Nenad, VARDA*, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, I. Lučića 5, 10000 Zagreb*
Nastia, DEGIULI*, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, I. Lučića 5, 10000 Zagreb*
Marta, PEDIŠIĆ BUČA*, Brodarski Institute, Avenija V. Holjevca 20, 10000 Zagreb*

RESISTANCE PREDICTION OF SEMIPLANING TRANSOM STERN HULLS

Summary

Reliable methods to predict resistance characteristics form the basic tool for the preliminary hydrodynamic design of semiplaning hulls. The total resistance is calculated for five models of semiplaning ships series „Sklad“ with transom stern developed at the Brodarski Institute in Zagreb. The Lahtiharju and Mercier-Savitsky methods for the total resistance prediction of semiplaning hulls were used. Both methods were developed by using regression analysis which was based on the total resistance data for the transom stern hull forms. The total resistance calculated with both methods is compared with measured total resistance for wide range of the Froude number $Fn_{\nabla} = 0.482 - 3.618$. Model tests were conducted in the towing tank B2 at the Brodarski Institute in Zagreb. Measured total resistance and total resistance obtained by the Lahtiharju method is compared for wider range of the Froude number than suggested by the author. It has been concluded that the Lahtiharju method is more reliable than the Mercier-Savitsky method which can give deviations up to 50%. Results pointed out the applicability of the Lahtiharju method for wider range of the Froude number than suggested.

Key words: *resistance, semiplaning hull, transom stern*

PROCJENA OTPORA POLUDEPLASMANSKIH BRODOVA SA ZRCALNOM KRMOM

Sažetak

Pouzdane metode predviđanja otpora tvore osnovni alat za preliminarni hidrodinamički projekt poludeplasmanskih brodova. Izračunati su ukupni otpori za pet modela serije poludeplasmanskih brodova sa zrcalnom krmom, razvijene u Brodarskom institutu u Zagrebu u okviru serije „Sklad“. Za prognozu ukupnog otpora za poludeplasmanske forme brodova korištene su metode Lahtiharju i Mercier-Savitsky. Obje metode su razvijene pomoću regresijske analize rezultata mjerenja ukupnog otpora modela brodova sa zrcalnom krmom. Ukupni otpori dobiveni navedenim metodama uspoređeni su s izmjerenim ukupnim otporom za široki raspon Froudeovih brojeva $Fn_{\nabla} = 0,482 - 3,618$. Mjerenja su provedena u bazenu B2 Brodarskog instituta u Zagrebu. Izmjeren ukupni otpor i ukupni otpor dobiven metodom Lahtiharju su uspoređeni za širi raspon Froudeovih brojeva od onog predloženog samom metodom. Ustanovljeno je da je metoda Lahtiharju pouzdanija od metode Mercier-Savitsky, koja može dati odstupanja i do 50%. Pored toga metoda Lahtiharju je primjenjiva za širi raspon Froudeovih brojeva od preporučenog.

Ključne riječi: *otpor, poluistisniska forma, zrcalna krma*

1. Introduction

Accurate prediction of the ship resistance in full scale is important for the prediction of the propulsion power, and for calculation of the propeller thrust, which again is of crucial importance when selecting the right propeller. The choice of adequate propulsion system has impact on ship weight arrangement. Propulsion system with a higher power has a higher fuel consumption, which requires larger fuel tanks to maintain the same radius of navigation. Underestimating or overestimating the power of the engine immediately leads to different ship weight arrangement i.e. the center of gravity shifts which significantly affects the total resistance. Fuel economy and environmental concerns are dominant factors nowadays that demand that resistance be accurately predicted in the early design stage. Because of that it is important to choose the most appropriate propulsion system to suit the vessel´s resistance characteristics.

The basic approaches in the prediction of ship resistance can be roughly classified into empirical/statistical approaches, experimental approaches, either in model tests or in full-scale trials and numerical approaches, either analytical or using computational fluid dynamics (CFD). Design engineers need simple and reasonably accurate estimates, e.g. of the power requirements of a ship. Common approaches combine a physical model and regression analysis to determine required coefficients either from one parent ship or from set of ships. The coefficients may be given in the form of constants, formulae, or curves [1].

The aim of the paper was to investigate the accuracy of the resistance prediction methods for fast mono-hull vessels. The “Sklad” series [2], which have undergone exhaustive tank testing at the Brodarski Institute, was chosen because of the availability of the experimental results. To estimate the total resistance, the Lahtiharju method was chosen, because “Sklad” series parameters are within the range of application of the Lahtiharju method which can be applied over a wide range of Froude numbers. At low speeds, resistance is calculated by using the Mercier-Savitsky method, which give reliable results over low speed range.

2. Models

Models of the “Sklad” series [2] have round frames and displacement form characteristics on the largest part of hull, except on the stern part where hard chine is applied. The bottom of the stern is flat with small inclination from centreline to side, which gives the lifting surfaces at higher speeds. In longitudinal sense, the bottom is slightly convex, leaving enough space for screw arrangement, reducing the slope of shafting and decreasing the angle of dynamic trim. Frames on the bow have a “V” shape that goes into the mild “S” shape towards the middle part of the hull. From the bow to the middle of the hull, chine is descending until it becomes parallel to the waterline. The shape of the bow frames with chine breaks the bow wave and keeps the deck dry. The waterlines at the bow are flat. The stern ends with a relatively large transom. The bilge decreases towards the stern and becomes sharp. Fig. 1 shows the body plane of the basic model of “Sklad” series.

All the tested models were made of fiberglass, except the model M-813A, which was made of paraffin. Model scales were determined with respect to a hypothetical ship. Wires of 1.0 mm diameter were used for turbulence stimulation and were situated about 50 mm aft of the contour of the bow. The total resistance of the model was measured during the test. The total resistance force was measured using a linear dynamometer, the device that allowed that resistance force was always parallel to the surface of still water in the towing tank. The point of application of the resistance force was approximately in the centre of gravity of model (at $v_M = 0$). All resistances were calculated with a constant length and static wetted surface

($v_M = 0$) except the resistance of model M-813A, which was calculated with a variable length and dynamic wetted surface ($v_M \neq 0$). The resistance tests in calm water were made in the B2 towing tank at the Brodarski Institute, which is 302.5 m long, 5 m wide and 3.2 deep, for the bare hull condition (i.e. without appendages).

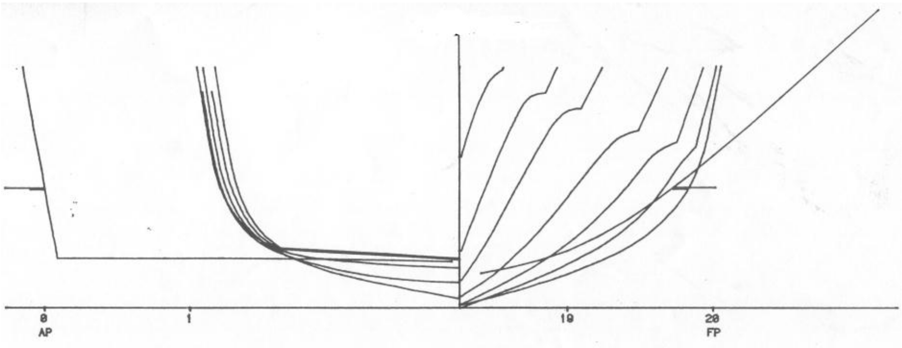

Fig. 1 Basic model M 839 of the "Sklad" series
Slika 1. Osnovni model M 839 serije "Sklad"

3. Lahtiharju method

The Lahtiharju method was developed by using regression analysis based on parameters and resistance of NPL-series (Bailey) from the bases and five new models. Fig. 2 shows the body and lines planes of NOVA I, which was the basic model for the Lahtiharju method. The Lahtiharju method is considered for speed range $Fn_\nabla = 1.8 - 3.2$ [3] (where Fn_∇ is the displacement Froude number defined by $Fn_\nabla = v \big/ \sqrt{g\nabla^{1/3}}$), because the top speeds of many modern high-speed vessels are in this range. The Mercier-Savitsky, which is based on regression analysis of resistance data of semi-displacement hulls, was selected as the parent formula for developing the resistance prediction equations for the Lahtiharju method.

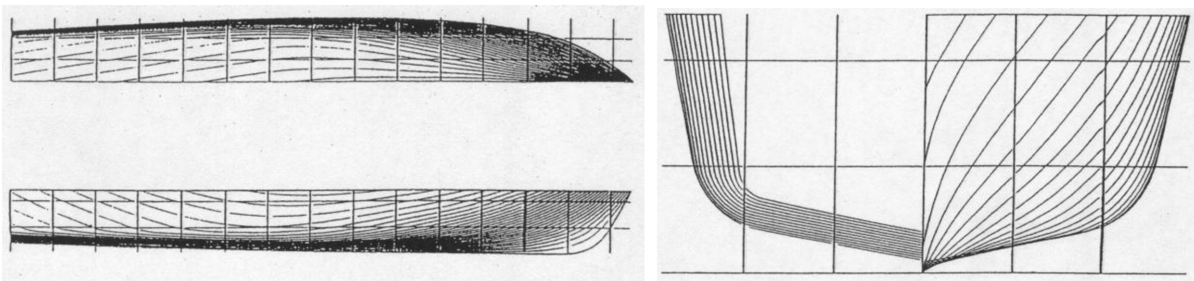

Fig. 2 Basic model NOVA I for the Lahtiharju method
Slika 2. Osnovni model NOVA I za Lahtiharju metodu

As already mentioned the resistance equation was developed by using regression analysis [3]. The most important hull form parameters and their cross-products were selected as explanatory variables, and the coefficients of the variables were determined. The equation predicts the total resistance-displacement weight ratio $R_T / \Delta_{(100000)}$ for a 100 000 lbs (45.36 metric tons) ship. The total resistance-displacement weight ratio can be calculated in the same way as by the Mercier-Savitsky method. The general form of the equation for vessels with round bilge is:

$$R_T / \Delta_{(100000)} = A_0 + \sum_{i=1}^{6} A_i \cdot P_i + \left(\sum_{i=7}^{10} A_i \cdot P_i\right) Fn_\nabla + \left(\sum_{i=11}^{13} A_i \cdot P_i\right) Fn_\nabla^2 + \left(\sum_{i=14}^{16} A_i \cdot P_i\right) Fn_\nabla^3 + \left(\sum_{i=17}^{24} A_i \cdot P_i\right) Fn_\nabla^4 \quad (1)$$

where:

- $R_T / \Delta_{(100000)}$ - the total resistance-displacement weight ratio R_T / Δ_{100000} for a 100000 lbs (45.36 metric tons) vessel,
- A_i - coefficients determined by the regression analysis,
- P_i - the hull form parameters.

The resistance prediction equation for round bilge vessels is valid for the range of hull form parameters given in Table 1, where L is waterline length, ∇ is displaced volume, B is maximum waterline beam, T is draft, A_T/A_X is the transom area-maximum section area ratio and C_X is maximum section area coefficient. The values of the coefficients in Eq. (1) are given in Table 2 for different powers of Fn_∇.

Table 1 Limits of applicability of Eq. (1)
Tablica 1. Područje primjene jednadžbe (1)

$L/\nabla^{1/3}$	4.47…8.30
B^3/∇	0.68…7.76
L/B	3.33…8.21
B/T	1.72…10.21
A_T/A_X	0.13…0.82
C_X	0.567…0.888

Table 2 Parameters and coefficients of the Eq. (1)
Tablica 2. Parametri i koeficijenti u jednadžbi (1)

i	P_i	A_i
1		
0	1	0.08599480
1	$(\nabla^{1/3}/T)^2$	0.00403360
2	$(L/T)^2$	0.00005043
3	$(B/L)\cdot(A_T/A_X)$	0.50375400
4	$(B/T)^2\cdot(A_T/A_X)$	0.00441950
5	$(B/T)^2\cdot C_X^2$	0.01006670
6	$(L/T)^2\cdot C_X^2$	0.00022960
Fn_∇		
7	$L/\nabla^{1/3}$	0.00648520
8	B^3/∇	0.01716090
9	$(B^3/\nabla)\cdot C_X^2$	0.09291540
10	$(L/T)^2\cdot(A_T/A_X)$	0.00007032
Fn_∇^2		
11	$(L/\nabla^{1/3})\cdot(A_T/A_X)$	0.01034440
12	$(L/\nabla^{1/3})\cdot C_X^2$	0.02305310
13	$(B^3/\nabla)\cdot C_X^2$	0.01596980

i	P_i	A_i
Fn_∇^3		
14	$(L/T)^2$	0.00000325
15	A_T/A_X	0.04651030
16	C_X^2	0.07468910
Fn_∇^4		
17	B^3/∇	0.00103410
18	$(B^3/\nabla)\cdot(A_T/A_X)$	0.00069420
19	$(B^3/\nabla)\cdot C_X^2$	0.00336950
20	$(\nabla^{1/3}/T)^2\cdot C_X^2$	0.00012500
21	$(B/L)\cdot(A_T/A_X)$	0.05312710
22	$(B/L)\cdot C_X^2$	0.11749790
23	$(L/T)^2\cdot(A_T/A_X)$	0.00000220
24	$(A_T/A_X)\cdot C_X^2$	0.00470560

The correction of frictional resistance is made by the formula:

$$\left(R_T/\Delta\right)_{corr} = \left(R_T/\Delta\right)_{100000} + [(C_F + C_A) - C_{F100000}]\cdot 0.5\frac{S}{\nabla^{2/3}} Fn_\nabla^2 \tag{2}$$

where:

- $\left(R_T/\Delta\right)_{corr}$ - corrected total resistance-displacement weight ratio,

- $C_{F100000}$ - frictional resistance coefficient of the 100000 lbs vessel,
- C_F - frictional resistance coefficient of the vessel according to ITTC-57 model-ship correlation line,
- C_A - incremental resistance coefficient for ship-model correlation
- S - wetted surface.

4. Mercier-Savitsky method

In 1973, Mercier and Savitsky conducted a regression analysis of the smooth-water resistance data of seven transom-stern hull series which included 118 separate hull forms [4]. An analytical procedure was developed for predicting the resistance of transom-stern hulls in non-planing range.

Least-squares curve fitting was applied starting with a general 27-term equation and terms which were of small significance eliminated until further elimination of terms produced a significant degradation of correlation. The equation selected for the eleven Fn_∇ involve 14 terms:

$$\begin{aligned} R_T/\Delta_{(100000)} &= A_1 + A_2X + A_4U + A_5W + A_6XZ + A_7XU + A_8XW + A_9ZU \\ &+ A_{10}ZW + A_{15}W^2 + A_{18}XW^2 + A_{19}ZX^2 + A_{24}UW^2 + A_{27}WU^2 \end{aligned} \tag{3}$$

Coefficient used in Eq. (3) are for $Fn_\nabla = 1-2$ with a step of 0.1. Parameters used in the curve-fitted Eq. (3) are: $X = \nabla^{1/3}/L$, $Z = \nabla/B^3$, $U = \sqrt{2i_e}$, $W = A_T/A_X$, where i_e is the waterline half-entrance angle.

Values for the coefficient are given in Table 3 for a displacement of 100000 lbs. These equations and coefficient are based on the scheme of minimizing the percentage difference between measured and calculated resistance. For other values of displacement, water conditions, incremental resistance coefficient C_A, or friction coefficients, the result can be corrected according to the Eq. (2).

Table 3 Coefficients for resistance-estimating equation (3)
Tablica 3. Koeficijenti za procjenu otpora prema jednadžbi (3)

	A_1	A_2	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{15}	A_{18}	A_{19}	A_{24}	A_{27}
Fn_∇	1	X	U	W	XZ	XU	XW	ZU	ZW	W^2	XW^2	ZX^2	UW^2	WU^2
1.0	0.0647	-0.487	-0.01	-0.065	0	0.1063	0.9731	-0.003	0.0109	0	-1.41	0.2914	0.0297	-0.002
1.1	0.1078	-0.888	-0.016	-0.134	0	0.1819	1.8308	-0.004	0.0147	0	-2.467	0.4731	0.0588	-0.004
1.2	0.0948	-0.637	-0.015	-0.136	-0.16	0.168	1.5597	-0.003	0.0348	0	-2.156	1.0299	0.052	-0.003
1.3	0.0348	0	-0.01	-0.051	-0.219	0.1043	0.4351	-0.002	0.0411	0	-0.927	1.0639	0.0221	-0.001
1.4	0.0301	0	-0.007	-0.055	-0.194	0.0961	0.5182	-0.002	0.039	0	-0.953	0.9776	0.0241	-0.001
1.5	0.0316	0	0	-0.105	-0.205	0.0601	0.5823	-0.004	0.0479	0.0832	-0.709	1.1974	0	0
1.6	0.0319	0	0	-0.086	-0.194	0.0619	0.5205	-0.004	0.0444	0.0737	-0.721	1.1812	0	0
1.7	0.0434	0	0	-0.133	-0.181	0.0549	0.782	-0.003	0.0419	0.1215	-0.959	1.0156	0	0
1.8	0.0504	0	0	-0.156	-0.178	0.051	0.9286	-0.003	0.0411	0.1493	-1.122	0.9314	0	0
1.9	0.0561	0	0	-0.187	-0.183	0.0474	1.1857	-0.002	0.0412	0.1809	-1.386	0.7841	0	0
2.0	0.0597	0	0	-0.198	-0.202	0.0465	1.3003	-0.002	0.0434	0.1977	-1.551	0.7828	0	0

5. Results

The basic model is M 839. From this model, models M 840 and M 841 are derived and they differ from the basic model by the ratio L/B. Other models derived from model M 839 are M 839 KN and M 839 KM, which have different transom stern and therefore have a different the transom stern-maximum section area ratio A_T/A_X. In addition to these models in our paper we also included model M 813A, which has inclined stem.

When Fn_∇ is smaller than 1.5, the Mercier-Savitsky method is applied. When Fn_∇ is larger than 1.8, the Lahtiharju method is used. The weighted average value is determined between these speeds [3].

5.1. Model M 813A

Model M 813A is an analytical form, obtained by minimizing the wave resistance [5], with main hull parameters $L/B = 6.44$, $B/T = 2.96$ and $C_B = 0.44$ [7]. Original form has a vertical stem, while the model M-813A has an inclined stem, close to real vessels. Bow frames are adjusted to the inclined stem.

In Figs. 3-8 R_{TL} denotes the total resistance calculated by the Lahtiharju method, R_{TS} the total resistance calculated by the Mercier-Savitsky method and R_{TM} measured total resistance. The total resistance obtained by the Lahtiharju and Mercier-Savitsky methods show good correlation with measured total resistance as can be seen from Fig. 3. From $Fn_\nabla \approx 2.5$ some deviation of the Lahtiharju method from measured values can be noticed.

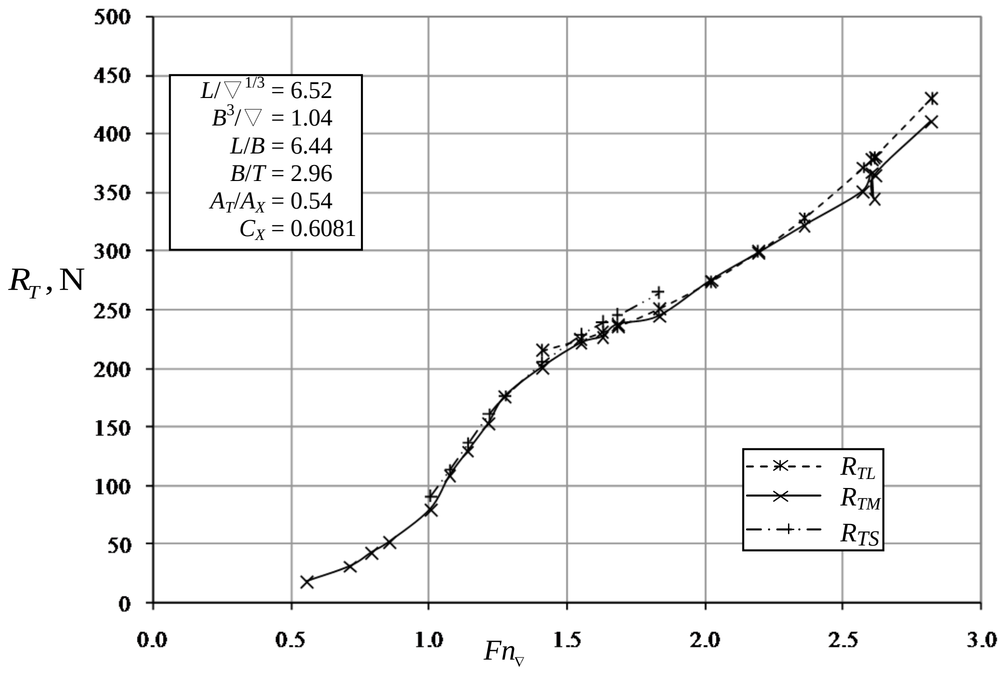

Fig. 3 Comparison of measured and calculated total resistance for model M 813A
Slika 3. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 813A

5.2. Model M 839

Model M 839 is the basic model of series "Sklad" with main hull parameters $L/B = 5.99$, $B/T = 4$ and $C_B = 0.45$ [6]. For model M-839 the difference between the measured and calculated resistance obtained by the Lahtiharju method is practically negligible, Fig. 4. The Mercier-Savitsky method has good correlation but gives slightly lower values of the total resistance.

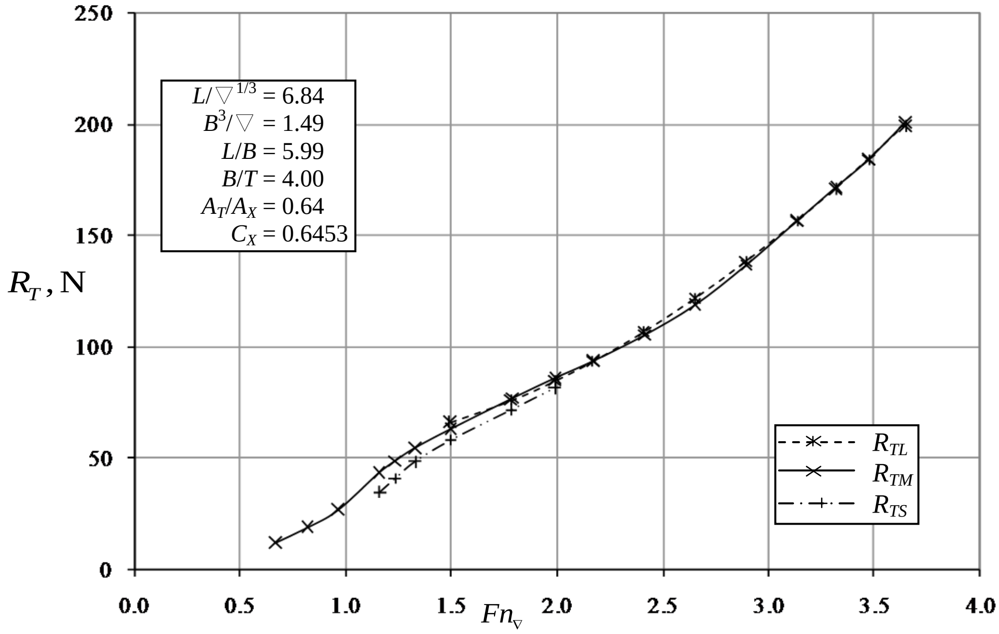

Fig. 4 Comparison of measured and calculated total resistance for model M 839
Slika 4. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 839

5.3. Model M 840

Model M 840 is wider than the basic model M 839, with main hull parameters $L/B = 4$, $B/T = 4.01$ and $C_B = 0.45$ [6]. The Mercier-Savitsky method has good correlation but gives considerably lower values of the total resistance than measured ones. The Lahtiharju method predicts the total resistance with good correlation and results agree fairly well, Fig. 5.

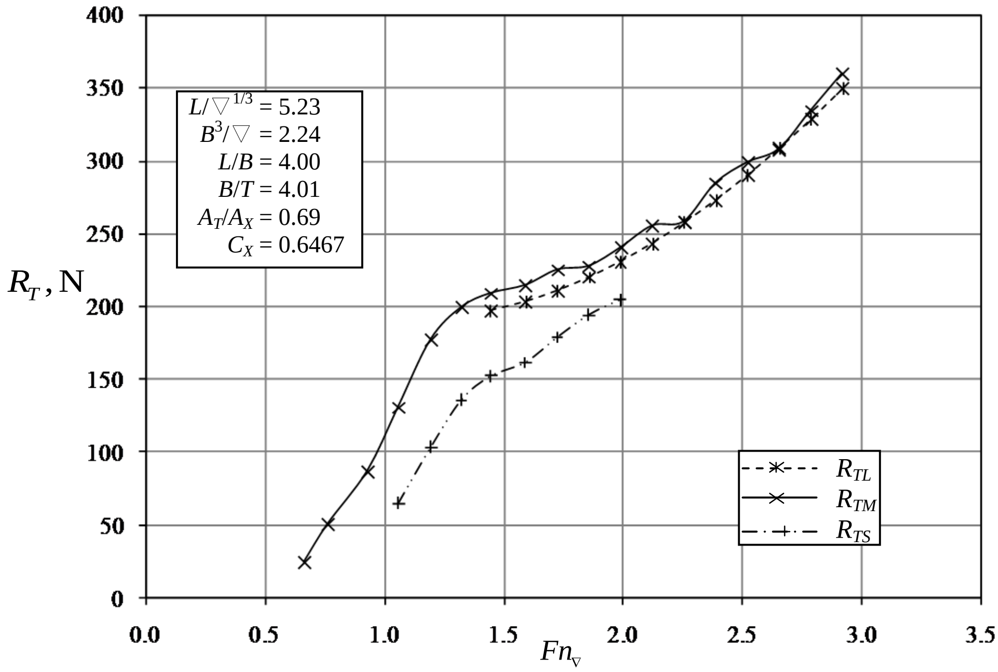

Fig. 5 Comparison of measured and calculated total resistance for model M 840
Slika 5. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 840

5.4. Model M 841

Model M 841 is narrower and longer model than the basic model M 839, with main hull parameters $L/B = 8.02$, $B/T = 4.01$ and $C_B = 0.45$ [6]. Model M 841 has the lowest displacement of all considered models and therefore the smallest total resistance. From Fig. 6 it can be seen that the total resistance calculated by the Lahtiharju method has good correlation but gives higher values of total resistance than measured, especially in the speed range $Fn_\nabla > 2.0$. The Mercier-Savitsky method has good correlation with measured values and offers acceptable prediction of total resistance in the range of application.

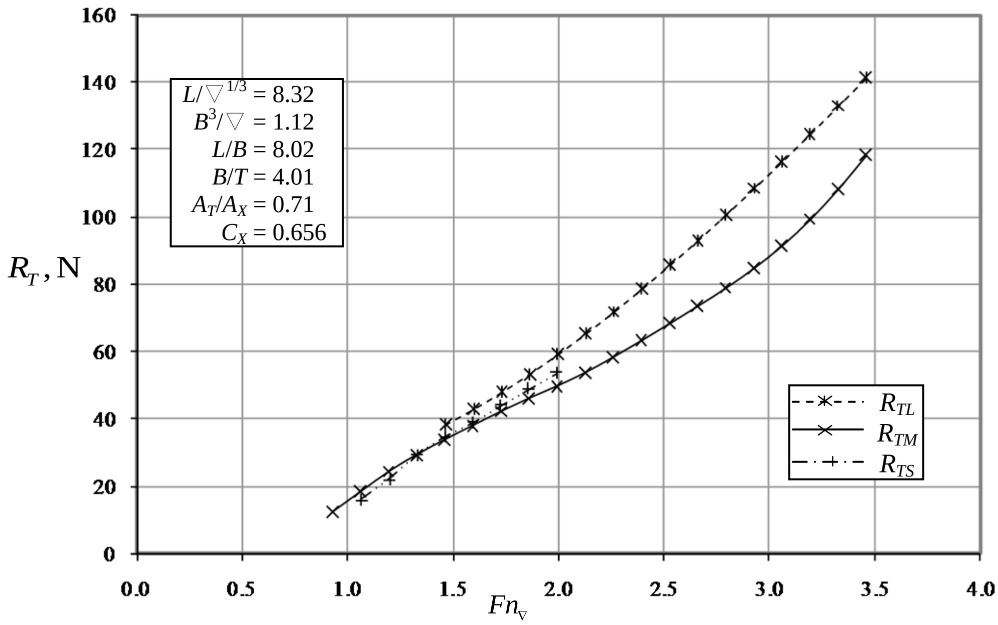

Fig. 6 Comparison of measured and calculated total resistance for model M 841
Slika 6. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 841

5.5. Model M 839 KN

Model M 839 KN has greater deadrise angle $\beta = 19^\circ$ and the transom stern-maximum section area ratio is outside the limits of applicability of the Lahtiharju method. The main hull parameters are $L/B = 5.99$, $B/T = 4.0$ and $C_B = 0.45$ [7]. For model M 839 KN measured values of the total resistance have good correlation with calculated values obtained by the Lahtiharju method up to $Fn_\nabla \approx 2.7$. The Lahtiharju method underpredicts the total resistance in the whole range and for $Fn_\nabla > 2.7$ gives significant deviation from measured total resistance, as shown in Fig. 7. The Mercier-Savitsky method has good correlation over whole speed range and also underpredicts the total resistance even more than the Lahtiharju method.

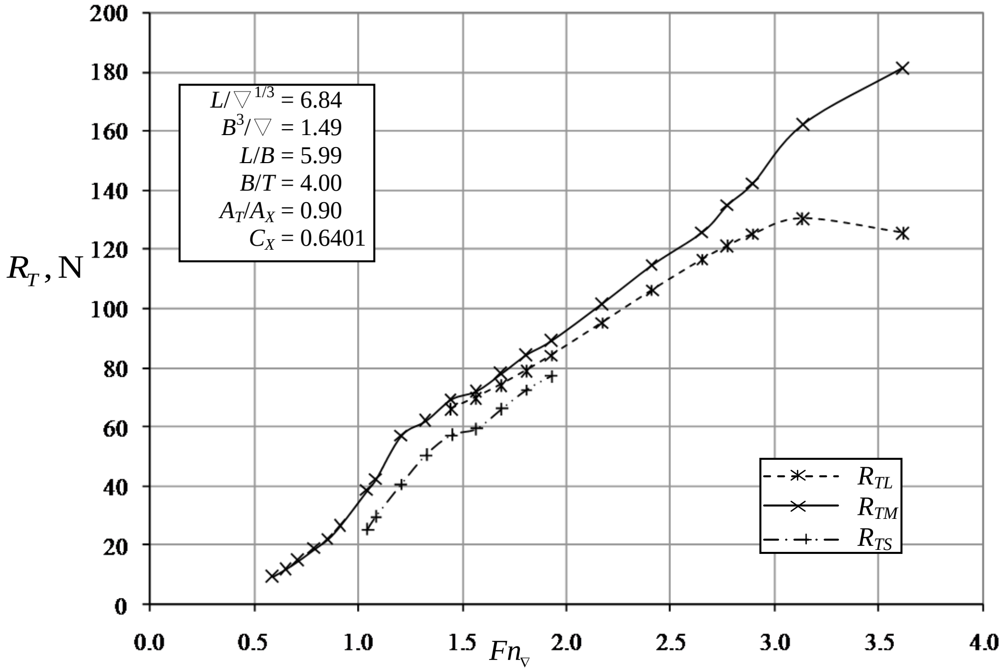

Fig. 7 Comparison of measured and calculated total resistance for model M 839 KN
Slika 7. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 839 KN

5.6. Model M 839 KM

Model M 839 KM has even greater deadrise angle $\beta = 26^\circ$ than model M 839 KN and has lower baseline. This model has the transom stern-maximum section area ratio close to the upper limit of application [7]. The Lahtiharju method significantly underpredicts the total resistance values but gives satisfactory correlation in the whole range. The Mercier-Savitsky

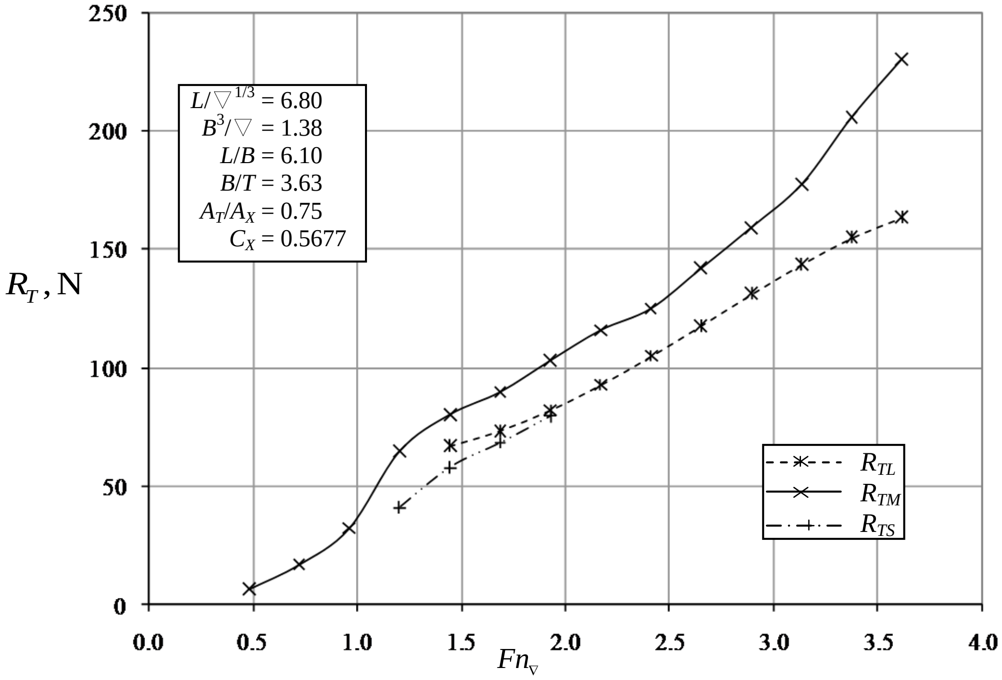

Fig. 8 Comparison of measured and calculated total resistance for model M 839 KM
Slika 8. Usporedba izmjerenog i izračunatog ukupnog otpora za model M 839 KM

method has also good correlation in the range of application and also underpredicts the total resistance, Fig. 8.

5.7. Comparison of the results

Correlation *r* and average deviation *p* [8] of calculated and measured values of the total resistance obtained by the Lahtiharju and Mercier-Savitsky methods are presented in Table 4.

Table 4 Correlation and average deviation from measured total resistance
Tablica 4. Korelacija i prosječno odstupanje od izmjerenog ukupnog otpora

Model	Lahtiharju, r_L	Lahtiharju, p_L	Mercier-Savitsky, r_S	Mercier-Savitsky, p_S
M 813A	0.9932	3.3%	0.9985	5.5%
M 839	0.9995	0.5%	0.9965	-11.3%
M 840	0.9965	-3.5%	0.9881	-28.2%
M 841	0.9966	21.4%	0.9984	-15.9%
M 839KN	0.9530	-9.8%	0.9958	-21.4%
M 839KM	0.9874	-19.8%	0.9950	-27.6%

6. Conclusion

The Lahtiharju method for the prediction of the total resistance of semiplaning hulls is applicable for wider range of the Froude displacement number than recommended by the author if one keeps within the limits of the recommended ratio of the main particulars (M 813A, M 839 and M 840). Significant deviations were observed at the model M 841, whose ratio $L/\nabla^{1/3} = 8.32$ is out of the limits of recommended range of application, and at the model M 839 KN whose ratio $A_T/A_X = 0.9$ is above the recommended upper limit. The correlation is satisfactory for all models except for the model M 839KN which has a different shape of the transom stern. For the same reason model M 839 KM has a slightly poorer correlation. For the models with modified angle of deadrise (M 839 KN and M 839 KM) the prediction of the total resistance for speeds over $Fn_\nabla \approx 3.0$ by the applied method did not gain satisfactory results. It can be emphasized that neither the obtained values nor the curve trend is similar to the ones obtained by experiment. Any deviation from standard form like different baseline or deadrise angle gives unsatisfactory predictions of the total resistance.

The Mercier-Savitsky method has a high degree of correlation for all tested models. However, the calculated values of the total resistance deviate significantly from the measured values except in the case of the model M 813A, within the recommended range of the Froude displacement number.

It is gratifying to note the relatively good continuity of the two calculation methods in the speed range where they overlap. The total resistance is mainly well predicted regarding the shape of the curve with both methods.

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