order so any differences in performance could be attributed directly to keel shape. It should be noted that this differs from full size design conditions where the lower VCG of a wing keel increases the gyradius and also lends itself to design of a lighter displacement canoe body for a given sail-carrying power.

The hull was fitted with turbulating studs in accordance with standard tank practice. The keels and wings were also fitted with studs, not so much to simulate full-scale flow conditions as to improve reliability of comparisons between the two keels.

The model was attached to the dynamometer by three posts. Sideforce is measured on the forward and aft posts, resistance on the forward post. The middle post is strain-gauged via a transverse arm to obtain righting moment data. Motions are measured by linear voltage displacement transducers on the forward and aft posts. Wave frequency and amplitude are measured by a capacitance probe at one point in the tank. A further probe was attached to the carriage for measuring wave phase angles.

The model pitch gyradius was determined by the bifilar suspension method. This method assumes the moment of inertia in pitch and yaw to be the same, which is reasonable for a yacht model without ballast in the keel.

Tests were conducted head on into regular waves over a range of amplitudes and steepness ratios. Heel angles of 0 and 15 degrees were investigated at a Froude number of 0.38, with the upright case also tested at Froude number of 0.34. A total of 143 runs were conducted.

6.0 COMMENTS ON RESULTS

R.M.S. errors in the tests are 4% for motions and 9% for added resistance. The results show two particularly interesting phenomena. First, the wing keel has little effect on the responses (Figures 1, 2, 3).

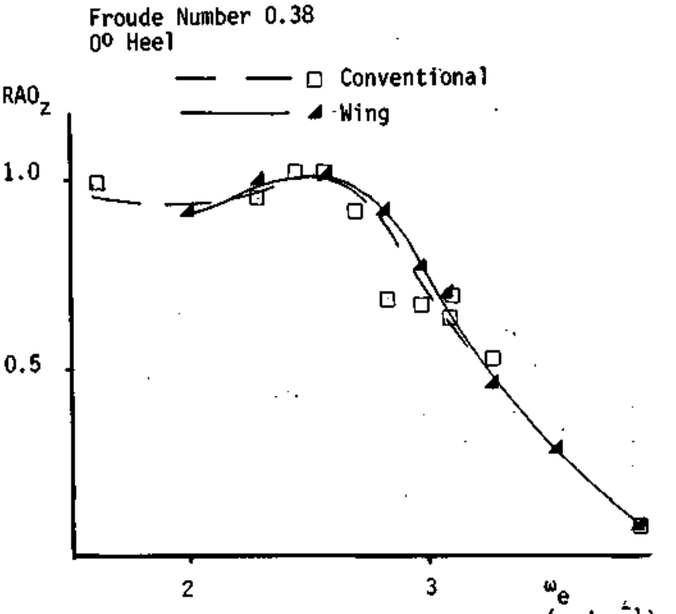

Figure 1.

Conventional and Wing Keel Heave Amplitude.

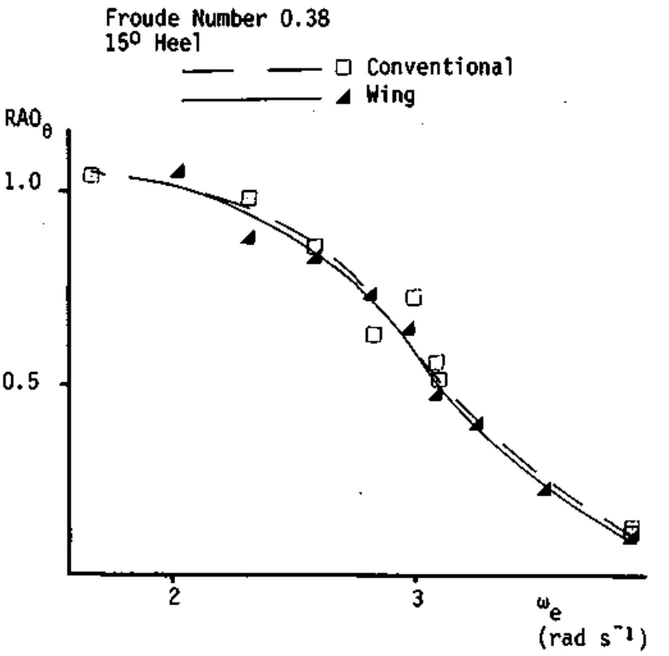

Figure 2.

Conventional and Wing Keel Pitch Amplitude.

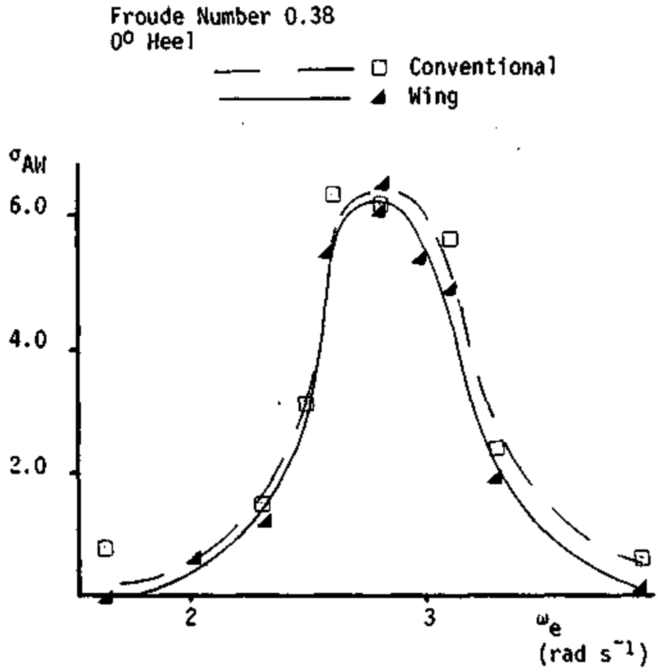

Figure 3.

Conventional and Wing Keel Added Resistance.

Second, the effect of heel angle on added resistance is to halve it, rather less so for motion amplitudes (Figures 4, 5, 6).

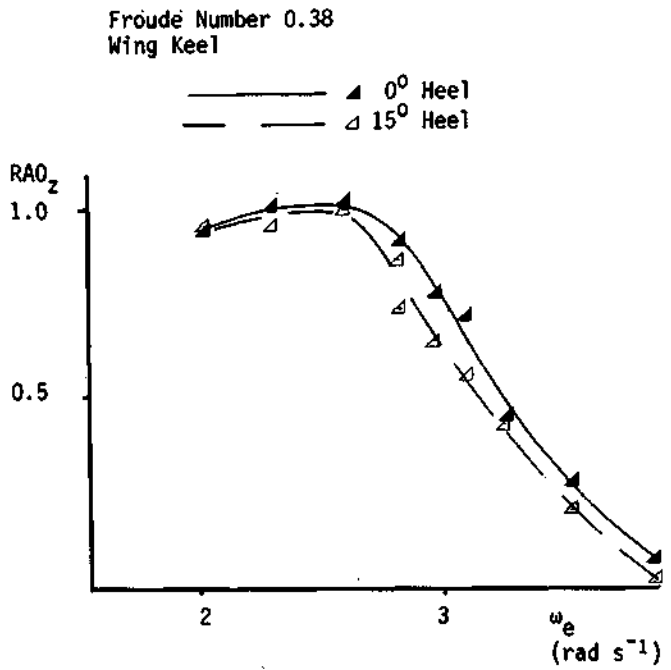

Figure 4.

Heeled and Upright Heave Amplitude.

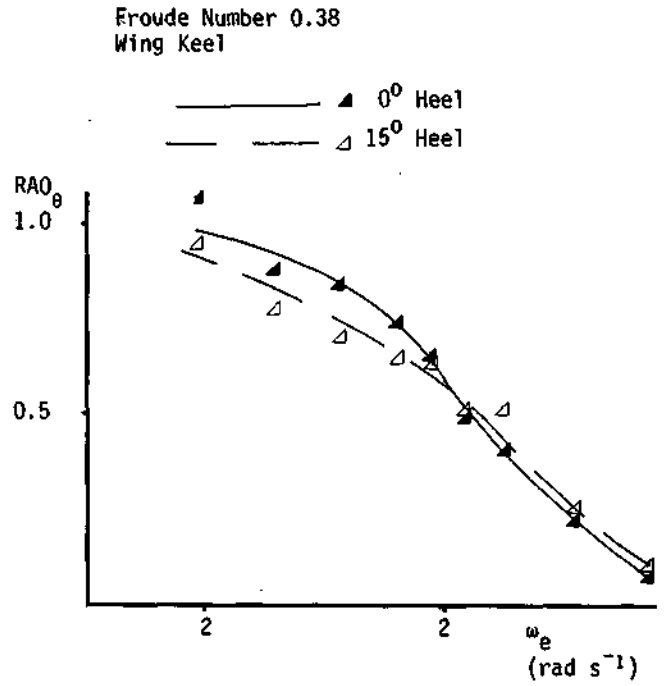

Figure 5.

Heeled and Upright Pitch Amplitude.

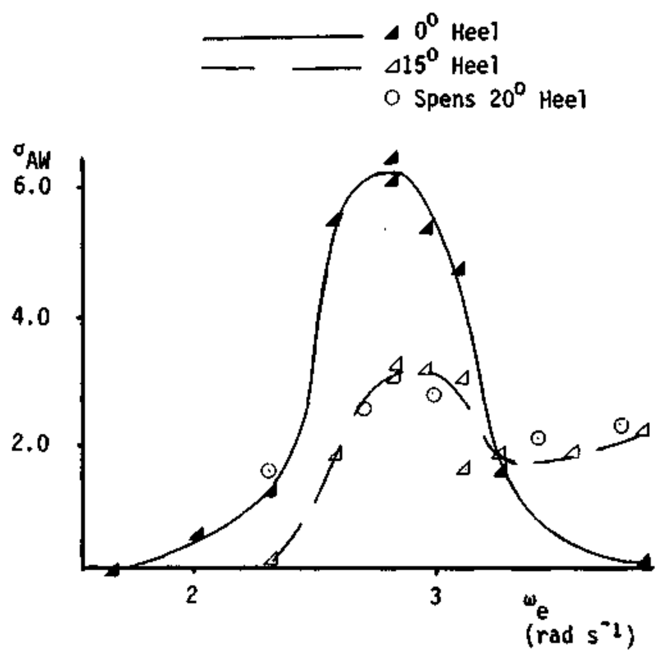

Figure 6.

Heeled and Upright Added Resistance.

The extent to which the wing will increase added resistance depends on the relationship between the wing trajectory and the local streamlines. It may be that for these tests the wing is contouring the flow, with no consequent influence on the response. However this seems unlikely to hold true for both the upright and the heeled condition.

It is frequently suggested by yacht designers that the parasitic drag of a wing keel in waves is offset by the effect of increased pitch and heave damping diminishing the added resistance, and reducing the airflow oscillation over the sails. The lack of effect of the wing on motions and phase angles in these tests weighs against these arguments.

The effect of heel on added resistance is more open to avenues of explanation, as a heeled shape will exhibit quite different added mass and damping characteristics. The importance of the heeled results cannot be overestimated: upright yacht testing alone is inadequate for the prediction of speed loss due to waves.

The shape of the added resistance curves might suggest that waves of very high frequency make a significant contribution to resistance. However it can be seen from Figure 7 that the peak in the wave encounter spectrum lies well to the left of the peak in the response curve. Fortunately the left hand tail-off of the response curve is fairly well-defined.

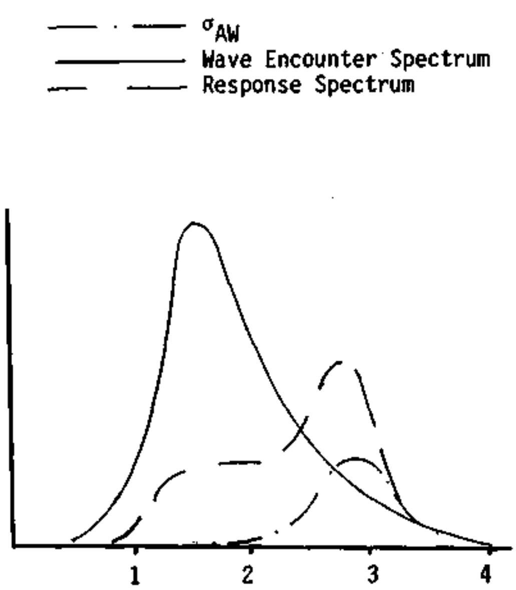

Figure 7.

Formation of Response Spectrum.

The assumption that motion amplitude is proportional to wave amplitude was found to be well supported whilst the square law for wave amplitude and added resistance is not reliable for all frequencies (Figure 8). The behaviour at wave amplitudes greater than 5.5 cm is indeterminate.

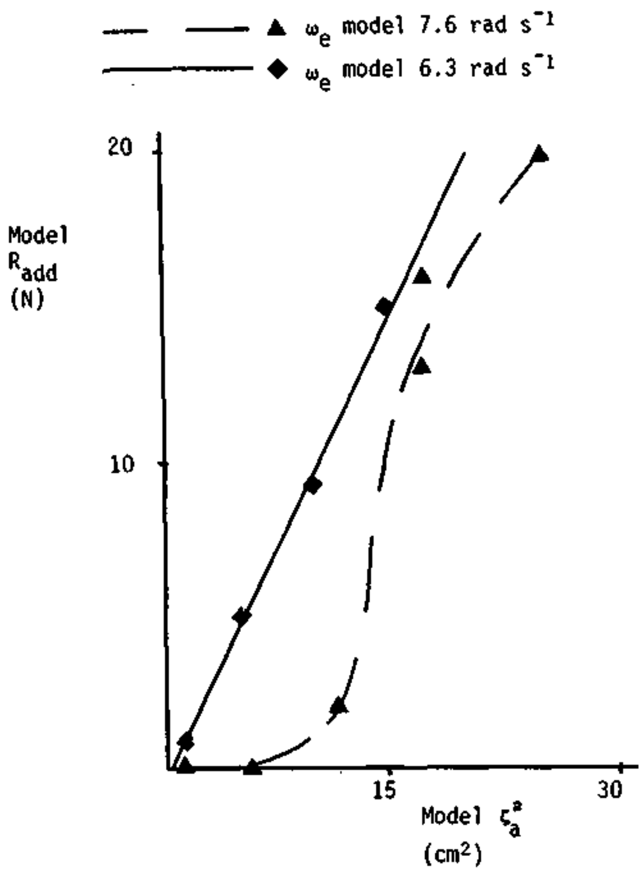

Figure 8.

Added Resistance v. (wave amplitude)^2

The increase in righting moment between static and calm-water-dynamic conditions was measured at 5% , though the measurement is heavily obscured by the presence of slight sideforce due to imperfect zero-leeway alignment (± 0.1 deg). The mean rough-water righting moment is the same as the calm-water-dynamic value, with a superimposed amplitude fluctuation of the order 3%. of calm water righting moment.

7.0 COMPARISONS WITH OTHER WORK

Added resistance for a similar shaped hull (Spens) at 20 degrees heel and similar Froude number is plotted in Figure 6, indicating comparable results. Unfortunately no results are known to the authors on a similar hull in the upright condition. Gerritsma (1971) found that heel angle had only a slight effect on added resistance but this was for a radically different hull form.

The negligible effect of the wing keel disagrees with Gerritsma & Keuning (1986) who found a 9% increase in added resistance for a wing keel.This may be due to differences in keel geometry.

8.0 VELOCITY PREDICTION PROGRAM

The rough water performance has been determined by altering a calm water VPP to include wave effects on added resistance. The effects of waves on sail force have not yet been included.

The calm water VPP estimates straight line resistance by modification of the Delft standard series data (Gerritsma et al (1981)) for improved accuracy outside the series test conditions. Leeway effects are determined from van Oossanen (1981) with modifications.The wing keel is modelled by assuming an optimum configuration and altering the effective keel span in accordance with published findings (Milgram (1984), Hoerner (1975)). Whilst this does not permit the VPP to provide a keel design facility it is appropriate for prediction from a pre-optimised keel shape. Sail force coefficients are based on Hazen (1982) with empirical modifications. A reefing function has been adopted similar to that of Kerwin (1976).

The determination of added resistance employs the tank-derived response curves and a wave spectrum supplied by an associate researcher. The ocean wave field is computer-modelled from a chosen wind field and output as a two-dimensional sea at the desired geographical position. In order to minimize computer storage space the spectrum is converted to a one-dimensional sea . It is then applied to the response curves in the usual manner:

$$Sradd\ (\omega_e) = S_\zeta(\omega_e) * \sigma$$

The mean added resistance is determined from the area under the response spectrum. This is a function of boat heading, boatspeed and heel angle. When incorporated in the VPP therefore it increases computing time considerably. In order to keep this under control the program is provided with limiting values of sailing condition which restrict the calculation to typical windward sailing.

9.0 REAL-TIME DATA

The real-time data serves two purposes within this project: first to determine the speed loss due to sea state; second to provide an estimate of the accuracy of the VPP.

Determination of speed loss from on-board measurement first requires a knowledge of calm water speed. There follows a multi-variate analysis of performance factors which is then regressed with boatspeed. The result can be used to check the accuracy of the speed loss predicted by the VPP, but includes several factors not considered by the VPP and various sources of noise. To date the real-time data has predicted speed loss no more reliably than the VPP. However it does provide a basis boatspeed at which to aim the VPP, and calm-water data provides a direct check on the calm water VPP. Further, if real-time performance for two different boats is compared with their VPP output, then the accuracy of the VPP for comparative studies can be assessed. This work is in hand .

10.0 CONCLUSIONS

Upright yacht testing alone is inadequate for the prediction of speed loss due to waves.

The wing keel tested has no significant effect on motions or added resistance.

The relationship between added resistance and wave amplitude is frequency dependent.

Response amplitude operators for head seas applied to a one-dimensional sea provide useful predictions of performance change due to waves when sailing close-hauled.

There is little effect of waves on mean righting moment for the the tested conditions.

11.0 ACKNOWLEDGEMENTS

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