Theoretical and Experimental Investigation of Appendages and Heeling Angle Influence on the Hydrodynamic Resistance of a Sailing Yacht

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Abstract. The hydrodynamic resistance of a sailing yacht is strongly influenced by the large appendages and heeling angles. The paper presents a comparative analyze of the theoretical and experimental results related to the influence of the appendages and heeling angle on the hydrodynamic resistance of a yacht, of 14.23 m length. The theoretical approach was based on the method proposed by Larson and Eliasson. The residuary resistance was calculated using the empirical relations developed by Gerritsma, on the basis of Delft systematic yacht series. The components of the yacht resistance including the keel, rudder and additional weight influence were estimated by using a computer code performed in Java language, in the Research Centre of Naval Architecture Faculty. The experimental model tests have been carried out in the Towing Tank of the Naval Architecture Faculty of "Dunarea de Jos" University of Galati. A set of combinations of appendages and heeling angles of 5°, 10° and 15° has been considered. The comparative diagram between the theoretical and experimental results of the yacht resistance shows large differences. The important influence of the heeling angles and large appendages on the yacht hydrodynamic resistance was highlighted. As a consequence, the increasing of the accuracy level of the resistance prediction methods and the appendages resistance optimisation become very important objectives, during the initial design stages.

Keywords. Yacht, hydrodynamic resistance, theoretical prediction, experimental model test

1. Introduction

The hydrodynamic resistance of the yachts is an important problem of the initial design process and is strongly influenced by the own waves, extended appendages, drift angle and heeling angle ([1], [2]). A comparative analyze of the theoretical and experimental results was performed in this paper related to the hydrodynamic resistance of a yacht of 14.23 m length. The main characteristics of the sailing yacht are presented in Table 1: L_{max}, L_{WL}, L_{BP}, B_{max}, B_{WL}, D, T and LCB represent the length overall, length of waterline,

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length between perpendiculars, maximum breadth, breadth of waterline, depth, medium draught and longitudinal centre of buoyancy; Δ, A_{WL}, S_{Whull}, C_B and C_P are the ship's displacement, waterplane area, wetted surface of the hull, block coefficient and prismatic coefficient; also, v and F_n are the design speed and Froude number. The displacement, the wetted surface of the hull, the fineness coefficients and the longitudinal center of buoyancy refer to the bare hull. The medium draught and depth are measured from the base plan of the bare hull.

The appendages of the yacht are: the keel and the suspended rudder NACA 0012, having large aspect ratios and an additional weight with hydrodynamic profile. The geometric characteristics of the appendages are presented in Table 2. H_K and c_K are the span and the medium chord of the keel, H_R and c_R are the span and the medium chord of the rudder and L_{AW} and D_{AW} are the length and the maximum diameter of the additional weight.

Table 1. Main characteristics of the yacht

Characteristics	Full scale	Model scale
L_{max}	14.230 m	1.423 m
L_{WL}	12.780 m	1.278 m
L_{BP}	12.500 m	1.250 m
B_{max}	3.040 m	0.304 m
B_{WL}	2.612 m	0.261 m
D	1.440 m	0.144 m
T	0.570 m	0.057 m
LCB	5.591 m	0.559 m
Δ	8.600 t	8.600 kg
A_{WL}	22.600 m^2	0.226 m^2
S_{Whull}	26.500 m^2	0.265 m^2
C_B	0.409	0.409
C_P	0.545	0.545
v	9.220 Kn	1.500 m/s
F_n	0.424	0.424

Table 2. Main characteristics of the appendages

Characteristics	Full scale	Model scale (1/10)
H_K	2.800 m	0.280 m
c_K	1.200 m	0.120 m
H_R	1.630 m	0.163 m
c_R	0.530 m	0.053 m
L_{AW}	2.750 m	0.275 m
D_{AW}	0.660 m	0.066 m

The theoretical prediction of the yacht resistance was performed on the basis of Larson and Eliasson method [2]. The residuary resistance was determined by using the empirical relations developed by Gerritsma, on the basis of Delft systematic yacht series [1].

A computer code was developed in Java language, in the Research Center of the Naval Architecture Faculty of "Dunarea de Jos" University of Galati, in order to estimate the yacht resistance components, including the hydrodynamic influences of the additional weight, keel and rudder and of the heeling angle, respectively.

Experimental model tests have been performed in the Towing Tank of the Naval Architecture Faculty, equipped with an automated carriage having maximum speed of 4 m/s, manufactured by Cussons Technology, Great Britain. The main dimensions of the Towing Tank are 45 x 4 x 3 m.

The yacht resistance tests were performed following the ITTC recommendations [3], using the R35 resistance dynamometer, manufactured by Cussons Technology. The full scale results have been obtained according to the ITTC 1957 method [4]. Figure 1 shows the scaled model of the yacht (scale 1:10). No turbulence stimulator was used. The experimental tests have been carried out in order to investigate both influences of appendages and heeling angle. During the heeling angles tests, the sinkage and the trim of the model were blocked. The model trim was unrestricted only for the tests investigating the appendages influences.

Figure 1. The 1:10 model of the yacht

2. Theoretical model

The theoretical method, developed Larson and Eliasson, was used in order to estimate the sailing yacht resistance [2]. The total yacht resistance R_{Ts} is the sum of the following components

$$R_{Ts} = R_F + R_R + R_H + R_A \tag{1}$$

where, R_F is the frictional resistance of the hull with appendages, R_R is the residuary resistance, R_H is the heel resistance component and R_A is the aerodynamic resistance of the yacht.

The frictional resistance of the hull with appendages can be computed using the relation

$$R_F = R_{FH} + R_{FK} + R_{FR} + R_{FAW} \tag{2}$$

where, R_{FH} is the frictional resistance of the bare hull, R_{FK} is frictional resistance of the keel, R_{FR} is frictional component of the rudder and R_{FAW} is frictional resistance of the additional weight with hydrodynamic profile. The frictional resistance components can be calculated based on the following expressions

$$R_{FH} = \frac{1}{2} \cdot C_{FH} \cdot \rho \cdot v^2 \cdot S_{WH} \tag{3}$$

$$R_{FK} = \frac{1}{2} \cdot C_{FK} \cdot \rho \cdot v^2 \cdot S_{WK} \tag{4}$$

$$R_{FR} = \frac{1}{2} \cdot C_{FR} \cdot \rho \cdot v^2 \cdot S_{WR} \tag{5}$$

$$R_{FAW} = \frac{1}{2} \cdot C_{FAW} \cdot \rho \cdot v^2 \cdot S_{WAW} \tag{6}$$

where, C_{FH}, C_{FK}, C_{FR}, C_{FAW} are the frictional resistance coefficients and S_{WH}, S_{WK}, S_{WR}, S_{WAW} are the wetted surfaces of the corresponding components; ρ represents the water density. In order to estimate the frictional resistance coefficients, the ITTC'57 formula was used, having the general form

$$C_F = \frac{0.075}{(\log R_n - 2)^2} \tag{7}$$

where, Reynolds number R_n is calculated using the relation

$$R_n = \frac{vL}{\nu} \tag{8}$$

The kinematic viscosity of the fluid was noted with ν. For the case of the bare hull, L is an equivalent length given by the relation

$$L = 0.7 \cdot L_{WL} \tag{9}$$

For the keel and rudder, L represents the medium chords of the corresponding hydrodynamics NACA profiles and for the additional weight L is the total length.

The residuary resistance R_R of the yacht was estimated using the expressions proposed by Gerritsma, which were developed based on Delft systematic yachts series

([1], [2]). The heel resistance component R_H depends on the heeling angle ϕ of the sailing yacht and can be calculated using the relation [2]

$$R_H = 0.5 \cdot C_H \cdot \rho \cdot v^2 \cdot S_{WH} \cdot F_n^2 \cdot \phi \tag{10}$$

where, C_H is the heel coefficient given by the empirical relation of Larsen and Eliasson, depending by the breadth, the draught of the bare hull and the total draught with appendages [2]. The aerodynamic resistance R_A is calculated by summing the bare hull R_{AH}, mast R_{AM} and rig R_{AR} components [2]

$$R_A = R_{AH} + R_{AM} + R_{AR} \tag{11}$$

A new computer code was performed on the basis of this method in Java language, in the Research Centre of the Naval Architecture Faculty, to evaluate the total sailing yacht resistance and the specific components.

3. Estimation of the yacht resistance

The total yacht resistance R_{Ts} was calculated without the influence of the aerodynamic resistance components of the mast R_{AM} and rigs R_{AR}, by using the following expression

$$R_{Ts} = R_F + R_R + R_H + R_{AH} \tag{12}$$

The diagram of the total yacht resistance R_{Ts} is presented in Figure 2, for zero heeling angles and zero wind speed, depending on the ship speed. The following components of the yacht resistance are also shown: frictional resistance of the hull with appendages R_F, residuary resistance R_R and aerodynamic resistance of the bare hull R_{AH}. The most important component of the total yacht resistance is the residuary resistance, when the yacht speed is greater than 8 knots.

Figure 3 shows the components of the frictional resistance of the hull with appendages R_F, as a function of the ship speed. The most important components are the frictional resistance of the bare hull R_{FH} and the frictional resistance of the keel R_{FK}. The frictional resistance of the additional weight R_{FAW} and of the rudder R_{FR} have small values. The total contribution of the large appendages is situated between 9.1 – 24.5 % from the total yacht resistance, depending on ship speed.

Figure 4 shows the heel resistance component of the yacht R_H, for heeling angles of 5º, 10º and 15º. It can be observed the increase of the heel resistance component with heeling angle and speed increasing. The contribution of the heel resistance component is situated between 1.9 – 9.5 % from the total yacht resistance.

4. Model tests results

Resistance tests were performed for the yacht model with zero initial trim, in order to evaluate the appendages influence and heeling angle effect. Firstly, the calibration of R35 resistance dynamometer and trim transducer was performed. During the experimental test program the model sinkage was blocked due to the hydrostatic buoyancy force of the model which was less than the weight of the measurement system.

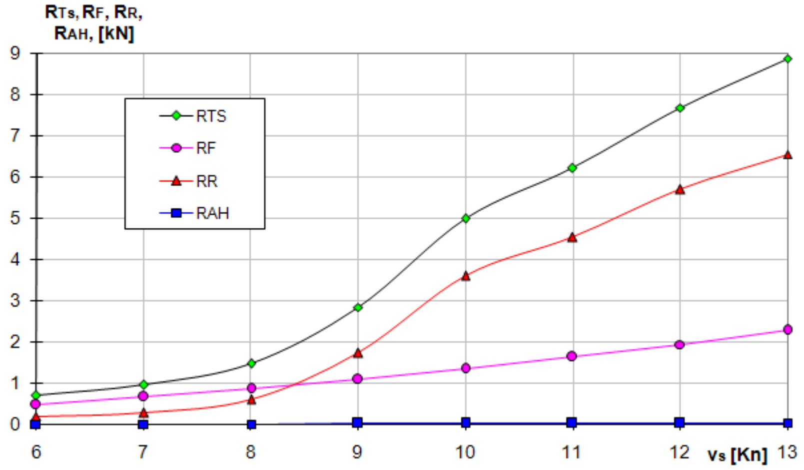

Figure 2. Total yacht resistance and its components

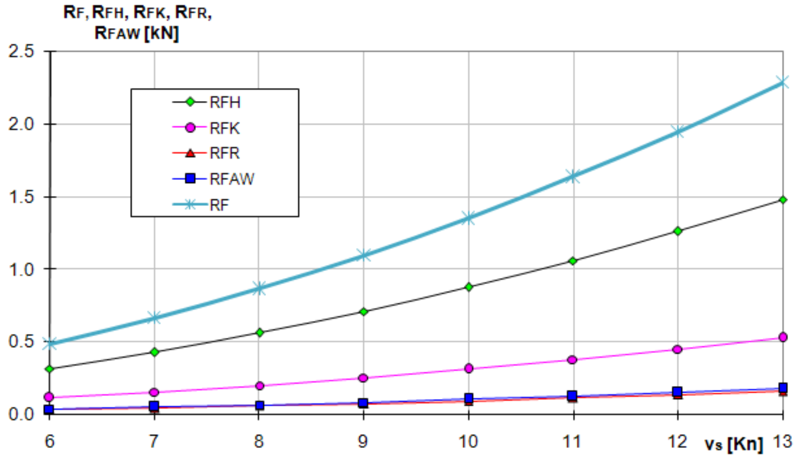

Figure 3. Frictional resistance of the hull with appendages and its components

During the tests related to the evaluation of appendages influence on the model resistance the trim of the model was free. In order to investigate the heeling angle influence on the model resistance, the constant displacement hypothesis was considered and the trim model was blocked. Consequently, a steady force component of the yacht resistance was determined. The speed range was situated between 1 m/s and 2 m/s, with an increment of 0.25 m/s. Full scale extrapolation of the model tests results was performed using ITTC 1957 ship-model correlation line, without blockage corrections. During the experimental tests, the wave pattern was recorded and visually analyzed.

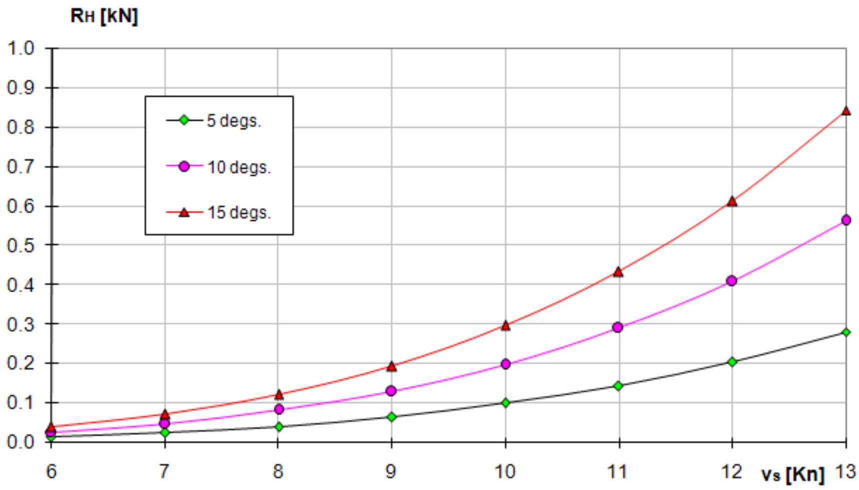

Figure 4. Heel resistance component of the yacht

Figure 5 shows the hydrodynamic flow around the model equipped with all appendages, for zero heeling angle and speed of 1.5 m/s, when the sinkage and trim were blocked. The own waves amplitudes increase with the model speed, on the bow part of the model. Two oblique wave crests appear on the aft part, due to the transom stern. A wave through with high amplitude can be observed in the aft part of the model.

Figure 5. Hydrodynamic flow, ϕ =0°, v=1.5 m/s (full scale 9.22 Kn)

Figure 6 shows the model resistance R_{Tm} as a function of the model speed v_m, with appendages influence. The most important component is represented by the keel and the additional weight. It was confirmed that the superposition principle is not valid as far as the resistance is much higher compared to the sum of each individual contribution of the hull, keel with additional weight and rudder.

The model tests results with and without appendages were extrapolated to the full-scale using the ITTC 1957 ship-model correlation line, without blockage corrections ([3], [4]). The coefficient β=0.7 was considered for the extrapolation of the appendages resistance. The yacht resistance diagram is presented in Figure 7. R_{Ts} is the total resistance of the yacht, without must and rig aerodynamics components. The heel resistance component was not considered in this stage.

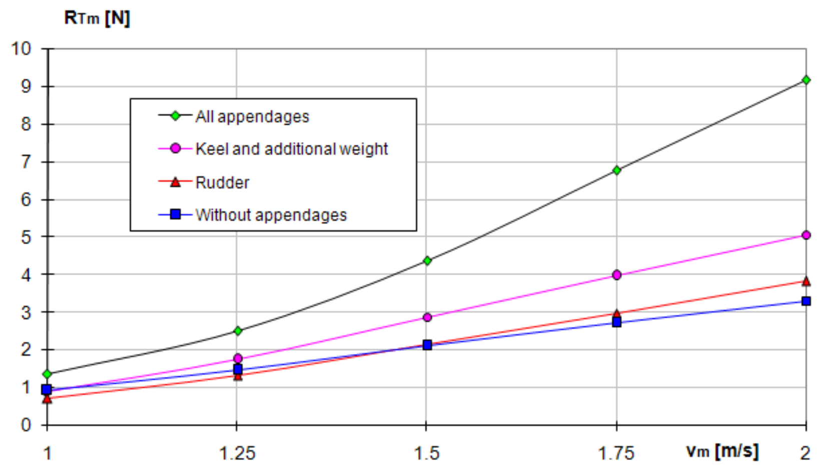

Figure 6. Appendages influence on the model resistance

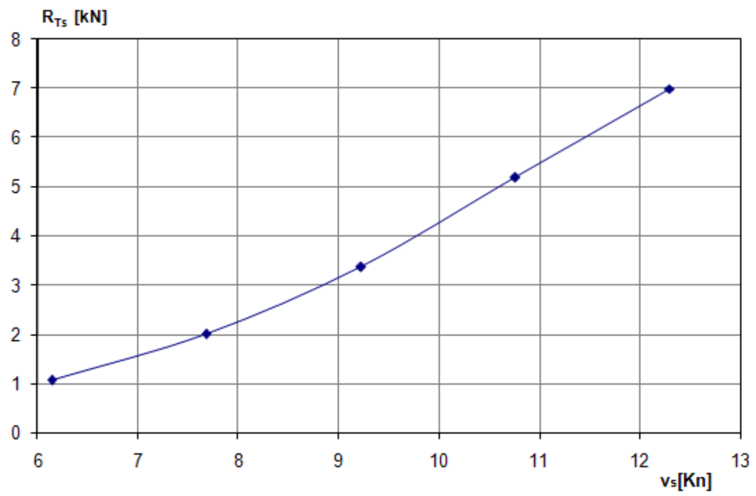

Figure 7. Full scale total yacht resistance (extrapolated)

Figure 8 presents the model resistance as a function of the model speed considering heeling angle influence. It can be observed that the model resistance increases with heeling angle values. A significant increasing at about 9% was noted at maximum speed and ϕ =15º.

Figure 9 describes the hydrodynamic flow around the model with all appendages, corresponding to the case of a heeling angle of 15° and speed of 1.5 m/s. The sinkage and trim were blocked. An asymmetrical flow can be observed, displaying high own wave amplitudes and a pronounced wake, when the speed of the model is greater than 1.5 m/s.

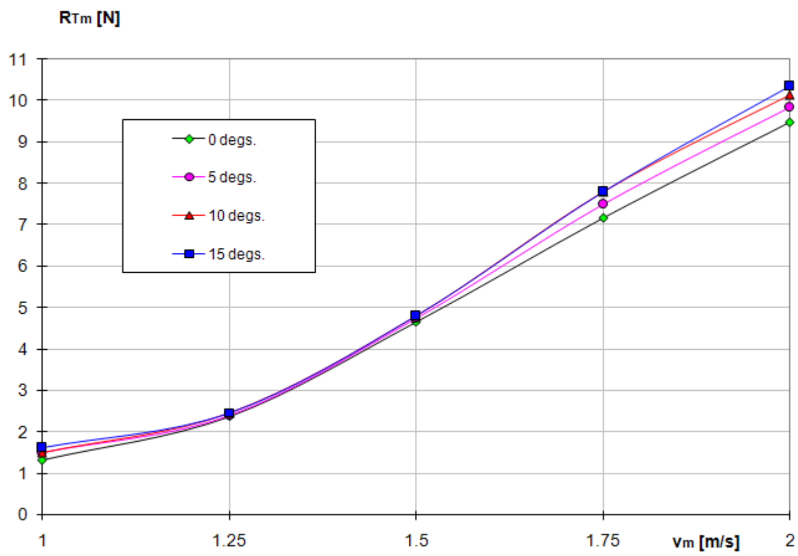

Figure 8. Heeling angle influence on the model resistance

Figure 9. Hydrodynamic flow, ϕ =15°, v=1.5 m/s (full scale 9.22 Kn)

5. Conclusions

The yacht resistance is strongly influenced by the large appendages and heeling angles. The paper is highlighting these significant influences, based on theoretical calculations and systematic model tests.

The theoretical method proposed by Larson and Eliasson was used in order to develop a new computer code in Java language and to estimate the resistance components, including the keel, rudder and additional weight influence and the heeling angle effect too. The experimental model tests have been performed in order to investigate the appendages and heeling angles influences.

A comparative theoretical-experimental yacht resistance diagram is presented in Figure 10. Very important differences can be noticed within the speeds domain. The experimental values are greater than the theoretical results for the range speeds under 9 knots and become smaller for higher speeds.

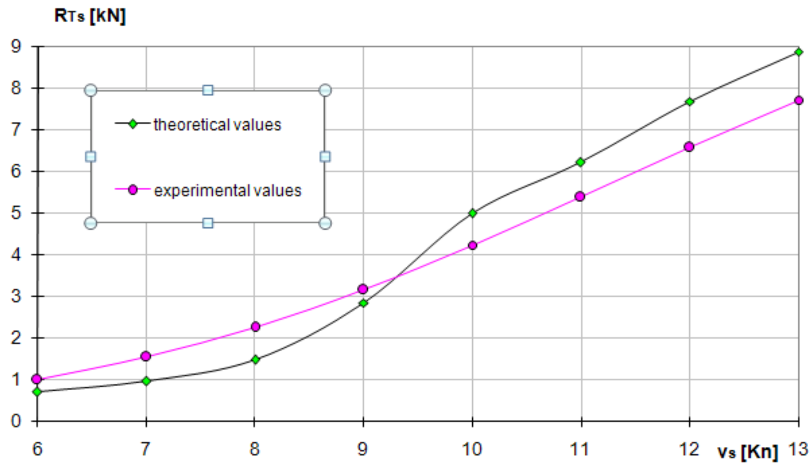

Figure 10. Theoretical and experimental total yacht resistance

The influence of the large appendages on the hydrodynamic resistance of the yacht is important and has to be taken into account. The most significant component is the frictional resistance of the keel with additional weight. The optimisation of the appendages resistance becomes a very important issue during the initial design stages. The heel resistance component of the yacht must be also considered.

In order to increase the level of accuracy of the yacht hydrodynamic resistance, the theoretical methods, which are going to be used during the early design stage, must be improved.

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