PERFORMANCE OF LIGHT- AND HEAVY DISPLACEMENT SAILING YACHTS IN WAVES.
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Report nr. 773-P-1
December 1987
Second Tampa Bay Sailing Yacht Symposium

Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2
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THE SECOND TAMPA BAY SAILING YACHT SYMPOSIUM

at

THE UNIVERSITY OF SOUTH FLORIDA BAYBORO CAMPUS

ST. PETERSBURG, FLORIDA

Saturday, February 27, 1988

Southeast Section of The Society of Naval Architects and Marine Engineers

University of South Florida, Bayboro
USF St. Pete Sail Club
PERFORMANCE OF LIGHT- AND HEAVY DISPLACEMENT SAILING YACHTS IN WAVES

Prof. ir. J. Gerritsma* and Ir. J.A. Keuning*

SYNOPSIS

Experiments with light and moderate displacement sailing yacht models have been carried out in the Delft Ship Hydromechanics Laboratory to investigate heave, pitch and added resistance in regular waves. The experiments included conditions with and without heel- and leeway angles. The results are analysed and compared with calculations based on a strip theory method. Numerical methods are used to predict and to compare the performance of sailing yachts in realistic irregular wave conditions.

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INTRODUCTION

During the period 1977-1981 tank test results of twenty two systematic variations of one particular yacht hull form have been published by the Delft Ship Hydromechanics Laboratory. This extensive experimental program and the corresponding analysis of the results was carried out to provide a data base for the velocity prediction of sailing yachts in the design stage. The Delft Systematic Series I experiments included a range of hull form parameters, stabilities and speed-length ratio's to cover contemporary design concepts of cruiser-racing yachts at that time.

The lines of the parent model of this series are given in Figure 1 and the considered ranges of form parameters are summarized in Table 1. [1,2].

Table 1

Form parameters Delft Systematic Series I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWL/V&lt;sup&gt;1/s&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
<td>4.3 - 5.1</td>
</tr>
<tr>
<td>LCB</td>
<td>0 - 5 % LWL</td>
</tr>
<tr>
<td>CP</td>
<td>0.53 - 0.60</td>
</tr>
<tr>
<td>LWL/BWL</td>
<td>2.8 - 3.6</td>
</tr>
<tr>
<td>BWL/T&lt;sub&gt;c&lt;/sub&gt;</td>
<td>2.8 - 5.4</td>
</tr>
</tbody>
</table>

The results of these model tests are the basis of the resistance and side force determination for a given yacht geometry in the International Measurement System (I.M.S.). In combination with sailforces, which correspond to the sailplan of the considered yacht, a speed polar diagram results for a range of windspeeds and this information is used to determine racing handicaps. The I.M.S. speed polar predictions or similar methods may be used to compare alternative designs prior to the building of the yacht. Such methods presume ideal sailing conditions: constant windspeeds and no waves.

In general however, sea waves can have an important influence on the performance of a sailing yacht, in particular when the wave direction is forward of the beam and the wave length is approximately one or two times the length of the yacht. Model experiments have shown that a low L/V<sup>1/s</sup> ratio may induce a higher speed loss in waves.
Concentration of mass near the midships is effective to increase relative pitch damping, which reduces pitching and added resistance in waves [3].

Calculation of the windward performance of three sailing yachts with equal waterline-lengths (10 m) but different displacements (8.2, 9.8, 11.4 tons) in irregular bow waves have been carried out to demonstrate the effect of added resistance in waves on the windward performance.

In Figure 2 the speed-made-good as calculated for the three yachts is given for three true wind speeds: VTW - 7 kn, 14 kn and 20 kn on a base of significant wave height.

In the same wind and wave conditions. In these calculations it was assumed that the added resistance in waves is not influenced by a heel angle. The results demonstrate a considerable influence of waves on the performance of a sailing yacht. For the considered range of displacements the lightest yacht (i.e. \( L/V_c^{1/3} = 5 \)) has the best performance in calm water as well as in waves. With increasing wind speed the difference between the three designs becomes smaller. The lightest yacht in this comparison is certainly not a light displacement yacht with \( LWL/V_c^{1/3} = 5 \); ultra light designs may exceed \( LWL/V_c^{1/3} = 7 \).

Modern very light displacement yachts have beam-draught ratio's up to 9 or 10 and in case of maxi's and very large cruising yachts the length-beam ratio's are exceeding those of the Delft Systematic Series I.

For the determination of the upright resistance some extrapolation of the available data is acceptable, as shown in Figure 4. Here the upright resistance of an Admiral's Cupper with a beam-draught ratio 6.3 was calculated by using the Systematic Series I data and the result is compared with model test results. The correlation is
satisfactory, although the actual beam-draught ratio exceeds the maximum beam-draught ratio of the Series I by approximately 17%.

The modern trends in yacht design have led to an extension of the original Delft Systematic Series I with six models. The main particulars of these models are given in Table 2. The length-displacement ratio varies from 5 to 8, the length-beam ratio varies from 3.5 to 4.5 and the beam-draught ratio ranges from 2.4 to 12.5.

The bodyplans of the two models used for this study are given in figure 5A. Model 406 is the parent model of the series and model 407 is equal to model 408 but with a larger displacement.

All models have a prismatic coefficient $CP = 0.548$ and the same longitudinal position of the centre of buoyancy: $LCB = -2\%$. The bodyplan of the parent model is given in Figure 5, together with the parent body plan of the Series I. The model experiments for the series II are now in progress.

In this paper the results of the models 407 and 455 will be given, in particular with regard to the motions and the added resistance in waves. Model 455 has a moderate volume of displacement $V_c = 7.9$ m$^3$ and a very small beam-draught ratio $BWL/T_c = 2.4$, whereas model 407 has $V_c = 3.2$ m$^3$ and $BWL/T_c = 9.6$. 
The experimental results for pitch, heave and added resistance are compared with strip theory calculations, taking into account the effects of the heel angle. In addition the added resistance has been calculated for both models in realistic irregular waves, assuming that the wave direction is equal to the wind direction.

MODEL EXPERIMENTS
1. Resistance and side force in calm water

The experiments have been carried out with 2.3 m GRP models in the nr. 1 towing tank of the Delft Hydromechanics Laboratory. Keel and rudder are identical to those of the Series 1, see Figure 1.

The models were equipped with a turbulence stimulation as described in [1]. From a Prohaska's plot: \( C_T/C_F \) versus \( F_{n4}/C_F \) a form factor of 1.12 for model 445 and a factor 1.22 for model 407 has been found from the upright resistance tests in calm water, see Figure 6. These plots indicate a satisfactory turbulence stimulation in both cases. The difference in form factor reflects the different hull form of the two considered canoe bodies.

In Figure 7 full scale upright resistances are given on a base of forward speed, (LWL = 14 m). The difference between the moderate and the light displacement yacht is clear: a steep increase of resistance for the heavier displacement yacht for speeds exceeding the hull speed (\( V = 9.1 \) knots),
where as the light yacht's resistance curve resembles that of a planing hull to some extend. Some points are calculated with the existing polynomial expression for the upright resistance derived from Series I.

For both models resistance and sideforce has been measured for a range of forward speeds, leeway angles and heel angles. In Figure 8 the dimensionless sideforce is plotted on a base of leeway angle. The influence of the larger asymmetry of the underwater part of the light displacement hull is clearly demonstrated.

With a 30 degree heel angle the light yacht needs approximately a 5 degrees leeway for zero sideforce, whereas the other hull form needs only 1 degree, assuming that the extrapolation of the experimental data to zero sideforce is permissible.
The difference between the heeled resistance $R_\phi$ and the upright resistance $R_T$ can be expressed by equation (1):

$$ R_\phi - R_T = \frac{(C_0 + C_2\phi^2) F_H^2}{q S_c} \frac{F_c^2}{q^2 S_c^2} + C_H \phi^2 \quad (1) $$

where: $\phi$ - heel angle in radians.

The coefficients $C_0$ and $C_2$ for both models have been determined from model experiments and are given in Table 3.

The first term in (1) may be regarded as the induced resistance, whereas the second term represents the resistance due to heel only.

---

**Table 3**

Heeled Resistance Coefficients

<table>
<thead>
<tr>
<th>Modelnr.</th>
<th>$C_0$</th>
<th>$C_2$</th>
<th>$10^3 C_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>407</td>
<td>2.00</td>
<td>9.15</td>
<td>10.6</td>
</tr>
<tr>
<td>455</td>
<td>1.24</td>
<td>0.10</td>
<td>4.0</td>
</tr>
</tbody>
</table>

In Figure 9 the experimental results and their representation by equation (1) are given. The results show that the heel angle has a large influence on the heeled resistance in case of the light yacht, when compared
**Figure 8.** Sideforce versus leeway angle.

**Figure 9.** Heeled resistance for models 455 and 407.
with the moderate displacement yacht. The heeled resistance, which for the major part consists of induced resistance, differs approximately by a factor 2 for equal sideforce at a heel angle of 20 degrees.

2. EXPERIMENTS IN WAVES

Experiments in waves have been carried out with the two models to compare the pitching and heaving motions as well as the added resistance. The tests were carried out in regular head waves both in the upright condition and with a heel angle of 20 degrees. In addition the influence of a leeway angle has been studied by including in all test conditions zero and 5 degrees leeway.

The experiments were carried out at one constant speed: \( F_n = 0.30 \), corresponding to 6.8 knots for \( \text{LWL} = 14 \text{ m} \), in wave lengths varying from 1 to 2\( \sqrt{2} \) LWL and wave heights up to 0.025 LWL. The models were free to heave and pitch, but restrained in all other modes of motion. The pitch radius of inertia in both cases was 0.245 LOA. The experimental set up is given in Figure 10. This drawing is not to scale; the aft guidance of the model is a very light construction to avoid unacceptable variation in the pitch mass moment of inertia.

The experimental results are given in the Figures 11a and 11b, where the dimensionless heave and pitch amplitudes and the added resistance are plotted on a base of the ratio waterline-length/wave-length. The dimensionless motion amplitudes and added resistance are defined by:

- heave: \( z' = z_a/\zeta_a \)
- pitch: \( \theta' = \theta_a/L/2\pi \zeta_a \)
- added resistance: \( R_{AW}' = R_{AW}/\rho g L^2 \zeta_a \)

It may be concluded that the leeway angle \( \beta \) and the hereby induced side force on keel and
rudder has a negligible influence on the pitch and heave motion, as well as on the added resistance in waves for both models. The effect of the 20 degrees heel angle on the motions and the added resistance is very small for the light displacement yacht. In case of the moderate displacement yacht the influence of the heel angle on the heave and pitch motion is small; the motion amplitudes in the heeled condition are slightly smaller compared with upright sailing.
Consequently the added resistance for this hull form is also smaller in the heeled condition. The maximum motion amplitudes of model 455 are approximately twice as large as those of the light displacement hull. This results from the relatively low pitch and heave damping of the moderate displacement hull, which has a small beam-draught ratio. Linearity of the motion with wave amplitudes in the considered range of wave heights (up to 0.025 L) was quite satisfactory.

To compare the performance of the two hull forms as sailing yachts, ballast weight and sailplan have been determined using the following reasoning. For model 407 a specific weight of 40 kg/m³ for the yacht without ballast keel has been assumed. And for model 455: 65 kg/m³. The height of the centre of gravity has been located at 80% of the depth of the canoe body. The difference of this weight and the weight of total displacement gives the maximum possible ballast weight. The sailplan follows from the ratio of sail area moment and stability moment at 30 degrees heel angle, as taken from existing satisfactory designs.

These considerations have led to the following stabilities and sail dimensions, see Table 3.

<table>
<thead>
<tr>
<th>Tabel 3</th>
<th>Sail dimensions and righting moment (LWL = 14 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model nr 407</td>
<td>Model nr 455</td>
</tr>
<tr>
<td>I</td>
<td>19.23 m</td>
</tr>
<tr>
<td>J</td>
<td>6.41 m</td>
</tr>
<tr>
<td>P</td>
<td>17.78 m</td>
</tr>
<tr>
<td>E</td>
<td>5.08 m</td>
</tr>
<tr>
<td>Δ</td>
<td>9.900 ton</td>
</tr>
<tr>
<td>GM</td>
<td>3.01 m</td>
</tr>
<tr>
<td>RM</td>
<td>5101 Nm/deg</td>
</tr>
</tbody>
</table>

Velocity predictions have been made for both yachts. A speed polar diagram for a true windspeed VTW = 15 knots is given in Figure 12. The optimum true wind angle close hauled is 37 degrees for model 455 and 43 degrees for model 407 and the optimum speeds made good are respectively 6.2 and 5.8 knots. However for true wind angles larger than 90 degrees the light yacht is faster, the maximum yacht speeds being 9.0 knots for model 455 and 10.2 for 407. This seems to agree with practical experience: light displacement yachts do not point as high as heavier sailing yachts. For light yachts a sufficient
righting moment is very important. If model 407 should have a GM = 2 m, instead of 3 m, the maximum speed made good would decrease 1 knot at VTW = 15 knots!

EXPERIMENTAL AND CALCULATED MOTIONS AND ADDED RESISTANCE IN WAVES

1. Regular waves

To investigate the possibility to include the effects of seawaves in the velocity prediction of sailing yachts, the motions and the added resistance of the two considered hull forms have been calculated by using a strip-theory method. The added resistance calculation is based on the method given in [4], assuming that this resistance component is related to the radiated damping waves, which are generated by the pitching and heaving yacht and the corresponding relative motion of the hull with respect to the surrounding water. Damping coefficients and hydrodynamic mass of 2-dimensional cross-sections have been determined with Frank's close fit method [6], including the case with 20 degrees heel angle.

The computed motion amplitudes and added resistances agree very well with the corresponding experimental values in case of the light yacht, as can be concluded from Figure 11a.
For the moderate displacement hull the heave motion correlates satisfactory with the calculated results, whereas the maximum pitch amplitudes are underestimated by the calculation for zero heel angle as well as for 20 degrees heel angle, see Figure 11b. A similar difference occurs in the case of fast and slender cargo ships. In general the agreement between calculation and experiment improves with increasing beam-draught ratio.

The calculated added resistance for the moderate displacement yacht is close to the experimental results for the upright condition, but for 20 degrees heel angle the calculation gives higher values, see Figure 11b. However, it should not be excluded that in case of the heavier model the guidance apparatus aft was not sufficiently strong, resulting in an erroneous resistance measurement. In general the experiments show that for the light displacement yacht the heel angle has only a small influence on the motion amplitudes and the added resistance. This trend is confirmed by the calculations. In case of the medium displacement hull, with the relatively small beam-draught ratio, the measured motion amplitudes are somewhat smaller in the heeled condition and in particular the experimental added resistance of this hull is smaller when heeled. The calculation does not confirm this trend.

It should be noted here that an even larger difference of experimental added resistance between the upright condition and heeled has been found by Kakla & Penrose [5] for a 12 m model.

2. CALCULATION OF ADDED RESISTANCE IN IRREGULAR WAVES

The added resistance in irregular waves has been calculated for a range of wave spectra with wave periods from 1.5 s to 8 s and unit wave height.

For the wave spectra the formulation by Bretschneider for a long crested sea has been used:

\[ S_{5}(\omega) = A\omega^{-5} \exp(B\omega^{-4}) \]

with: \( A = 173 \frac{H}{s}^{2/T_{1}} \)

and: \( B = 691/T_{1}^{4} \)

where: \( H/s \) - significant wave height

\( T_{1} \) - \( 2\pi m_{0}/m_{1} \), average wave period.
### Table 4

**Added Resistance (N)**

\( F_n = 0.3 \) \( V = 6.83 \text{ kn} \)

<table>
<thead>
<tr>
<th>MODEL 455</th>
<th>Unidirectional sea</th>
<th>cos-sq spreaded sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVE DIRECTION: degrees off stern</td>
<td>WAVE DIRECTION: degrees off stern</td>
<td></td>
</tr>
<tr>
<td>wave period</td>
<td>180</td>
<td>170</td>
</tr>
<tr>
<td>1.20</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>2.00</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>3.00</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>4.00</td>
<td>7.0</td>
<td>6.0</td>
</tr>
<tr>
<td>5.00</td>
<td>8.0</td>
<td>7.0</td>
</tr>
<tr>
<td>6.00</td>
<td>9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>7.00</td>
<td>10.0</td>
<td>9.0</td>
</tr>
<tr>
<td>8.00</td>
<td>11.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MODEL 407</th>
<th>Unidirectional sea</th>
<th>cos-sq spreaded sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAVE DIRECTION: degrees of stern</td>
<td>WAVE DIRECTION: degrees of stern</td>
<td></td>
</tr>
<tr>
<td>wave period</td>
<td>180</td>
<td>170</td>
</tr>
<tr>
<td>1.20</td>
<td>4.0</td>
<td>3.0</td>
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<tr>
<td>2.00</td>
<td>5.0</td>
<td>4.0</td>
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<tr>
<td>3.00</td>
<td>6.0</td>
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<td>4.00</td>
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<td>5.00</td>
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<td>6.00</td>
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<tr>
<td>7.00</td>
<td>10.0</td>
<td>9.0</td>
</tr>
<tr>
<td>8.00</td>
<td>11.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Also the influence of directional spreading of wave energy has been considered, using a cosine squared spreading function,

\[ S_s(\omega, \mu) = \frac{2}{\pi} \cos^2 \mu. \]

where: \( \mu \) - wave direction.

In view of a velocity prediction for all headings, it has been assumed that the wave direction is equal to the wind direction in all cases.

In Table 4 the calculated added resistance is given for one speed \( F_n = 0.30 \) (\( V = 6.83 \) kn, \( LWL = 14 \) m), and a uniform wave height of 1 meter, as a function of the wave period and the true wind-wave angle.

It should be mentioned here that added resistance is to a fair degree proportional to wave height squared. For instance, when \( H_1/s = 0.5 \) m the values in Table should be multiplied by \((0.5)^2 = 0.25\).

The data in Table 4 show that in a sea with directional spreading of the wave components the added resistance is about 10-15% lower than in unidirectional long crested waves. The velocity prediction in waves will be carried out for longcrested seas only.

The difference in added resistance for the two hull forms is clearly shown in Table 4. The light yacht has a much lower added resistance, also taking the displacement into account.

It should be kept in mind that the added resistance for model 455 is overestimated by approximately 30% when the yacht has a heel angle of 20 degrees. Maximum added resistance in the close hauled condition (true wind angle 40-50 degrees) occurs at a wave period \( T_1 = 2.5 \sim 3 \) s for model 455 and at \( T_1 = 2 \sim 2.5 \) s for model 407. This corresponds to the difference in the natural pitch periods of the two considered hull forms: the light displacement yacht has the smallest pitching period.

By using the data in Table 4 a velocity prediction in waves has been made for both yachts, in particular for wind and wave direction <90 degrees.

In Table 5 the wave conditions, as used in these calculations, are summarized.

In Table 6 the speed loss due to the added resistance in waves is given as a percentage of the calm water speed for a true wind speed of 15 knots.

The light displacement yacht has a lower speed loss in waves than the medium displacement yacht.
Table 5
Wave conditions

<table>
<thead>
<tr>
<th>$T_1$ (s)</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{1/3}$ (m)</td>
<td>0.40</td>
<td>0.45</td>
<td>0.475</td>
<td>0.50</td>
<td>0.75</td>
<td>1.30</td>
<td>2.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 6
Speed loss in waves in %

<table>
<thead>
<tr>
<th>True wind angle</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODENR. 407 wave period(s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>40</td>
<td>0.9</td>
<td>2.7</td>
<td>2.6</td>
<td>3.1</td>
<td>3.1</td>
<td>4.1</td>
<td>7.0</td>
<td>11.4</td>
</tr>
<tr>
<td>50</td>
<td>1.5</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.7</td>
<td>2.9</td>
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<tr>
<td>60</td>
<td>1.4</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>2.1</td>
<td>2.1</td>
<td>3.3</td>
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<tr>
<td>70</td>
<td>1.2</td>
<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td>1.8</td>
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<tr>
<td>80</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
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<td>0.6</td>
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<tr>
<td>90</td>
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</table>

<table>
<thead>
<tr>
<th>MODENR. 455</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>60</td>
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<tr>
<td>70</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>90</td>
</tr>
</tbody>
</table>

It depends on the wave conditions and the wind speed if this compensates the lower speed-made-good when sailing to wind-ward in calm water. For wave directions larger than 90 degrees the calculation of motions and added resistance is less reliable. In general the added resistance is small in these conditions and far less important compared with sailing to wind-ward as regard speed reduction.

CONCLUSIONS

The calculation of motions and added resistance in waves compares satisfactory with
experimental results in the case of light displacement yachts having high beam-draught ratio's. For medium displacement yachts with a small beam-draught ratio the correlation is somewhat less satisfactory.

Calculated added resistance, based on a strip theory method can be used for a velocity prediction in waves. Such information may be useful for design purposes as well as for the determination of racing handicaps.

ACKNOWLEDGEMENT

The Authors are indebted to R. Onnink who carried out the model experiments, and to J.M.J. Journée and A. Versluis for doing the computer calculations for the velocity prediction in calm water and in waves.

NOMENCLATUUR

**BWL** : waterline breadth

**C<sub>f</sub>** : frictional resistance coefficient

**C<sub>T</sub>** : total resistance coefficient

**CP** : prismatic coefficient

**F<sub>H</sub>** : side force

**I** : sail dimensions

**F<sub>n</sub>** : Froude number

**GM** : metacentric height

**g** : acceleration due to gravity

**H<sub>1/3</sub>** : significant wave height

**LCB** : Longitudinal centre of buoyancy in % LWL

**LWL,L** : Waterline length

**q** : stagnation pressure - \( \frac{1}{2} \rho V^2 \)

**R<sub>T</sub>** : total resistance in upright position

**RM** : righting moment

**R<sub>AW</sub>** : added resistance in waves

**S<sub>c</sub>** : wetted area, canoe body

**S<sub>f</sub>** : spectral density

**T<sub>1</sub>** : wave period \( T_1 = 2\pi m_0/m \)

**T<sub>c</sub>** : draught of canoe body

**V<sub>s</sub>** : yacht speed

**VMG** : speed made good

**VTW** : true wind speed

**z<sub>a</sub>** : heave amplitude

**β** : leeway angle

**θ<sub>a</sub>** : pitch amplitude

**ζ<sub>a</sub>** : wave amplitude

**φ** : heel angle

**λ** : wave length

**ρ** : density of water

**ω** : circular frequency

**V<sub>c</sub>** : volume of displacement, canoe body

**Δ** : weight of displacement
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Performance of Light- and Heavy-Displacement Sailing Yachts in Waves

J. Gerritsma¹ and J. A. Keunling¹

Experiments with light- and moderate-displacement sailing yacht models have been carried out in the Delft Ship Hydromechanics Laboratory to investigate heave, pitch, and added resistance in regular waves. The experiments included conditions with and without heel and leeway angles. The results are analyzed and compared with calculations based on a strip theory method. Numerical methods are used to predict and to compare the performance of sailing yachts in realistic irregular-wave conditions.

Introduction

During the period 1977–1981, tank test results of 22 systematic variations of one particular yacht hull form were published by the Delft Ship Hydromechanics Laboratory. This extensive experimental program and the corresponding analysis of the results were carried out to provide a database for the velocity prediction of sailing yachts in the design stage. The Delft Systematic Series I experiments included a range of hull form parameters, stabilities, and speed-length ratios to cover contemporary design concepts of cruiser yachts at that time.

The lines of the parent model of this series are given in Fig. 1 and the considered ranges of form parameters are summarized in Table 1 [1,2].²

The results of these model tests are the basis of the resistance and side force determination for a given yacht geometry in the International Measurement System (IMS). In combination with sail forces, which correspond to the sail plan of the considered yacht, a speed polar diagram results for a range of windspeeds, and this information is used to determine racing handicaps. The IMS speed polar predictions or similar methods may be used to compare alternative designs prior to the building of the yacht. Such methods presume ideal sailing conditions: constant wind speeds and no waves.

In general, however, sea waves can have an important influence on the performance of a sailing yacht, in particular when the wave direction is forward of the beam and the wave length is approximately one or two times the length of the yacht. Model experiments have shown that a low L/√V³ ratio may induce a higher speed loss in waves.

Concentration of mass near midships is effective in increasing relative pitch damping, which reduces pitching and added resistance in waves [3].

Calculation of the windward performance of three sailing yachts with equal waterline lengths (10 m) but different displacements (8.2, 9.8, 11.4 tons) in irregular bow waves has been carried out to demonstrate the effect of added resistance in waves on the windward performance.

Figure 2 gives the speed-made-good as calculated for the three yachts for three true wind speeds—VTW = 7, 14, and 20 knots—on the basis of significant wave height.

Figure 3 shows the optimum true wind angles for the lightest yacht (Δ = 8.2 tons) in the same wind and wave conditions. In these calculations it was assumed that the added resistance in waves is not influenced by heel angle. The results demonstrate a considerable influence of waves on the performance of a sailing yacht. The considered range of displacements the lightest yacht (that is, L/√V³ = 5) has the best performance in calm water as well as in waves. With increasing wind speed the difference between the three designs becomes smaller. The lightest yacht in this comparison is certainly not a light-displacement yacht with LWL/√V³ = 5: ultralight designs may exceed LWL/√V³ = 7. Modern very-light-displacement yachts have beam-draft ratios up to 9 or 10 and in the case of maxi's and very large cruising yachts the length-beam ratios are exceeding those of the Delft Systematic Series I.

To determine the upright resistance, some extrapolation of the available data is acceptable, as shown in Fig. 4. Here the upright resistance of an Admiral’s Cupper with a beam-draft ratio 6.3 was calculated by using the Systematic Series I data and the result is compared with model test results. The correlation is satisfactory, although the actual beam-draft ratio exceeds the maximum beam-draft ratio of the Series I by approximately 17 percent.

The modern trends in yacht design have led to an extension of the original Delft Systematic Series I with six models. The main particulars of these models are given in Table 2. The length-displacement ratio varies from 5 to 8, the length-draft ratio from 3.5 to 4.5, and the beam-draft ratio ranges from 2.4 to 12.5.

The body plans of the two models used for this study are given in Fig. 5(a). Model 406 is the parent model of the series and Model 407 is equal to Model 408 but with a larger displacement. All models have a prismatic coefficient CP = 0.548 and the same longitudinal position of the center of buoyancy: LCB = −2 percent. The body plan of the parent model also is given in Fig. 5 together with the parent body plan of Series I. The model experiments for Series II are now in progress. In this paper the results of Models 407 and 455 will be given, in particular with regard to the motions and the added resistance in waves. Model 455 has a moderate volume of displacement V₃ = 7.9 m³ and a very small beam-draft ratio BWL/Tₚ = 2.4, whereas Model 407 has V₃ = 3.2 m³ and BWL/Tₚ = 9.6.

The experimental results for pitch, heave, and added resistance are compared with strip-theory calculations, taking into account the effects of the heel angle. In addition, the added resistance has been calculated for both models in realistic irregular waves, assuming that the wave direction is equal to the wind direction.

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²Numbers in brackets designate References at end of paper.
³Presented at the February 27, 1988 meeting of the Southeast Section of THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS.
Model experiments

Resistance and side force in calm water

The experiments have been carried out with 2.3-m glass-fiber reinforced plastic (GRP) models in the No. 1 towing tank of the Delft Hydromechanics Laboratory. Keel and rudder are identical to those of the Series I; see Fig. 1.

The models were equipped with turbulence stimulation as described in reference [1]. Figure 6 shows Prähaska plots of $C_T/C_F$ versus $F_{n4}/C_F$ from the upright resistance tests in calm water; a form factor of 1.12 for Model 445 and 1.22 for Model 407. These plots indicate satisfactory turbulence stimulation in both cases. The difference in form factor reflects the different hull forms of the two considered canoe bodies.

Figure 7 shows full-scale upright resistance on the basis of forward speed ($LWL = 14$ m). The difference between the moderate- and the light-displacement yacht is clear: a steep increase of resistance for the heavier-displacement yacht for speeds exceeding the hull speed ($V = 9.1$ knots), whereas the light yacht's resistance curve resembles that of a planing hull to some extent. Some points are calculated with the existing polynomial expression for the upright resistance derived from Series I.

For both models, resistance and side force have been measured for a range of forward speeds, leeway angles, and heel angles.

In Fig. 8 the dimensionless side force is plotted on the basis of leeway angle. The influence of the larger asymmetry of the underwater part of the light-displacement hull is clearly demonstrated.

With a 30-deg heel angle the light yacht needs approximately a 5-deg leeway for zero side force, whereas the other hull form needs only 1 deg, assuming that the extrapolation of the experimental data to zero side force is permissible.

The difference between the heeled resistance $R_\phi$ and the upright resistance $R_T$ can be expressed by

$$\frac{R_\phi - R_T}{qS_c} = \frac{(C_0 + C_2\phi^3)S_H}{q^2S_c^2} + C_3\phi^5$$

where $\phi$ is the heel angle in radians. The coefficients $C_0$ and $C_2$ for both models have been determined from model experiments and are given in Table 3.

The first term in equation (1) may be regarded as the induced resistance, whereas the second term represents the resistance due to heel only.

In Fig. 9 the experimental results and their representation by equation (1) are given. The results show that the heel angle has a large influence on the heeled resistance in the case of the light yacht, when compared with the moderate-displacement yacht. The heeled resistance, which for the major part consists of induced resistance, differs approximately by a factor of 2 for equal side force at a heel angle of 20 deg.

### Table 1: Form parameters, Delft Systematic Series I

| $LWL/V_c$ | 4.3 to 5.1 |
| LCB | 0 to 5% $LWL$ |
| CP | 0.53 to 0.60 |
| $LWL/BWL$ | 2.8 to 3.6 |
| $BWL/T_c$ | 2.8 to 3.6 |

### Nomenclature

- $BWL =$ waterline breadth
- $C_f =$ frictional resistance coefficient
- $C_T =$ total resistance coefficient
- $CP =$ prismatic coefficient
- $F_n =$ side force
- $I =$ sail dimensions
- $P =$ sail dimensions
- $E =$ sail dimensions
- $Fn =$ Froude number
- $GM =$ metacentric height
- $g =$ acceleration due to gravity
- $H_{1/3} =$ significant wave height
- $LCB =$ longitudinal center of buoy-
- $\Delta =$ weight of displacement
- $\omega =$ circular frequency
- $V_c =$ volume of displacement, canoe body
- $V_r =$ yacht speed
- $VMG =$ speed made good
- $VTW =$ true wind speed
- $z_v =$ heave amplitude
- $\beta =$ leeway angle
- $\theta_v =$ pitch amplitude
- $\zeta_v =$ wave amplitude
- $\phi =$ heel angle
- $\lambda =$ wave length
- $\rho =$ density of water
- $\omega =$ circular frequency
- $V_c =$ volume of displacement, canoe body

JANUARY 1989
Experiments in waves

Experiments in waves have been carried out with the two models to compare the pitching and heaving motions as well as the added resistance. The tests were carried out in regular head waves both in the upright condition and with a heel angle of 20 deg. In addition, the influence of a leeway angle has been studied by including in all test conditions zero and 5-deg leeway.

The experiments were carried out at one constant speed, $F_n = 0.30$, corresponding to 6.8 knots for $LWL = 14$ m, in wave lengths varying from 1 to $2\sqrt{LWL}$ and wave heights up to 0.025 $LWL$. The models were free to heave and pitch, but restrained in all other modes of motion. The pitch radius of inertia in both cases was 0.245 $L_{OA}$. The experimental setup is given in Fig. 10. This drawing is not to scale; the aft guidance of the model is a very light construction to avoid unacceptable variation in the pitch mass moment of inertia.

The experimental results are given in the Figs. 11(a) and 11(b), where the dimensionless heave and pitch amplitudes and the added resistance are plotted on the basis of the waterline-length/wave-length ratio. The dimensionless motion amplitudes and added resistance are defined by

\[
\begin{align*}
\zeta_h &= \frac{z_h}{L_{OA}} \\
\theta_h &= \frac{\theta_h}{L/2\pi L_{OA}} \\
R_{AW} &= \frac{R_{AW}}{\rho g L_{OA}^2}
\end{align*}
\]

It may be concluded that the leeway angle $\beta$ and the side force induced thereby on the keel and rudder have a negligible influence on the pitch and heave motion, as well as on the added resistance in waves for both models. The effect of the 20-deg heel angle on the motions and the added resistance is very small for the light-displacement hull. In case of the moderate-displacement yacht the influence of the heel angle on the heave and pitch motion is small; the motion amplitudes in the heeled condition are slightly smaller compared with upright sailing. Consequently, the added resistance for this hull form is also smaller in the heeled condition. The maximum motion amplitudes of Model 455 are approximately twice those of the light-displacement hull. This results from the relatively low pitch and heave damping of the moderate-displacement hull, which has a small beam-draft ratio.

The linearity of the motion with wave amplitudes in the considered range of wave heights (up to 0.025 $L$) was quite satisfactory.

To compare the performance of the two hull forms as sailing yachts, the ballast weight and sail plan have been determined using the following reasoning. For Model 407 a specific weight of 40 kg/m$^3$ for the yacht without ballast keel has been assumed, and for Model 455 a specific weight of 65 kg/m$^3$. The height of the center of gravity has been located at 80 percent of the depth of the canoe body. The difference of this weight and the weight of total displacement gives the maximum possible ballast weight.

The sail plan follows from the ratio of sail area moment of inertia to the square of the waterline length.

<table>
<thead>
<tr>
<th>Model</th>
<th>LWL (m)</th>
<th>BWL (m)</th>
<th>$T_c$ (m)</th>
<th>$V_{c1}$ (m$^3$)</th>
<th>LWL/BWL</th>
<th>BWL/V_{c1}</th>
<th>LWL/\sqrt{V_{c1}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>355</td>
<td>10</td>
<td>2.86</td>
<td>0.73</td>
<td>7.974</td>
<td>3.50</td>
<td>3.9</td>
<td>5.0</td>
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<tr>
<td>357</td>
<td>10</td>
<td>2.86</td>
<td>0.27</td>
<td>3.000</td>
<td>3.50</td>
<td>10.6</td>
<td>6.9</td>
</tr>
<tr>
<td>406</td>
<td>10</td>
<td>2.50</td>
<td>0.48</td>
<td>4.617</td>
<td>4.00</td>
<td>5.2</td>
<td>6.6</td>
</tr>
<tr>
<td>407</td>
<td>10</td>
<td>2.50</td>
<td>0.26</td>
<td>3.217</td>
<td>4.00</td>
<td>9.6</td>
<td>8.6</td>
</tr>
<tr>
<td>408</td>
<td>10</td>
<td>2.50</td>
<td>0.20</td>
<td>1.972</td>
<td>4.00</td>
<td>12.5</td>
<td>8.0</td>
</tr>
<tr>
<td>455</td>
<td>10</td>
<td>2.24</td>
<td>0.94</td>
<td>7.915</td>
<td>4.47</td>
<td>2.4</td>
<td>5.0</td>
</tr>
<tr>
<td>457</td>
<td>10</td>
<td>2.21</td>
<td>0.34</td>
<td>3.923</td>
<td>4.52</td>
<td>6.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>
and stability moment at 30-deg heel angle, as taken from existing satisfactory designs. These considerations have led to the stabilities and sail dimensions given in Table 4.

Velocity predictions have been made for both yachts. A speed polar diagram for a true wind speed $VTW = 15$ knots is given in Fig. 12. The optimum true wind angle close-hauled is 37 deg for Model 455 and 43 deg for Model 407 and the optimum speeds-made-good are, respectively, 6.2 and 5.8 knots. However, for true wind angles larger than 90 deg, the light yacht is faster, the maximum yacht speeds being 9.0 knots for Model 455 and 10.2 for Model 407. This seems to
Fig. 8 Side force versus leeway angle

Fig. 9 Heeled resistance for Models 455 and 407

Fig. 10 Experimental setup for heeled wave experiments
agree with practical experience: light displacement yachts do not point as high as heavier sailing yachts. For light yachts a sufficient righting moment is very important. If Model 407 should have a $GM = 2 \text{ m}$, instead of $3 \text{ m}$, the maximum speed made good would decrease 1 knot at $V_{TW} = 15 \text{ knots}$.

Experimental and calculated motions and added resistance in waves

Regular waves

To investigate the possibility of including the effects of seaways in the velocity prediction of sailing yachts, the motions and the added resistance of the two considered hull forms were calculated by a strip-theory method. The added resistance calculation is based on the method given in [4], assuming that this resistance component is related to the radiated damping waves, which are generated by the pitching and heaving yacht and the corresponding relative motion of the hull with respect to the surrounding water.

---

Table 3 Heeled resistance coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>$C_0$</th>
<th>$C_2$</th>
<th>$10^3C_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>407</td>
<td>2.00</td>
<td>9.15</td>
<td>10.6</td>
</tr>
<tr>
<td>455</td>
<td>1.24</td>
<td>0.10</td>
<td>4.0</td>
</tr>
</tbody>
</table>

---

Fig. 11(a) Motions and added resistance in regular waves, Model 407

Fig. 11(b) Motions and added resistance in regular waves, Model 455
Damping coefficients and hydrodynamic mass of two-dimensional cross sections have been determined by Frank's close-fit method [5], including the case with 20-deg heel angle.

The computed motion amplitudes and added resistances agree very well with the corresponding experimental values in the case of the light yacht, as can be concluded from Fig. 11(a). For the medium-displacement hull the heave motion correlates satisfactorily with the calculated results, whereas the maximum pitch amplitudes are underestimated by the calculation for zero heel angle as well as for 20-deg heel angle; see Fig. 11(b). A similar difference occurs in the case of fast and slender cargo ships. In general, the agreement between calculation and experiment improves with increasing beam-draft ratio.

The calculated added resistance for the moderate-displacement yacht is close to the experimental results for the upright condition, but for 20-deg heel angle the calculation gives higher values; see Fig. 11(b). However, it should not be concluded that in the case of the heavier model the guidance apparatus aft was not sufficiently strong, resulting in an erroneous resistance measurement. In general, the experiments show that for the light-displacement yacht the heel angle has a small influence on the motion amplitudes and the added resistance. This trend is confirmed by the calculations. In the case of the medium-displacement hull, with the relatively small beam-draft ratio, the measured motion amplitudes are somewhat smaller in the heeled condition and in particular the experimental added resistance of this hull is smaller when heeled. The calculation does not confirm this trend.

It should be noted here that an even larger difference of experimental added resistance between the upright and heeled conditions has been found by Kakla and Penrose [6] for a 12-m model.

**Table 4** Sail dimensions and righting moment ($LWL = 14$ m)

<table>
<thead>
<tr>
<th></th>
<th>Model 407</th>
<th>Model 455</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>19.23 m</td>
<td>21.42 m</td>
</tr>
<tr>
<td>$J$</td>
<td>6.41 m</td>
<td>7.14 m</td>
</tr>
<tr>
<td>$P$</td>
<td>17.78 m</td>
<td>19.97 m</td>
</tr>
<tr>
<td>$E$</td>
<td>5.08 m</td>
<td>5.71 m</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>9.900 ton</td>
<td>23.620 tons</td>
</tr>
<tr>
<td>$GM$</td>
<td>3.01 m</td>
<td>1.22 m</td>
</tr>
<tr>
<td>$RM$</td>
<td>5101 Nm/deg</td>
<td>4934 Nm/deg</td>
</tr>
</tbody>
</table>

**Calculation of added resistance in irregular waves**

The added resistance in irregular waves was calculated for a range of wave spectra with wave periods from 1.5 to 8 sec and unit wave height.

For the wave spectra the formulation by Bretschneider for a long-crested sea was used:

$$S_d(\omega) = A \omega^{-5} \exp(B\omega^{-4})$$

with

$$A = 173H_{1/3}^2/T_1^4$$

and

$$B = 691/T_1^4$$

where $H_{1/3}$ is the significant wave height and $T_1 = 2\pi m_0/m_1$, the average wave period. Also, the influence of directional spreading of wave energy has been considered, using a cosine-squared spreading function:

$$S_d(\omega, \mu) = 2/\pi \cos^2 \mu \cdot S_d(\omega)$$

where $\mu$ is the wave direction.

In view of a velocity prediction for all headings, it has been assumed that the wave direction is equal to the wind direction in all cases.

In Table 5 the calculated added resistance is given for one speed, $F_n = 0.30$ ($V = 6.83$ knots, $LWL = 14$ m), and a uniform wave height of 1 m, as a function of the wave period and the true wind-wave angle.

It should be mentioned here that added resistance is to a fair degree proportional to wave height squared. For instance, when $H_{1/3} = 0.5$ m the values in Table 5 should be multiplied by $(0.5)^2 = 0.25$.

The data in Table 5 show that in a sea with directional spreading of the wave components the added resistance is about 10 to 15 percent lower than in unidirectional long-crested waves. The velocity prediction in waves is carried out for long-crested seas only.

The difference in added resistance for the two hull forms is clearly shown in Table 5. The light yacht has a much lower added resistance, taking the displacement into account also.

It should be kept in mind that the added resistance for
locity prediction in waves has been made for both yachts, in the smallest pitching period. By using the data in Table 5 a considered hull forms: the light-displacement yacht has the added resistance in the close-hauled condition (true wind angle 40 deg) occurs at a wave period $T_1 = 2.5 - 3 \text{s}$ for Model 455 and at $T_1 = 2 - 2.5 \text{s}$ for Model 407. This corresponds to the difference in the natural pitch periods of the two considered hull forms: the light-displacement yacht has the smallest pitching period. By using the data in Table 5 a velocity prediction in waves has been made for both yachts, in particular for wind and wave direction < 90 deg.

In Table 6 the wave conditions as used in these calculations are summarized. In Table 7 the speed loss due to the added resistance in waves is given as a percentage of the calm-water speed for a true wind speed of 15 knots. The light-displacement yacht has a lower speed loss in waves than the medium-displacement yacht. It depends on the wave conditions and the wind speed if this compensates the lower speed-made-good when sailing to windward in calm water. For wave directions larger than 90 deg the calculation of motions and added resistance is less reliable. In general, the added resistance is small under these conditions and far less important compared with sailing to windward as regards speed reduction.

### Table 5 Added resistance ($N$): $F_n = 0.30 \, V_e = 6.83 \text{knots}$

<table>
<thead>
<tr>
<th>Period</th>
<th>Wave Direction: degrees off stern</th>
<th>Wave Direction: degrees off stern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>1.70</td>
<td>1.50</td>
</tr>
<tr>
<td>2.00</td>
<td>2.70</td>
<td>2.00</td>
</tr>
<tr>
<td>2.50</td>
<td>3.70</td>
<td>2.50</td>
</tr>
<tr>
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<td>4.70</td>
<td>3.00</td>
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<td>4.50</td>
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<td>4.50</td>
</tr>
<tr>
<td>5.00</td>
<td>8.70</td>
<td>5.00</td>
</tr>
</tbody>
</table>

### Table 6 Wave conditions

<table>
<thead>
<tr>
<th>$T_1$ (s)</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$ (m)</td>
<td>0.40</td>
<td>0.45</td>
<td>0.47</td>
<td>0.45</td>
<td>0.50</td>
<td>0.75</td>
<td>1.30</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### Table 7 Speed loss in waves, percent

<table>
<thead>
<tr>
<th>True Wind</th>
<th>Wave Period, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>6.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

### Conclusions

The calculation of motions and added resistance in waves compares satisfactorily with experimental results in the case of light-displacement yachts having high beam-draft ratios. For medium-displacement yachts with a small beam-draft ratio the correlation is somewhat less satisfactory. Calculated added resistance, based on a strip-theory method, can be used for a velocity prediction in waves. Such information may be useful for design purposes as well as for the determination of racing handicaps.
Acknowledgment

The authors are indebted to R. Onnink, who carried out the model experiments, and to J. M. J. Journée and A. Versluis for doing the computer calculations for the velocity prediction in calm water and in waves.

References


Metric Conversion Factors

1 m = 3.28 ft
1 m² = 35.31 ft²
1 kg/m³ = 0.062 lb/ft³