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PRELIMINARY COMPUTATION OF YACHT RESISTANCE COMPONENTS USING DELFT SERIES

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ABSTRACT

The evaluation of the yacht resistance components in the initial design stage raises an important problem. The present paper deals with the results obtained on the basis of an in-house computer code. The residuary resistance was determined by means of empirical relations developed from the Delft series, both in the low speed and high speed range. Also, the frictional resistance, heel resistance and aerodynamic resistance components were estimated with typical relations provided in the scientific references. The computer code may be used to perform the resistance and powering estimation in the initial yacht design.

Keywords: yacht resistance components, Delft series, computer code.

1. INTRODUCTION

The speed-power prediction with a good level of accuracy in the initial design stage of yachts is an important objective. Therefore, the estimation of the resistance components must be performed with an accurate level of confidence and typical computer software must be devised for intensive practical evaluations.

According to reference [1], the yacht resistance components are: frictional resistance, residuary resistance, heel resistance and aerodynamic resistance. A summary of the mathematical model used in order to compute the yacht resistance components is shown in the following chapter.

The practical evaluation of the residuary resistance was made by means of the empirical relations developed from the Delft series, both within the displacement domain (in the low speed range, with the Froude number F_n between 0.125 … 0.45) and for semi-planning (F_n between 0.475 … 0.75). The Delft series [2] were generated by Gerritsma and his fellow researchers in the 1970s, and contain a number of 22 models ranging from medium to heavy displacement. An extension of the Delft series by 17 models to lighter displacement was developed by van de Stadt and Partners in the 1980s [1].

The main restrictions of all the models from the Delft series are shown in Table 1, where L_{WL} is the length of the waterline, B_{WL} is the beam of the waterline, T_C is the draught of the hull without keel, ∇_C is the volumetric displacement without keel, LCB is determined in % from L_{WL} (+ for LCB situated forward of the midship section) and C_{P_C} is the prismatic coefficient of the hull without keel.

Table 1. Range of parametres

L_{WL}/B_{WL}	2.76 … 5
B_{WL}/T_C	2.46 … 19.32
$L_{WL}/\nabla_C^{1/3}$	4.34 … 8.5
LCB	-6.0 … 0
C_{P_C}	0.52 … 0.6

2. MATHEMATICAL MODEL

The total yacht resistance has four components: the frictional resistance R_F, the residuary resistance R_R, the heel resistance R_H and the aerodynamic resistance R_A. In this chapter, each component is calculated and the formulas are discussed.

The *frictional resistance* of the yacht R_F has three components: the frictional resistance of the hull, keel and rudder

$$R_F = R_{Fhull} + R_{Fkeel} + R_{Frudder} \quad (1)$$

The first component may be estimated by the relation

$$R_{Fhull} = 0.5 \cdot C_{Fhull} \cdot \rho \cdot v^2 \cdot S_{Whull} \quad (2)$$

where C_{Fhull} is the coefficient of the frictional resistance of the hull, S_{Whull} is the wetted surface of the hull in upright position, v is the yacht speed and ρ is the water density.

The second component may be determined by the expression

$$R_{Fkeell} = 0.5 \cdot C_{Fkeel} \cdot \rho \cdot v^2 \cdot S_{Wkeel} \quad (3)$$

where C_{Fkeel} is the coefficient of the frictional resistance of the keel and S_{Wkeel} is the wetted surface of the keel.

The frictional resistance of the rudder may be estimated by the following relation

$$R_{Frudder} = 0.5 \cdot C_{Frudder} \cdot \rho \cdot v^2 \cdot S_{Wrudder} \quad (4)$$

where $C_{Frudder}$ is the coefficient of the frictional resistance of the rudder and $S_{Wrudder}$ is the wetted surface of the rudder.

All the frictional resistance coefficients may be determined by means of the ITTC'57 ship model correlation line, depending on the Reynolds number R_n of the hull, keel and rudder

$$C_F = \frac{0.075}{(\log R_n - 2)^2} \quad (5)$$

$$R_n = \frac{vL}{\nu} \quad (6)$$

where ν is the kinematic viscosity of the fluid.

The Reynolds number of the hull is defined by the hull length L equal to 70% of the water plane length.

For the Reynolds numbers of the keel and the rudder, L represents the mean chords of the keel and the rudder respectively.

The *residuary resistance* R_R within the low speed range (F_n=0.125 … 0.45) is determined by the expression [1]

$$\frac{R_R}{g \cdot m_c} \cdot 10^3 = a_0 + a_1 \cdot C_{Pc} + a_2 \cdot LCB + a_3 \cdot \frac{B_{WL}}{T_c} + a_4 \cdot \frac{L_{WL}}{\nabla_c^{1/3}} + a_5 \cdot (C_{Pc})^2 + a_6 \cdot C_{Pc} \cdot L_{WL} / \nabla_c^{1/3} + a_7 \cdot (LCB)^2 + a_8 \cdot \left(\frac{L_{WL}}{\nabla_c^{1/3}}\right)^2 + a_9 \cdot \left(\frac{L_{WL}}{\nabla_c^{1/3}}\right)^3 \quad (7)$$

which contains the regression coefficients a_0 ... a_9 and the following parameters: B_{WL}/T_C, $L_{WL} / \nabla_C^{1/3}$, LCB and C_{P_C}. g represents the gravity acceleration and m_c represents the displacement of the hull without keel.

The residuary resistance within the high speed domain (F_n=0.475 … 0.75) depends on the regression coefficients c_0 … c_5 and the parameters L_{WL}/B_{WL}, $LCB, A_{WL} / \nabla_C^{2/3}$, and may be determined by the relation [1]

$$\frac{R_R}{g \cdot m_c} \cdot 10^3 = c_0 + c_1 \cdot \frac{L_{WL}}{B_{WL}} + c_2 \cdot \frac{A_{WL}}{\nabla_c^{2/3}} + c_3 \cdot LCB + c_4 \cdot \left(\frac{L_{WL}}{B_{WL}}\right)^2 + c_5 \cdot \left(\frac{L_{WL}}{B_{WL}}\right) \cdot \left(\frac{A_{WL}}{\nabla_c^{2/3}}\right)^3 \quad (8)$$

The above mentioned regression coefficients are shown in tabular form [1].

The *heel resistance* component R_H is estimated on the basis of the Froude number, by means of the following relation [1]

$$R_H = 0.5 \cdot C_H \cdot \rho \cdot v^2 \cdot S_{Whull} \cdot F_n^2 \cdot \phi \quad (9)$$

where ϕ is the heeling angle of the yacht and C_H is the heel coefficient, determined by the formula

$$C_H = 10^{-3} \cdot \left(6.747 \cdot \frac{T_c}{T} + 2.517 \cdot \frac{B_{WL}}{T_c} + 3.71 \cdot \frac{B_{WL}}{T}\right) \quad (10)$$

where T is the draught of the yacht with keel.

The *aerodynamic resistance* of the yacht R_A has three components: the aerodynamic resistance of the hull, mast and rig.

The first component may be estimated by the relation [1]

$$R_{AH} = 0.5 \cdot C_{AH} \cdot \rho_a \cdot v_a^2 \cdot B_{\max} \cdot F_F \qquad (11)$$

where C_{AH} is the wind resistance coefficient of the hull, $B_{\max}$ is the overall beam, F_F is the forward freeboard, v_a is the apparent wind speed and ρ_a is the air density.

The second component may be determined by the expression

$$R_{AM} = 0.5 \cdot C_{AM} \cdot \rho_a \cdot v_a^2 \cdot L_M \cdot t_M \qquad (12)$$

where C_{AM} is the wind resistance coefficient of the mast, L_M is the mast length and t_M is the average mast thickness.

The aerodynamic resistance of the rig is computed by the addition of the aerodynamic resistance of the rig components (shrouds and stays). The aerodynamic resistance of a specific rig component may be estimated by means of the following general relation

$$R_{AR} = 0.5 \cdot C_{AR} \cdot \rho_a \cdot v_a^2 \cdot L_R \cdot t_R \qquad (13)$$

where C_{AR} is the wind resistance coefficient, L_R is the length and t_R is the average thickness of the rig component.

The total yacht resistance R_T is the sum of all the components mentioned above and may be determined by the following expression

$$R_T = R_F + R_R + R_H + R_A \qquad (14)$$

On the basis of this mathematical model, a computer code was devised in order to evaluate the total yacht resistance. The software can be used in the initial design stage.

3. PRACTICAL ASSESSMENT

A practical evaluation of the resistance performance of a racing sailboat is made in this chapter.

The main dimensions of the sailboat are shown in Table 2, where L_{OA} is the overall length and B_{max} is the maximum beam. The wetted surface areas are shown in Table 3, where S_{Wtotal} is the total wetted area of the sailboat. The main characteristics of the mast and rig are shown in Table 4. The wind speed was considered to be v_a =15 m/s, the heeling angle ϕ =13.6 degrees and the forward freeboard F_F=1.39 m.

Table 2. Main dimensions of the sailboat

L_{OA} [m]	L_{WL} [m]	B_{max} [m]	B_{WL} [m]	T [m]	T_c [m]
12.05	10.02	3.71	3.71	2.07	0.57

Table 3. Wetted surface areas

S_{Whull} [m^2]	S_{Wkeel} [m^2]	$S_{Wrudder}$ [m^2]	S_{Wtotal} [m^2]
25.2	4.4	1.3	30.9

Table 4. Mast and rig characteristics

t_M [m]	L_M [m]	t_R [m]	L_R [m]
0.139	16.9	0.010	24

The diagrams of the frictional resistance, residuary resistance, heel resistance, aerodynamic resistance and total sailboat resistance, are shown in Figures 1-5.

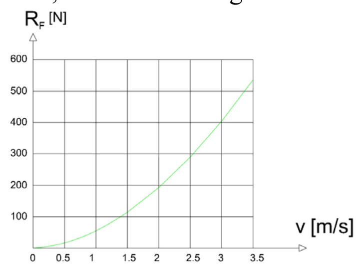

Fig.1. Frictional resistance

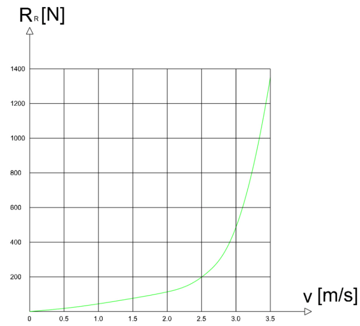

Fig.2. Residuary resistance

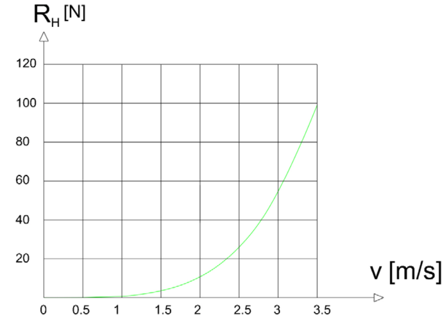

Fig.3. Heel resistance

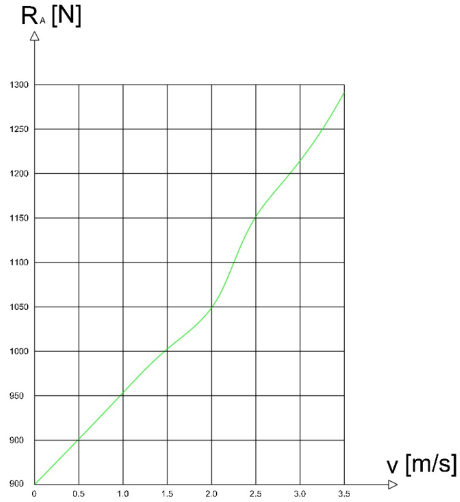

Fig.4. Aerodynamic resistance

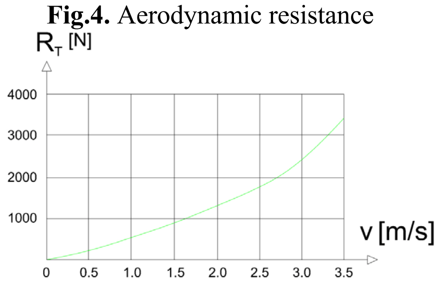

Fig.5. Total sailboat resistance

On the basis of the computer code results, the following observations may be made:

- the frictional resistance, the residuary resistance and the aerodynamic resistance represent the most important components of the total resistance;
- the heel resistance contribution depends on the value of the heeling angle;
- all the sailboat resistance components increase with the ship speed.

4. CONCLUDING REMARKS

The estimation of the yacht resistance with a satisfactory level of accuracy in the initial design stage represents a very important problem.

This paper deals with the results obtained by means of an in-house computer code, developed in order to calculate the components of the total yacht resistance: frictional resistance, residuary resistance, heel resistance and aerodynamic resistance.

The frictional resistance coefficients of the hull, keel and rudder were calculated by means of the ITTC'57 ship model correlation line.

The residuary resistance was determined by means of the empirical relations developed from the Delft series, both within the low speed and high speed range.

The heel resistance and aerodynamic resistance components were estimated by typical relations provided in the specialized literature.

On the basis of the new computer code, the optimum values of the main dimensions and form coefficients may be obtained in the initial yacht design stage, related to the resistance performance.

Acknowledgements

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