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A method of calculation of ship resistance on calm water useful at preliminary stages of ship design

Katarzyna Żelazny

West Pomeranian University of Technology, Faculty of Maritime Technology and Transport
71-065 Szczecin, al. Piastów 41, e-mail: katarzyna.zelazny@zut.edu.pl

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Abstract
During preliminary stages of ship design, decisions on ship properties are made only with little knowledge on ship hull geometry – a ship designer has only the basis dimensions at his disposal. Therefore on these initial stages of ship design, methods of calculation of ship properties (eg. resistance) on the basis of basic design criteria are indispensable. The article presents a new method of calculation of bulk carriers resistance which proves exact even with a minimum number of geometrical parameters of a ship's hull.

Introduction

Designing transport ship, apart from meeting technical criteria requirements (flotation, stability, subdivision) the needs of the ship owner have to be accommodated – often with maximizing future profits from ship exploitation in mind. One of such ship owner's requirements is reaching a set service speed by a ship. A number of decisions regarding a future ship is made at initial stages of design, when only basic geometric hull parameters are known. In order to design a ship effectively, it is necessary to work out simple relationship between ship properties, and basic geometric parameters which are already known at an initial stage of ship design. One of such ship properties is its resistance, which exerts significant influence on ship economic effectiveness, and can be calculated already at early / preliminary stages of ship design.

Ship resistance on calm water

Ship resistance is a basic parameter, on which the whole propulsion system depends – both propeller (and its geometry) as well as propulsion engine (power, rotations). In design practice, ship resistance is measured during tank tests, and subsequent prognosis of a ship velocity follows. For this purpose, a detailed documentation of ship's hull geometry has to be prepared. Prognosis of a ship resistance is also made using approximate methods e.g. Holtrop-Mennen's [1] or Holenbach's [2]. However, also in such case, a relatively large number of hull geometrical parameters has to be known in advance. Still, at initial stages of ship design only basic geometrical parameters are known – and the article presents a new, simplified method of calculation of bulk carriers resistance. Similar methods can be found in literature on the subject [3, 4], however, they are not exact enough.

Resistance approximation method on calm sea

Having analysed a number of scientific articles and publications on approximation of ship resistance also with respect to advantages and disadvantages of various methods, mainly with exactness and simplicity of approximating function in mind, a multiple linear regression has been used here.

Linear regression against ship model parameters takes the following general form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad (1)$$

where:

- β_i – model parameters;
- ε – random effect;
- y – dependent variable (ship resistance here);
- x_i – independent variables (in this case hull geometric parameters).

Searching for a form of approximating function has been made using the following algorithm:

- Defining a set of design parameters, which can significantly affect described value (resistance of a ship on calm water).
- Working out a set of design values to calculate resistance (database of built ships).
- Working out the ranges of these parameters – independent variables.
- Setting model resistance values – dependent variable.
- Searching for a model of approximating function.
- Determining approximating function of resistance on calm sea on the basis of chosen design parameters – an estimation.
- Statistical validation of a model on the basis of statistical analysis (significance testing, analysis of variance, residual analysis etc.)
- Factual verification of a model on the basis of comparison of results obtained from a model and results of exemplary ships between as well possibly tank tests (relative and absolute error).
- Final choice of a model – the form of approximating function.
- Evaluation of a model for selected ship parameters – checking the influence of chosen design parameters on ship resistance according to the results obtained from a model.

Defining a set of design parameters, affecting the defined value (ship resistance on calm water) in a significant way

Assumptions:

- dependent variable y – ship resistance on calm water R_T;
- independent variables x_i – selected from among parameters:
  - known already at the initial stages of ship design;
  - used as arguments in the Holltrop-Mennen's method [1] (or possibly in that of Hollenbach [2]);
  - on the basis of analyses presented in relevant literature [3];
  - initially selected ship parameters L_{WL}, B, T, C_B, C_{WP}, V:
    L_{WL} – ship length at waterline line;
    B – ship's breadth;
    T – draught;
    C_B – block coefficient;
    C_{WP} – waterplane coefficient;
    V – ship speed;
  - in relevant literature used as arguments in relation describing components of resistance on calm water [5];
  - supplemented with ∇: ∇ – ship displacement.

The choice of variables results from two stages: analysis of independent variables in order to check their changeability, the influence of individual independent variables on the dependent variable as well as establishing relationships among them.

On the basis of analysis of various entry data, whose basis was the database of exemplary ships (17) as well as the built ship base without type division (159) finally: L_{WL}, B, T, C_B, V, ∇ have been chosen. The C_{WP} variable – waterplane coefficient has been neglected, since the influence of this parameter on resistance variability was the same in character as C_B and was relatively small – even when it was a significant parameter in the model, its omission did not affect the exactness, however, such omission allowed for more simplification by elimination of one variable. On the other hand, however, ship displacement – by which parameter, the model has been supplemented in a slight degree improves model adjustment, but in model verification it turns out that it improves model adjustment to exemplary ships.

Variable analysis in order to check whether all assumptions for model linear regression have been met, that is whether the method of least squares can be used for estimation of model parameters.

Such analysis requires to check among other: whether independent variables are not random nor correlated to random factor ε, none of them is a linear combination of other independent variables, and each random factor has normal distribution.

Drawing up a set of design values for calculation of ship resistance (database of built ships)

Data for drawing up approximating function: calculation of ship resistance on calm water using the Holtrop-Menenn's method for built ships of the bulk carrier type – 45 (4 exemplary to test model; 41 ships to search for a model).

Working out the ranges of these parameters – independent variables

The range of examined parameters (independent variables) for analysed group of bulk carriers has been given in table 1.

Table 1. The range of examined parameters for bulk carriers

	L_{WL} [m]	B [m]	T [m]	C_B [–]	C_{WP} [–]	C_P [–]	∇ [m^3]	V [m/s]	L/B [–]
max	330	60	18	0.88	0.91	0.87	288 000	8	7.2
min	104	18	7	0.73	0.83	0.74	9770	2	5.4

Ranges for which the Holtrop-Mennen's method has been worked out:
– bulk carriers $L/B = 5.1–7.1$ $C_P = 0.73–0.85$

Determining exemplary resistance values – dependent variable

Exemplary resistance values have been calculated using Holtrop-Mennen's method for a selected group of built ships on the basis of available ship data. In this case it is necessary to know around 30 parameters describing ship geometry.

Searching for a model of approximating function

Models of approximate function examined here, have been drawn up on the basis of experience and intuition having analysed the influence of ship design parameters on its resistance. Approximating function (in the form below) has been chosen from the analysis carried out:

$$\frac{R_T}{V^2} = f(L_{WL}, B, T, C_B, \nabla) \tag{2}$$

where dependent variable has the form of:

$$y = \frac{R_T}{V^2} \tag{3}$$

Determining function approximating resistance on calm water on the basis of selected design parameters – an estimation

Following initial selection of design parameters (independent variables) which influencing ship resistance on calm water (dependent variable), the specific influence of each individual design parameter and pair of parameters on ship resistance (its changeability, approximate functional relationship, degree of correlation) have been determined at entry ship data of each type.

Examples of obtained functional relationships for a chosen model of bulk carriers:

$$\begin{aligned}
&R_T/V^2 = f(L_{WL}, B)\ R^2 = 0.976\ z = a + bx^3 + cy^{2.5}\\
&R_T/V^2 = f(L_{WL}, T)\ R^2 = 0.896\ z = a + bx + c/y\\
&R_T/V^2 = f(L_{WL}, C_B)\ R^2 = 0.866\ z = a + bx + c/y\\
&R_T/V^2 = f(L_{WL}, \nabla)\ R^2 = 0.987\ z = a + bx + cy\\
&R_T/V^2 = f(B, T)\ R^2 = 0.984\ z = a + bx^3 + cy^3\\
&R_T/V^2 = f(B, C_B)\ R^2 = 0.961\ z = a + bx^{0.5} + c\ln x\\
&R_T/V^2 = f(B, \nabla)\ R^2 = 0.987\ z = a + bx^3 + cy\ln y\\
&R_T/V^2 = f(T, C_B)\ R^2 = 0.913\ z = a + bx^2\ln x + cx^{2.5}\\
&R_T/V^2 = f(T, \nabla)\ R^2 = 0.987\ z = a + bx^3 + cy\ln y\\
&R_T/V^2 = f(C_B, \nabla)\ R^2 = 0.987\ z = a + b(\ln y)^2 + cy/\ln y
\end{aligned} \tag{4}$$

The following general form of a model of approximating function has been accepted:

$$R_T/V^2 = f(L_{WL}, B, T, C_B, \nabla) \tag{5}$$

Based on analyses of the influence of individual parameters (ship resistance on calm water) a detailed form of approximating function can be expressed as:

$$\frac{R_T}{V^2} = a_0 + a_1 L_{WL}^3 + a_2 B^2 \ln(B) + a_3 T^3 + a_4 (\ln(C_B))^2 + a_5 \nabla \ln(\nabla) \tag{6}$$

Coefficient values of a model of approximating function model have been estimated using the method of least squares, with Statistica computer programme.

Results obtained by estimation of coefficient of regression model for a selected form of approximating function in Statistica programme have been shown in table 2.

Tabela 2. Estimation of regression model coefficients – a summary

N = 440	Regression Summary for Dependent Variable: R/V2 (bulk carriers Vekor) R = 0.99371198 R² = 0.98746351 Adjusted R² = 0.98731908 F(5.435) = 6837.0 p < 0.0000 Std. Error of estimate: 1.5090						
	Beta		Std.Err. of Beta	B	Std.Err. of B	t(434)	p-level
Intercept		a_0		3.75096504	0.447197	8.38773	0.000000
L3	–0.098801	a_1	0.041288	–0.00000015	0.000000	–2.39300	0.017135
B2lnB	0.052435	a_2	0.042733	0.00024004	0.000196	1.22703	0.220478
T3	–0.081885	a_3	0.033475	–0.00063949	0.000261	–2.44615	0.014835
lnCB2	–0.015097	a_4	0.006036	–13.68642385	5.472390	–2.50100	0.012752
DlnD	1.113934	a_5	0.088367	0.00001726	0.000001	12.60579	0.000000

The summary presented in table 2 (Estimation of regression model coefficients) contains R^2 coefficient, standard error of estimate and BETA values in subsequent columns, values of estimated B coefficients of a model, standard error for B, t-Student statistics and level significant [6]. R^2 Coefficient can be treated as an adjustment measure of regression to experimental data. For the analysed example $R^2 = 0.987$ which means that 98.7% of general resistance variability is explained by the model. Standard error of estimate = 1.509 is small. BETA coefficients are a standardised form of an estimated model and can be used for comparisons between them and determining their influence on dependent variable. t-Student statistics with significant level p allows us to evaluate relevance of estimated parameters of a model. Significant level for defining variable B2lnB = $B^2 \cdot \ln(B)$ is $p > 0.05$ and indicates, that this variable is statistically insignificant and stepwise regression can be used to correct a model or check this model without B2lnB variable. Deleting such insignificant variable, however, may lead to worsening results while verifying the model against exemplary results.

Verification of a model

Each obtained model of regression should undergo verification. The most important steps at this stage are statistical and factual verification.

Verification of a model on the basis of statistical analysis

During statistical verification of an obtained model various statistical tests are carried out. They check, among other, significance of model parameters, significance of the whole model as well the assumptions of the method of least squares used for estimation of coefficients of regression equation. Significance tests (t-Student tests) show, whether given independent variable is relevant. A global F test (Fisher-Snedecor's test [6]) can be used for this purpose too. Test results for the model analysed here are shown in the summary of estimation of regression model coefficients in table 2.

Having estimated parameters of a model, an analysis of residuals should be carried out as well. It allows us to check whether a constructed model meets the assumptions of the least square method. One of the assumptions of this method is a normal distribution of model residuals. For the analysed model, for example, residuals normality graph and histogram of the residuals have been shown in figures 1 and 2.

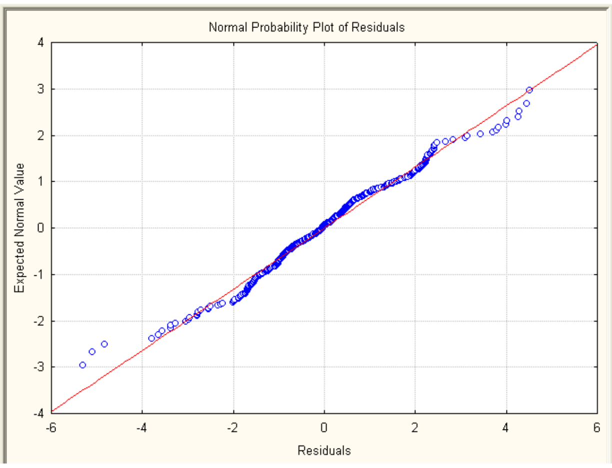

Fig. 1. Normal probability plot of residuals for a selected model of ship resistance

During verification of regression model, predicted value analysis is also helpful here. It allows for detecting untypical values (outliers values) or

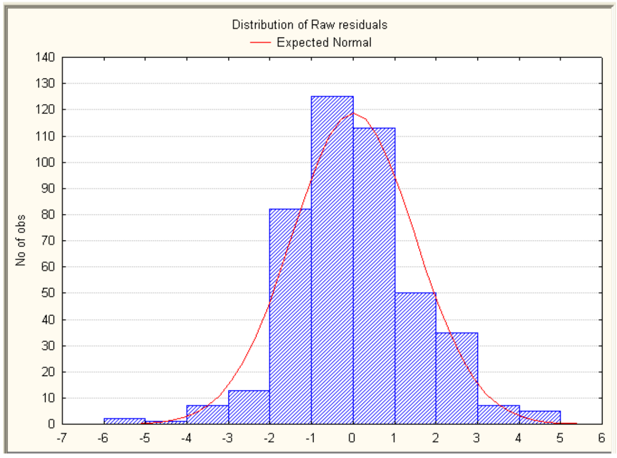

Fig. 2. Histogram of the residuals for a selected model of ship resistance

incorrectly entered data. Such untypical cases may interfere with test results and lead to wrong conclusions. In Statistica programme there are numerous forms of graphs available showing predicted and residual values. Figure 3, for example, shows distribution of predicted values (obtained from a model) in comparison to observed values (exemplary values).

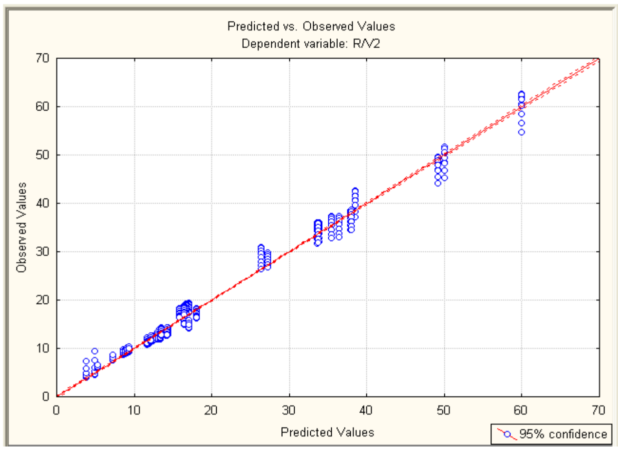

Fig. 3. Distribution of predicted against observed values for a selected model of ship

Factual verification of a model

Factual verification of a model was carried out comparing the results of regression model against calculations made for exemplary ships whose basic parameters are given in table 3, and well possibly tank tests (relative and absolute error). The results of verification of a model in the form of relative error value by comparison of values obtained from regression against the results of exact calculations for exemplary ships for analysed bulk carriers have been shown in Table 4 and in a graphic form in figure 4.

Table 3. Basic parameters of exemplary ships used for verification of a model

Parameter	Bulk carrier			
	M1	M2	M3	M4
Ship length on the line of floatation L_{WL} [m]	141.5	189.9	180.0	242.6
Ship breadth B [m]	23.0	25.3	32.2	32.2
draught T [m]	8.5	10.6	12.0	11.6
bulk coefficient C_B	0.804	0.820	0.805	0.815
waterplane coefficient C_{WP}	0.892	0.854	0.873	0.872
displacement ∇[m^3]	21 441	40 831	56 396	73 910
Ship speed V [m/s]	7.33	7.51	8.69	7.72

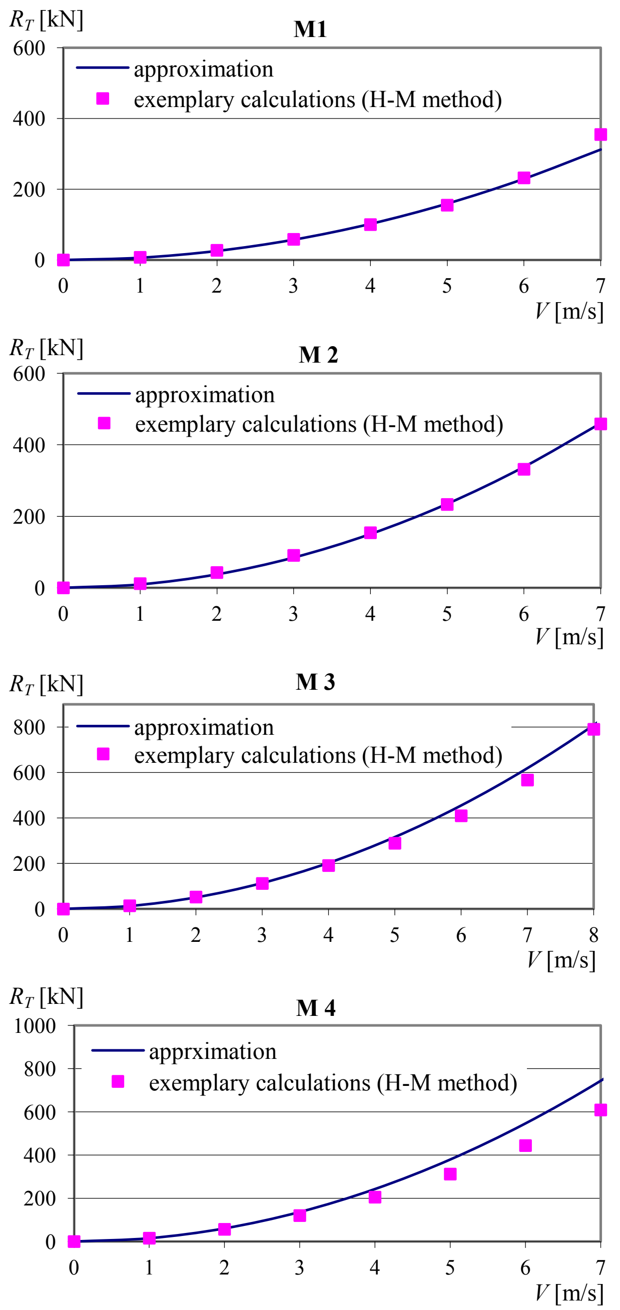

Fig. 4. Graphs showing resistance relationship on calm water – for an obtained model and for calculations made using the Holtropa-Mennen's method

Table 4. Results of verification of a model

Ship speed [m/s]	Relative error			
	M1 V_E = 7.3 m/s	M2 V_E = 7.5 m/s	M3 V_E = 8.7 m/s	M4 V_E = 7.7 m/s
1	15.55%	20.34%	12.87%	2.52%
2	6.48%	12.32%	4.42%	7.32%
3	1.86%	6.91%	1.04%	13.61%
4	1.75%	2.54%	5.62%	18.17%
5	2.67%	0.60%	9.19%	21.51%
6	1.31%	1.88%	10.89%	23.00%
7	12.09%	0.31%	9.11%	22.12%
Adjusted R^2	0.987			
Standard error of estimate	1.509			

Conclusions

The method presented here is simple, based on a few rudimentary design parameters but at the same exact, hence its high usability in bulk carriers design and optimisation. It is also more exact that other methods quoted in literature on this subject, e.g. than in [3] where a method using neuron networks has been used to calculate hauling power (which allows us to determine resistance values on calm water) also based on ship parameters known at initial stages of design. Comparison of the results from the approximation presented here and the ones from the method described in [3] is given in figure 5.

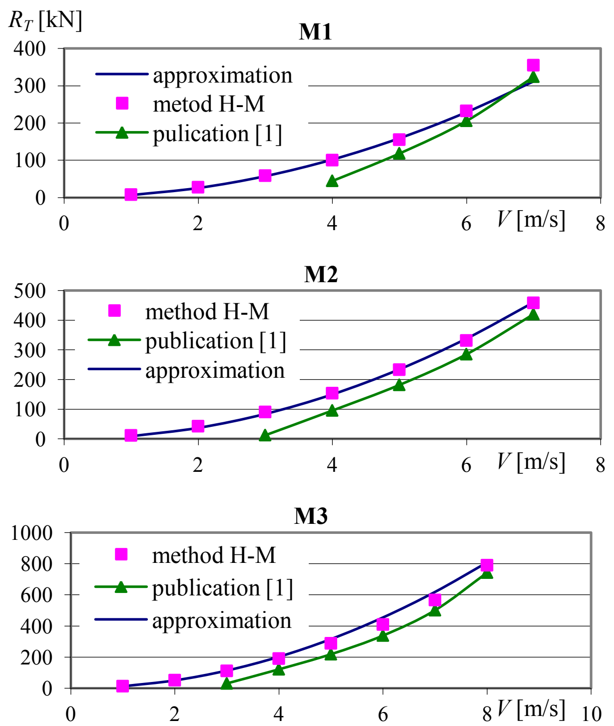

Fig. 5. Relationship graphs of resistance on calm water – for obtained model, for the Holtrop-Mennen's method and other publications [3]

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