

Theoretical and experimental comparative analyse on the hydrodynamic resistance of a racing sailboat

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Abstract. The large appendages have a very important influence on the hydrodynamic resistance of the sailboats. In this paper, a comparative analyse of the theoretical and experimental results was performed, related to the hydrodynamic resistance of a racing sailboat having an overall length of 12.8 m. The theoretical approach was performed based on the method proposed by Larson and Eliasson. In order to compute the residuary resistance it was used the formulations based on Delft systematic yacht series. The estimation of the resistance components, including the keel, rudder and additional weight influence was carried out based on a computer code in Java language. The experimental model tests have been carried out in the Towing Tank of the Naval Architecture Faculty of "Dunărea de Jos" University of Galati. A 1/10 scaled model with appendages was used for experimental investigations. The level of accuracy of the theoretical prediction was evaluated based on comparative theoretical/experimental diagrams. It was found that the influence of the large appendages is very important and an optimisation procedure becomes mandatory. Moreover, the theoretical methods specific to the preliminary design stage must be improved in order to increase the level of accuracy of hydrodynamic resistance predictions.

1. Introduction

The initial design process of a modern sailboat requires a complex iterative and convergent procedure in order to develop the optimum body lines, based on the multi-criterial optimization principle. Usually, powering performances are the most important hydrodynamic characteristics. For a given ship speed, the body lines plan must be designed in order to obtain both the minimum ship resistance and break power on board, respectively [4].

In order to increase ship's resistance performance, both theoretical and experimental approaches can be performed. The first step is to predict ship's resistance using appropriate theoretical methods. The optimum ship dimensions can be obtained by using the ship resistance as an important criterion. A second step can be based on CFD computation and the numerical models can lead to the optimization of the body lines using the same criterion. However, due to the complex hydrodynamic phenomena generated by the flow around the hull, the theoretical and numerical ship resistance results must be validated. Consequently, experimental model tests have to be performed as a last step of the whole process.

To this purpose, a comparative analysis of the theoretical and experimental results of the hydrodynamic resistance of a racing sailboat of 12.8 m overall length was performed. The main characteristics of the sailboat are presented in table 1: L_{max} , L_{WL} , B_{max} , B_{WL} , D , T and LCB are the length overall, waterline length, breadth overall, waterline breadth, depth, draught and longitudinal centre of



buoyancy; Δ , A_{WL} , S_{Whull} , C_B and C_P are ship's displacement, water plane area, wetted surface of the hull, block coefficient and prismatic coefficient; v and F_n are the design speed and Froude number respectively. The displacement, wetted surface of the hull, fineness coefficients and longitudinal centre of buoyancy refer to the bare hull. It has to be noted that the draught and depth are measured from the base plan of bare hull.

The racing sailboat also has the following extended appendages: a keel and a suspended rudder having NACA 0012 hydrodynamic profiles with large aspect ratios and an additional weight. 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; L_{AW} and D_{AW} are the length and the maximum diameter of the additional weight which also have a hydrodynamic profile.

Table 1. Main characteristics of the sailboat.

	Full scale	Model scale
L_{max}	12.800 m	1.280 m
L_{WL}	12.060 m	1.206 m
B_{max}	2.590 m	0.259 m
B_{WL}	2.390 m	0.239 m
D	1.160 m	0.116 m
T	0.500 m	0.050 m
LCB	6.450 m	0.645 m
Δ	6.200 t	6.200 kg
A_{WL}	20.100 m ²	0.201 m ²
S_{Whull}	27.200 m ²	0.272 m ²
C_B	0.395	0.395
C_P	0.567	0.567
v	9.200 Kn	1.500 m/s
F_n	0.436	0.436

Table 2. Main characteristics of the appendages.

	Full scale	Model scale (1/10)
H_K	3.250 m	0.325 m
c_K	0.970 m	0.097 m
H_R	1.760 m	0.176 m
c_R	0.500 m	0.050 m
L_{AW}	3.000 m	0.300 m
D_{AW}	0.800 m	0.080 m

The large sailboat appendages have an important influence on the total ship resistance. The optimization of the appendages resistance component represents a very interesting subject for a sailboat during the initial design stage.

The theoretical estimation of the sailboat resistance was performed on the basis of the method proposed by Larson and Eliasson [4]. The residuary resistance was calculated using the empirical relations based on Delft systematic yacht series [3].

In order to estimate the sailboat resistance components, including the additional weight, keel and rudder influence and of the heeling angle, a computer code was developed, in Java language, in the Research Centre of the Naval Architecture Faculty of “Dunărea de Jos” University of Galati.

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

The sailboat resistance tests were performed following the specific ITTC recommendations [2], using a R35 resistance dynamometer, manufactured by Cussons Technology. The full scale extrapolated results have been obtained on the basis of ITTC 1957 method [1].

The sailboat model manufactured on 1/10 scale is presented in figure 1. During the experimental tests the sinkage of the model has been blocked. Only the model trim was unrestricted. No turbulence device was used.

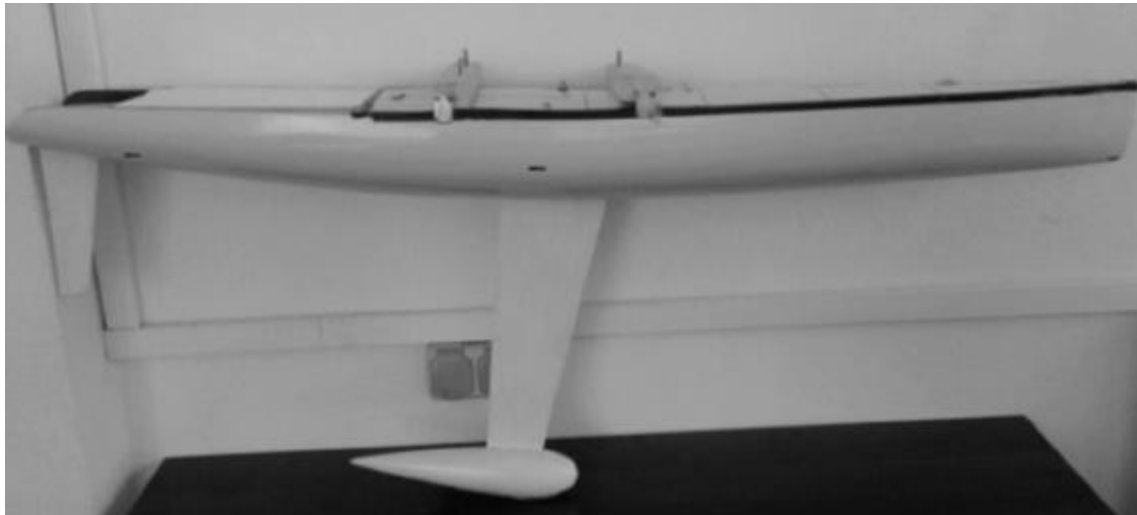


Figure 1. The sailboat model.

2. Mathematical model

In this chapter, is presented shortly the theoretical method, developed by Larson and Eliasson, which has been used to estimate the sailboat resistance.

The total sailboat resistance R_{Ts} is the sum of the following components [4]

$$R_{Ts} = R_F + R_R + R_H + R_A \quad (1)$$

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 sailboat.

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

$$R_F = R_{FH} + R_{FK} + R_{FR} + R_{FAW} \quad (2)$$

where, R_{FH} is the frictional resistance of the bare hull, R_{FK} is the frictional resistance of the keel, R_{FR} is the frictional component of the rudder and R_{FAW} is the frictional resistance of the additional weight. The frictional resistance components can be estimated by using the following expressions

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

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

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

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

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 is the water density.

In order to estimate the frictional resistance coefficients, the ITTC'57 ship model's correlation line can be used, given by the general form

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

The Reynolds number R_n is calculated using the following expression

$$R_n = \frac{vL}{\nu} \quad (8)$$

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

$$L = 0.7 \cdot L_{WL} \quad (9)$$

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

In order to compute the sailboat residuary resistance R_R , the expressions proposed by Gerritsma [4] on the basis of Delft systematic yachts series [3] were used. For the racing sailboat in focus, all the restrictions of the Delft yacht series are fulfilled. As a consequence, the typical relation and specific regression coefficients corresponding to a speed range of $F_n = 0.291 \div 0.581$, were applied.

The heel resistance component, R_H , depends on the sailboat heeling angle ϕ and can be calculated using the following expression [4]

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

where, C_H is the heel coefficient, given by the empirical relation of Larsen and Eliasson, depending on the waterline breadth and the draught [4]. In this paper, the study of the heel resistance component was not considered.

The aerodynamic resistance of the sailboat R_A is computed by summing the components due to the bare hull, R_{AH} , mast, R_{AM} and rig R_{AR} , [4]

$$R_A = R_{AH} + R_{AM} + R_{AR} \quad (11)$$

$$R_{AH} = 0.5 \cdot C_{AH} \cdot \rho_a \cdot v_a^2 \cdot B_{\max} \cdot F_F \quad (12)$$

$$R_{AM} = 0.5 \cdot C_{AM} \cdot \rho_a \cdot v_a^2 \cdot L_M \cdot t_M \quad (13)$$

$$R_{AR} = 0.5 \cdot C_{AR} \cdot \rho_a \cdot v_a^2 \cdot L_R \cdot t_R \quad (14)$$

where, C_{AH} , C_{AM} , C_{AR} are the specific aerodynamic resistance coefficients of the bare hull, mast and rig; v_a is the apparent wind speed and ρ_a is the air density; F_F is the forward freeboard; L_M , L_R are the lengths of the mast and the rig; t_M , t_R are the average thicknesses of the mast and rig. In this paper, only the aerodynamic resistance component of the bare hull was considered.

The computer code PHP Yacht Resistance was performed in Java language, on the basis of this method, to evaluate the total racing sailboat resistance and the specific components.

3. Theoretical estimation of the sailboat resistance

In order to perform the comparison between theoretical and experimental results, the total sailboat resistance R_{Ts} was calculated without the influence of the heel resistance component, R_H , and aerodynamic resistance components of the mast, R_{AM} and rig, R_{AR} , using the following relation

$$R_{Ts} = R_F + R_R + R_{AH} \quad (15)$$

Figure 2 depicts the total sailboat resistance R_{Ts} depending on the ship speed. The following components: frictional resistance of the hull with appendages, R_F , residuary resistance, R_R and aerodynamic resistance of the bare hull R_{AH} are also graphically presented. A zero wind speed was considered. The most important component of the total sailboat resistance is the residuary resistance.

The components of the frictional resistance of the hull with appendages, R_F , are presented in figure 3, depending on 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 minimum values.

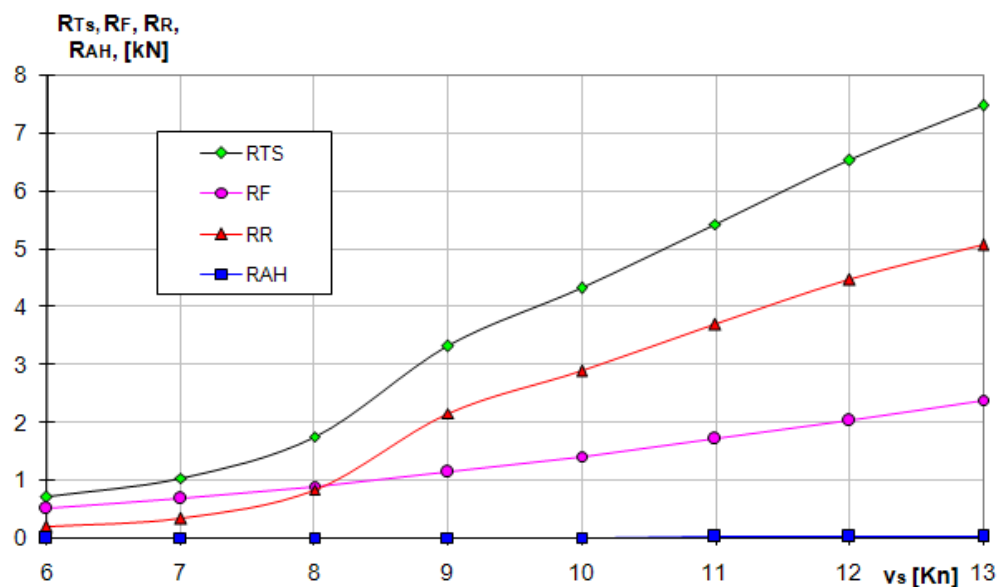


Figure 2. The total sailboat resistance and its components.

4. Model tests results

Experimental tests were performed for the case of the model without initial trim, in the following sequence: calibration of the resistance dynamometer and trim transducer; measurements of model resistance and trim angle during the tests; full scale extrapolation of the model tests results, using ITTC 1957 ship-model correlation line, without blockage corrections.

The speed range was situated between 1 m/s and 2 m/s, with a step of 0.25 m/s. The sinkage of the model was blocked but the trim was free. During the experimental tests the wave pattern was recorded and visually analysed. The experimental set up is presented in figure 4. For the above mentioned range of speeds the hydrodynamic flow spectrum around the model are presented in figure 5 to photo 9.

Regarding the flow around the model, the following observations can be made:

- Within the low range of speeds, $1 \div 1.25$ m/s, the own wave amplitude on the forward part increases with speed; two relative moderate oblique wave crests appear on the aft part, due to the transom stern;

- When the design speed is considered, $v = 1.5$ m/s, the aft immersion of the model can be observed, the forward part being out of the water; the turbulence of the wake increases;
- In the higher speed domain $1.75 \div 2$ m/s, a pronounced trim angle combined with a large turbulent energy at the aft part of the ship can be observed.

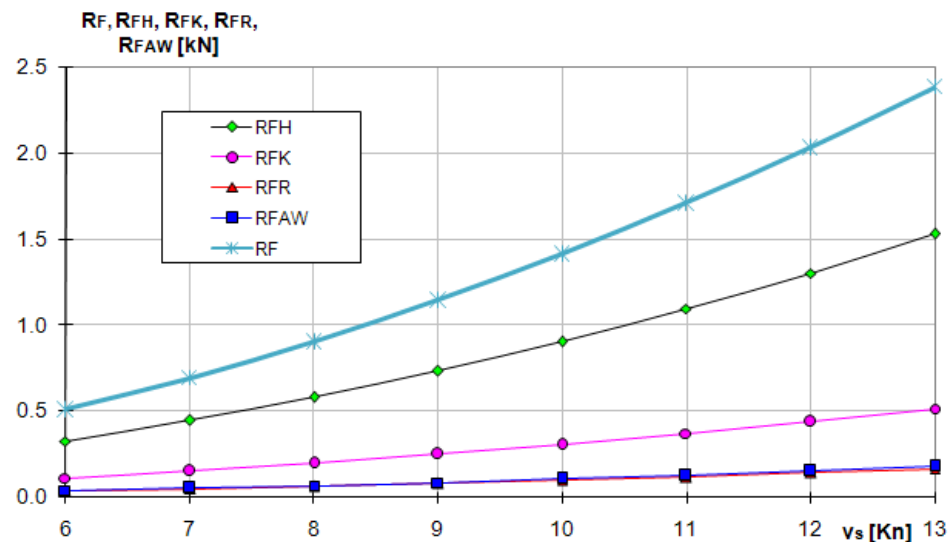


Figure 3. The frictional resistance of the hull with appendages and its components.

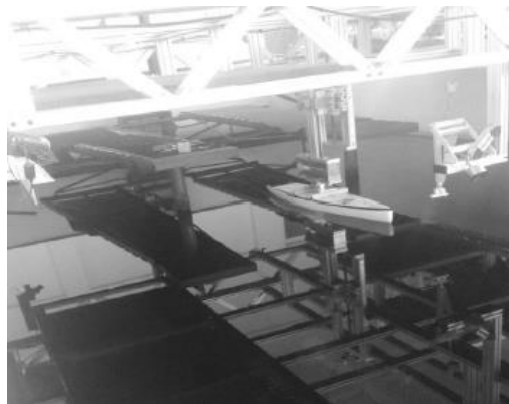


Figure 4. Experimental arrangement.



Figure 5. Hydrodynamic flow spectra, $v=1$ m/s (full scale 6.2 Kn).

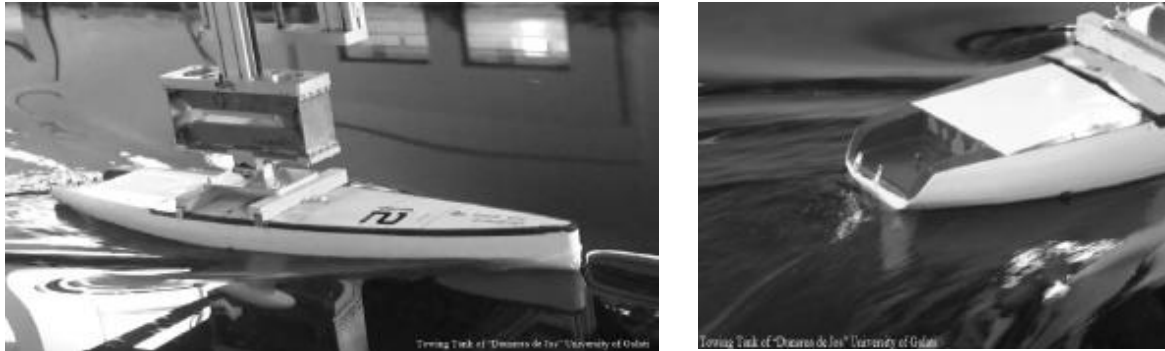


Figure 6. Hydrodynamic flow spectra, $v=1.25$ m/s (full scale 7.7 Kn).

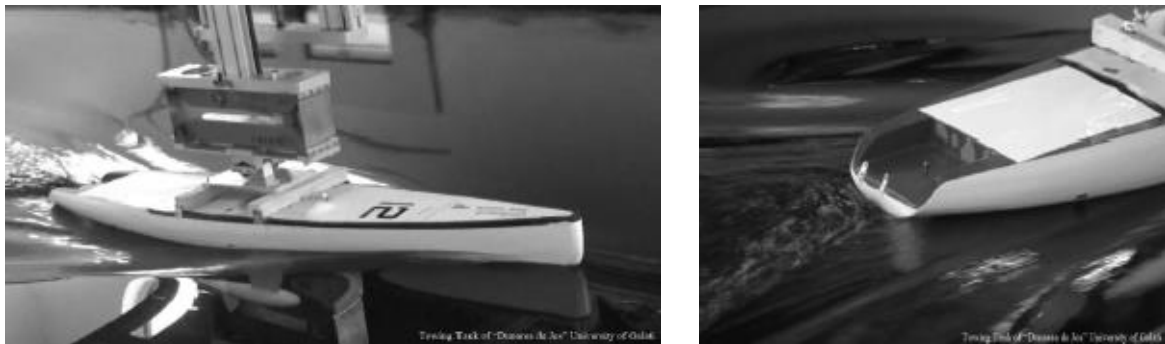


Figure 7. Hydrodynamic flow spectra, $v=1.5$ m/s (full scale 9.2 Kn).

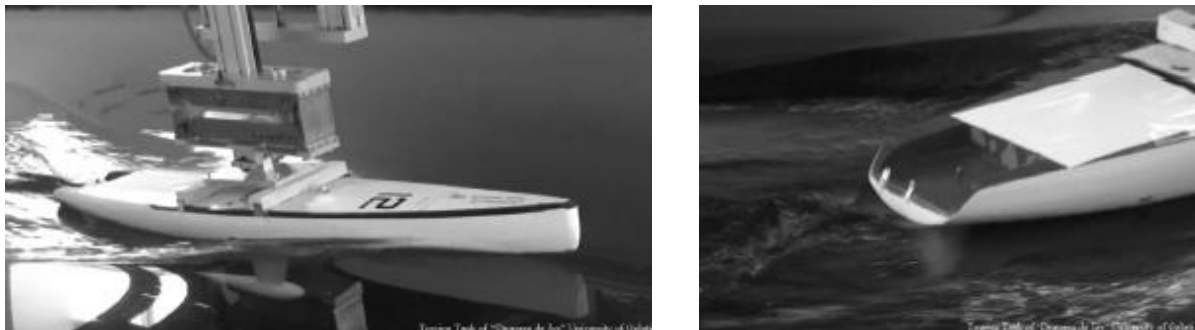


Figure 8. Hydrodynamic flow spectra, $v=1.75$ m/s (full scale 10.8 Kn).

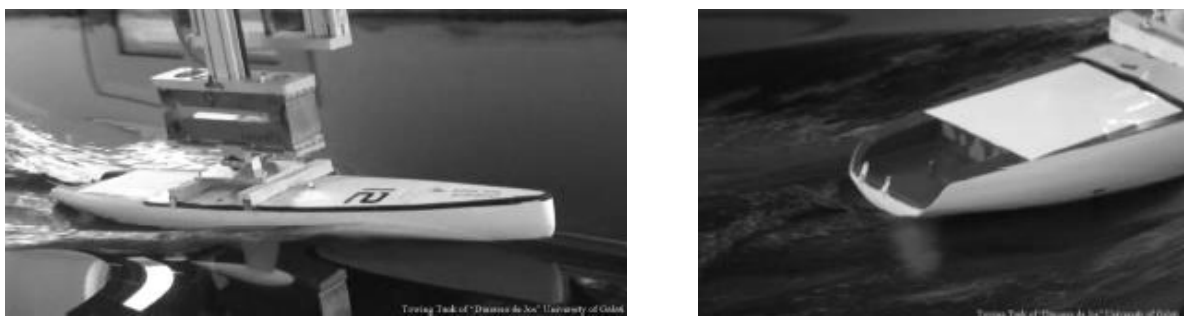


Figure 9. Hydrodynamic flow spectra, $v=2$ m/s (full scale 12.3 Kn).

Table 3 presents the experimental results of the model resistance tests. The following notations were used: v_s and v_m are the ship speed and model speed; R_{Tm} and θ_m are the total resistance of the

experimental model and model trim (+ aft trim). A significant trim angle increasing depending by the model speed was measured.

Table 3. Experimental results of the model resistance tests.

v_s [Kn]	v_m [m/s]	F_n [-]	R_{Tm} [N]	θ_m [deg.]
6.2	1	0.291	1.187	0.
7.7	1.25	0.363	2.081	0.28
9.2	1.5	0.436	4.007	1.31
10.8	1.75	0.509	5.925	2.71
12.3	2	0.581	8.067	3.22

Figure 10 presents the model resistance results as a function of the speed of the speed of the model. A linear dependence of the model resistance can be noticed in the tested range of speeds.

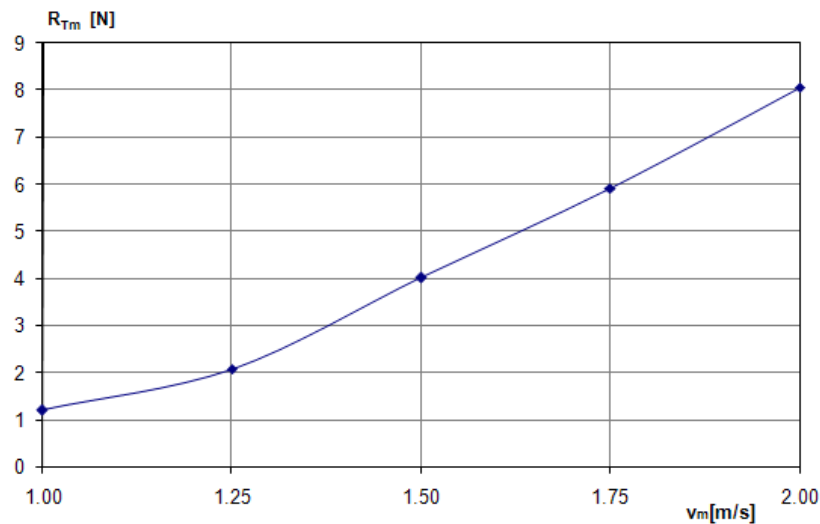


Figure 10. Model resistance diagram.

The model tests results were extrapolated to full scale using the ITTC 1957 ship-model correlation line, without blockage corrections ([1], [2]). The ITTC 1957 formula was used in order to determine the frictional resistance coefficient.

The full scale extrapolated results are given in the table 4 and the ship resistance diagram is presented in the figure 11. R_{Ts} is the total resistance of the racing sailboat, without must and rig aerodynamics components. The heel resistance component was not considered too.

Table 4. Sailboat resistance extrapolated results.

v_s [Kn]	F_n [-]	R_{Ts} [kN]
6.2	0.291	0.972
7.7	0.363	1.799
9.2	0.436	3.619
10.8	0.509	5.473
12.3	0.581	7.482

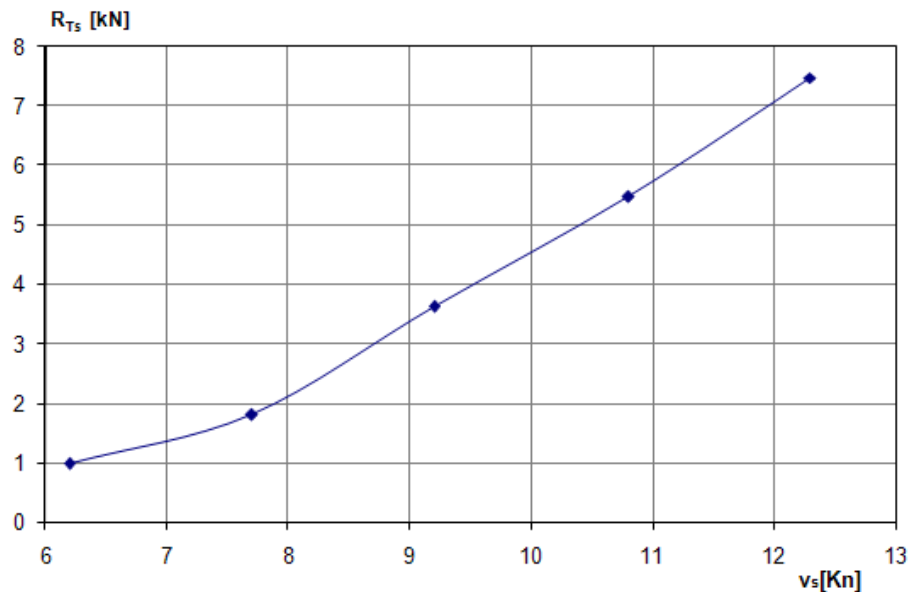


Figure 11. Diagram of the extrapolated sailboat resistance.

A comparative theoretical/experimental diagram is depicted in figure 12, in order to determine the level of accuracy of the theoretical prediction of the total sailboat resistance.

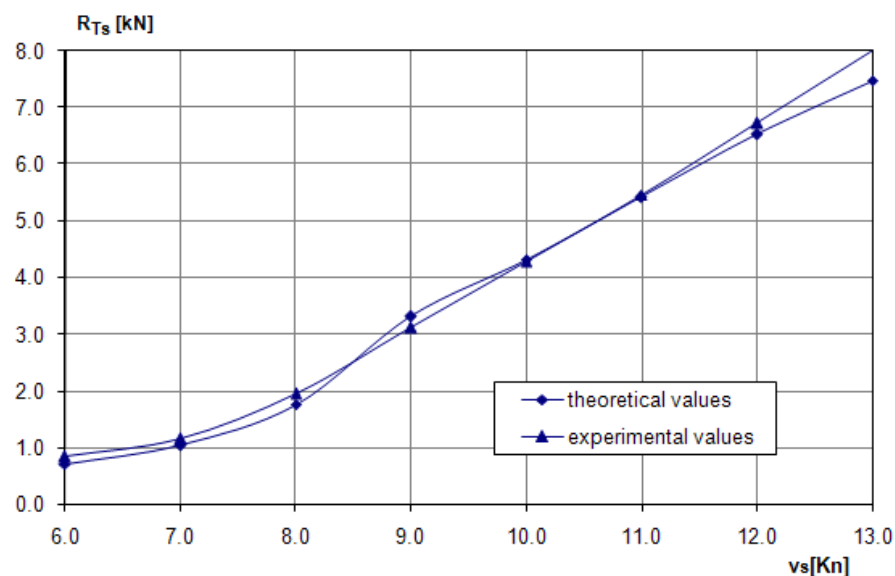


Figure 12. The total resistance of the sailboat.

In table 5 are presented the differences (in percentages) between the theoretical and experimental results. A relative satisfactory agreement can be noticed. The medium percentage difference over the speed domain is about - 4.7 %.

The hydrodynamic resistance of the sailboat is significantly influenced by its large appendages. In table 6 are presented the contributions of the appendages, in percentages, related to the total sailboat resistance. The most important component is the frictional resistance of the keel. Depending on the ship speed, the total contribution of the large appendages is situated between 11.1 ÷ 25.8 % of the total resistance.

Table 5. Total sailboat resistance results. Percentages differences.

v_s [Kn]	R_{Ts} [kN] Theory	R_{Ts} [kN] Exp.	Percentages differences %
6	0.706	0.838	-15.8
7	1.038	1.147	-9.5
8	1.757	1.938	-9.3
9	3.313	3.113	6.4
10	4.324	4.282	1.0
11	5.427	5.457	-0.5
12	6.533	6.736	-3.0
13	7.482	8.026	-6.8

Table 6. Percentage contribution of the appendages related to the total sailboat resistance.

v_s [Kn]	R_{FK} %	R_{FR} %	R_{FAW} %	$R_{FK}+R_{FR}+R_{FAW}$ %
6	15.6	5.0	5.2	25.8
7	14.4	4.5	4.9	23.8
8	11.1	3.5	3.8	18.4
9	7.5	2.4	2.5	12.4
10	7.1	2.2	2.4	11.7
11	6.8	2.2	2.3	11.3
12	6.7	2.1	2.3	11.1
13	6.9	2.2	2.4	11.5

5. Conclusions

A comparative analyse of the theoretical and experimental results was performed in this paper, related to the hydrodynamic resistance of a racing sailboat having a 12.8 m length overall. The theoretical approach was developed on the basis of the method proposed by Larson and Eliasson. A computer code was generated in Java language to estimate the sailboat resistance components, including the keel, rudder and additional weight influences. Experimental model tests have been carried out in the Towing Tank of the Naval Architecture Faculty of “Dunărea de Jos” University of Galati. The model with appendages was manufactured on a scale of 1/10.

It can be concluded that the theoretical methods, specific to the preliminary design stage, must be improved in order to increase the level of accuracy related to the evaluation of the hydrodynamic resistance of the racing sailboat.

Also, it has to be underlined the significant influence of the large appendages. Consequently, the optimisation of the appendages resistance becomes mandatory during the preliminary design stages.

6. References

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