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An approximate method for calculating the mean statistical service speed of container ships on a given shipping line and its application in preliminary design

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Key words: service speed, shipping lines, preliminary design, container ship, propulsion system, weather conditions

Abstract

During ship design, service speed is one of the crucial parameters in determining the operational economy of the vessel. As sufficiently exact calculation methods applicable to preliminary design stage are lacking, the so-called contract speed, the speed which a ship reaches in calm water, is usually cited. Żelazny (2015) developed a parametric method for calculating total ship resistance under actual weather conditions (wind, waves, sea current). This paper presents a parametric model of a ship's propulsion system (screw propeller – propulsion engine) as well as a method, based on both the resistance and propulsion system models, of calculating the mean statistical value of a ship's service speed under the seasonal weather conditions occurring on shipping lines. The method makes use only of basic design parameters, and may be applied in preliminary design phase of container ships.

Introduction

During ship design, one of the crucial parameters determining the economic viability of a ship is its service speed under the seasonal weather conditions typical of given shipping line (or several lines). The service speed for an existing ship can be determined during its operation, or calculated on the basis of complete design documentation or the results of ship model basin tests. The algorithm and results of such calculations were presented in (Szelangiewicz & Żelazny, 2006; 2007a, 2007b). The method cannot, however, be used in the preliminary ship design phase where important decisions are made on the basis only of the main design parameters (factors concerning ship hull geometry) which a ship designer then has at his disposal. For this reason, a contract speed – to be checked in calm water trials after completing the ship – is introduced into a ship building contract. Ship economic effectiveness mainly depends on service speed achieved under actual weather conditions (instantaneous or seasonal). Hence, development of a method that could be used in the preliminary design stage to estimate service speed would make it possible to optimize ship design parameters from the perspective of the ship-owner's profitability on a given shipping line.

Ship propulsion

In order to move a ship at a given speed, the ship propeller thrust, T, has to equilibrate with the total ship resistance, R_C, according to the following relationship:

$$T - \frac{R_C}{1-t} = 0 \tag{1}$$

Moreover, the engine power output, N, has to equilibrate with the propeller torque. Q, as follows:

$$Q - \frac{N\eta_G\eta_S\eta_{RT}}{2\pi n_S} = 0 \qquad (2)$$

where:

n_S – speed of engine rotation (in case of slow speed engine: $n_S = n_p$ – propeller rotational speed);

t – thrust deduction;

η_G – transmission gear efficiency (if applied);

η_S – shaft line efficiency;

η_{RT} – rotational "efficiency".

If weather conditions change during a voyage the total resistance, R_C, also changes. Hence, the propulsion engine load resulting from the torque, Q, will be changeable, too. Although the engine working can be changed by changes in power output, N, and the rotational speed, n_S, this point must still located within the engine working area. A complete algorithm for searching for the engine working point (as a function of N and n_S) under changeable weather conditions was presented by Szelangiewicz and Żelazny (Szelangiewicz & Żelazny, 2007a). Calculation results given in the publications (Szelangiewicz & Żelazny, 2007a) and (Szelangiewicz & Żelazny, 2007) were obtained from the model based on complete data concerning ship hull, screw propeller and propulsion engine. In order to make the model applicable to the preliminary design stage, estimates for the following parameters must be obtained: thrust, T, torque Q, power output, N, rotational speed, n_S, propulsion engine working area, and the coefficients t, w_T and η_{RT}.

Approximate relations for propeller thrust and torque

The mathematical model of a ship's propulsion system, developed under the assumption that complete documentation concerning screw propeller and propulsion engine is available, was presented by Szelangiewicz and Żelazny (Szelangiewicz & Żelazny, 2007a).

Calculations of exact values of thrust and torque acceleration (Szelangiewicz & Żelazny, 2007a) were conducted for 163 existing ships, with relationships developed specifically for bulk carriers, container ships, oil tankers and LNG tankers. The range of parameters found for container ships is given in Table 1.

Table 1. Range of examined parameters for container ships

Ship type		L [m]	B [m]	T [m]	C_B [–]	∇ [m^3]	V [m/s]	n_p [1/s]
Container ships	max	374.4	56.0	14.5	0.787	214620	14.7	3.12
	min	115.5	16.5	6.5	0.640	10046	2.5	0.46

The approximate model for propeller thrust and torque was developed on the basis of the results of making calculations based on these parameters. Of many tested methods, the best results were achieved by making use of artificial neural networks.

The first step in developing the model of approximating function was to determine a set of parameters which significantly affect changeability of the thrust and torque of the screw propeller, which can be known during the preliminary design stage, and which may serve as arguments of the function in question. On the basis of preliminary analyses and personal experience of the parameters of the examined groups of ships, the following quantities were finally selected to be arguments of approximating functions: ship length between perpendiculars, L, breadth, B, draught, T, hull block coefficient, C_B, displacement,∇, ship speed, V and propeller rotational speed, n_p.

The structure of artificial neural networks as well as activation functions to be used for the thrust and torque, were finally selected on the basis of a compromise between accuracy, simplicity and learning time. In order to simplify solution, the same structure (i.e. 7×11×1), Figure 1, and network parameters (input data and form of activation functions – sigmoidal and linear) were assumed for thrust and torque.

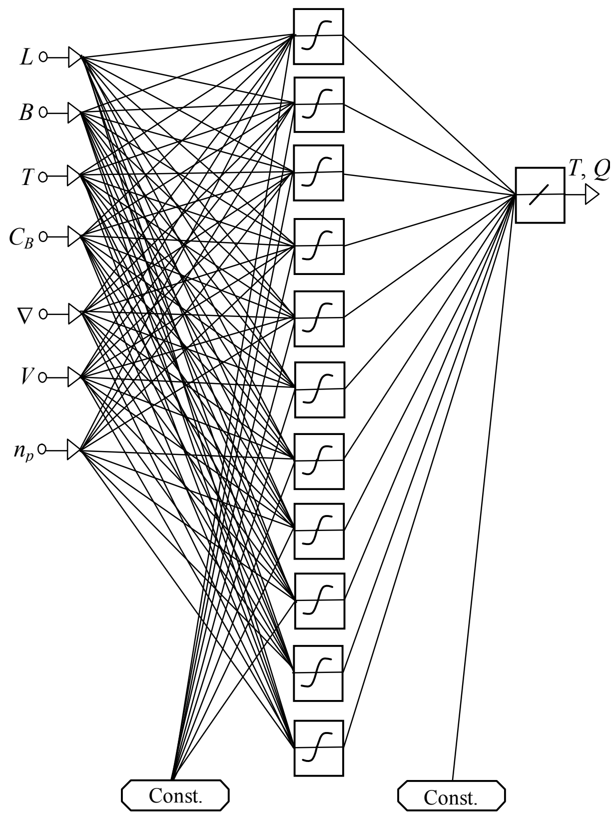


Figure 1. Structure of the designed neural network

Table 2. Values of coefficients for the network, acc. Eq. (4), which approximates the propeller thrust *T* for container ships

$a_{i,j}$	1	2	3	4	5	6	7	b_i	c_i
1	13.529	–4.516	6.843	0.237	–27.768	–0.130	–0.023	–8.469	–0.468
2	–0.931	–0.547	–0.529	–0.320	1.085	0.103	–0.703	1.678	–4.066
3	94.577	130.435	69.444	80.877	–212.077	0.018	–0.072	–149.602	–42.238
4	–1.365	16.454	–4.427	10.024	–3.484	0.067	–0.244	1.462	28.274
5	1.794	2.455	0.563	1.776	–9.202	–0.172	–0.257	–2.741	0.448
6	1.035	1.233	–0.031	2.624	–3.835	0.160	–0.880	1.668	–1.599
7	1.315	–16.646	4.551	–9.957	3.637	–0.063	0.216	–1.469	28.185
8	5.683	–2.114	1.271	–1.857	–10.439	–0.145	0.545	–4.449	–1.127
9	3.330	–1.061	0.354	–1.933	–6.141	–0.129	0.375	–2.242	1.528
10	0.593	1.850	1.262	–4.594	–10.517	–0.275	1.366	–12.741	–0.806
11	–4.251	8.947	4.543	–9.830	0.169	–0.071	0.375	8.057	–2.411
D					–36.272				

Table 3. Values of coefficients for the network, acc. Eq. (4), which approximates the propeller torque *Q* for container ships

$a_{i,j}$	1	2	3	4	5	6	7	b_i	c_i
1	–73.447	–104.641	–54.421	–77.293	163.830	0.070	–1.052	125.660	1.420
2	0.817	1.319	0.564	0.128	–1.541	0.007	0.414	–1.746	–140.910
3	–1.321	9.158	0.963	–1.264	–8.848	0.058	–0.795	1.708	–4.870
4	10.949	13.000	–6.470	9.369	–13.660	–0.008	0.093	–1.993	169.158
5	–19.287	5.776	5.805	1.263	19.698	–0.052	0.242	–0.158	93.537
6	–11.112	–13.304	6.506	–9.481	14.023	0.009	–0.100	2.077	173.157
7	–0.824	–1.316	–0.555	–0.124	1.541	–0.005	–0.422	1.767	–149.449
8	17.005	23.351	–8.431	14.061	–26.124	–0.044	0.384	–4.302	4.337
9	25.653	–26.772	–13.347	13.822	10.767	0.051	–0.436	4.056	–0.320
10	–1.501	–0.452	0.108	0.391	1.010	–0.107	–0.498	1.879	1.896
11	–19.263	5.682	5.778	1.253	19.772	–0.052	0.240	–0.138	–93.564
D					9.084				

The general form of the searched for approximating function is as follows:

$$T,Q = f\left(L, B, T, C_B, \nabla, V, n_p\right) \tag{3}$$

The approximating function developed for *T* and *Q* has the following form:

$$f(x_1 \cdots x_k) = \sum_{i=1}^{11}\left(c_i\left(\frac{2}{1+e^{-2\cdot\left(\sum_{k=1}^{7} a_{i,k}x_k + b_i\right)}} - 1\right)\right) + D \tag{4}$$

where: $x_k = [L, B, T, C_B, \nabla, V, n_p]$ are successive arguments of neural network (input data); whereas values of coefficients for each network (thrust *T* and torque *Q*) for container ships are contained in Tables 2 and 3.

The process of calculating values for the screw propeller thrust and torque, taking into account ship type, and making use of the structure and values of coefficients (weighting factors) of the designed artificial neural network, entailed the following steps:

1. Scaling (normalizing) the input data $x_k = [L, B, T, C_B, \nabla, V, n_p]$ for $x_{\max}$ and $x_{\min}$ values (minimum and maximum value of input data) from Table 1;
2. Calculating values from the network, acc. Eq. (4), and parameters in Tables 2 and 3;
3. Scaling the values obtained from the network and calculating final values for propeller thrust and torque as follows:

$$T,Q = \frac{(f(x_k)+1)(y_{\max} - y_{\min})}{2} + y_{\min} \tag{5}$$

where $y_{\min}$, $y_{\max}$ – minimum and maximum values of input quantity – numerical values from the learning set (Table 4).

Table 4. Range of examined parameters (thrust and torque) for container ships

Ship type		*T* [kN]	*Q* [kNm]
Container ships	max	15722.78	24992.25
	min	0.65	7.03

The bases for statistical verification were the correlation coefficient, R^2, the spread diagrams of expected values against observed values (i.e. estimated versus reference values), and the mean square error showing learned network quality (Table 5). Quality assessment of the estimates obtained were performed by an analysis of relative and absolute errors.

The subject matter verification was done for container ships built in Szczecin Shipyard (their

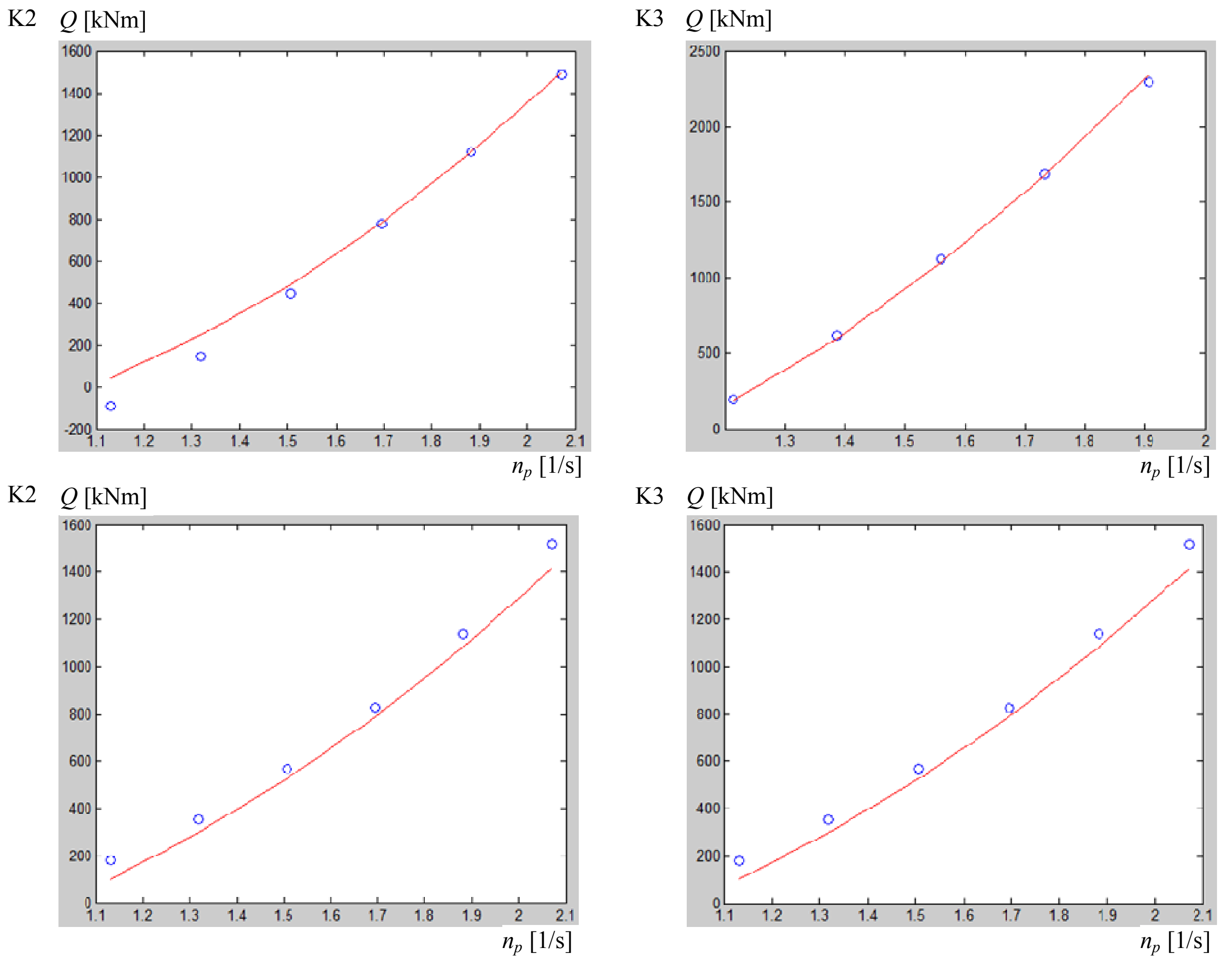


Figure 2. Propeller thrust and torque values calculated by means of the developed approximations (4) (points marked °) as well as by using the hydrodynamic characteristics of the screw propellers installed on the existing container ships

main parameters are described in Żelazny, 2015). Values of the screw propeller thrust, T, and torque, Q, calculated by with approximation (4), as well as results of the calculations performed in accordance with the algorithm given in Szelangiewicz and Żelazny (Szelangiewicz & Żelazny, 2007a), are presented in Figure 2 for the ships listed in Table 6.

Table 5. Selected statistical parameters obtained from the used neural networks for container ships

Ship type	Parameter	Correlation coefficient R^2	Mean square error
Container ships	T	0.998	0.0004
	Q	0.999	0.0002

Table 6. Basic parameters of exemplary ships used for verification of a model

Parameter	Container ships		
	K1	K2	K3
Length of the vessel L [m]	140.14	171.94	210.2
Ship breadth B [m]	22.3	25.3	32.24
Draught T [m]	8.25	9.85	10.5
Bulk coefficient C_B [–]	0.641	0.698	0.646
Waterplane coefficient C_{WP} [–]	0.809	0.828	0.807
Displacement ∇ [m^3]	17290	29900	47250
Ship speed V [m/s]	8.44	9.62	11.37

Approximate models for power output, rotational speed, and working area of propulsion engine

Ship propulsion engine working area is defined by its characteristics (see, for example, Szelangiewicz & Żelazny, 2007a). In order to calculate a ship's service speed and determine the engine working point for a designed ship, it is necessary to know rated values of power output and rotational speed of propulsion engine. Such values for the task in question were determined by analyzing the collected technical and operational data for existing ships.

Approximate models for engine power output

The propulsion engine rated power, N_n, for container ships, was approximated by using a linear regression. The analysis was performed for functional relations of only one parameter, or for the product of some parameters as an argument. In the case of engine power, a model of approximating function was also searched for a dependable variable in the form of the rated power/ship speed ratio N_n/V.

The best fit degree (R^2 = 0.9464) was reached for the model: $N_n/V = f(F_W)$, as shown in Figure 3.

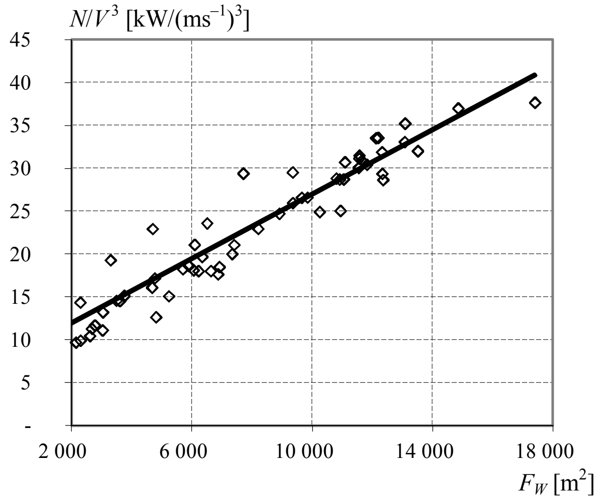


Figure 3. Approximation of the rated power/ship speed ratio N_n/V in function of F_W ($F_W = L·B·C_{WP}$, where: C_{WP} – water plane coefficient) for container ships

The following engine power approximation (of the auxiliary variable N_n/V in the function for F_W), was selected for further analysis:

$$N_n = (-2 \cdot 10^{-6} F_W^2 + 0.2 F_W + 219.44)V \tag{6}$$

The rated power value estimated according to Eq. (6) was compared to the rated power taken from documentation of the existing ships.

Table 7 presents illustrative results of the comparisons and calculated accuracy (relative error) of the obtained approximations.

Table 7. Accuracy of the calculated value of the propulsion engine rated power N_n for container ships

Ship No.	Power N_n [kW] according to ship's documentation	Power N_n [kW] according to approximation Eq. (6)	Relative error [%]
K1	6930	7745	11.8
K2	13320	13314	3.2
K3	26270	27234	3.7

Approximate models for rotational speed of propulsion engine

A search for an approximating function for the rated rotational speed of propulsion engine, n_{ns}, was conducted in relation to ship's length, L, displacement, ∇, draught, T and the product $L·B·C_{WP}$. The best results (R^2 = 0.685) were reached for the relationship of the engine rated rotational speed versus the ship's draught for container ships, i.e. $n_{ns} = f(T)$ as expressed by the expression:

$$n_{ns} = 4.5526 T^{-0,3986} \tag{7}$$

Figure 4 graphically shows the accuracy of the obtained approximations.

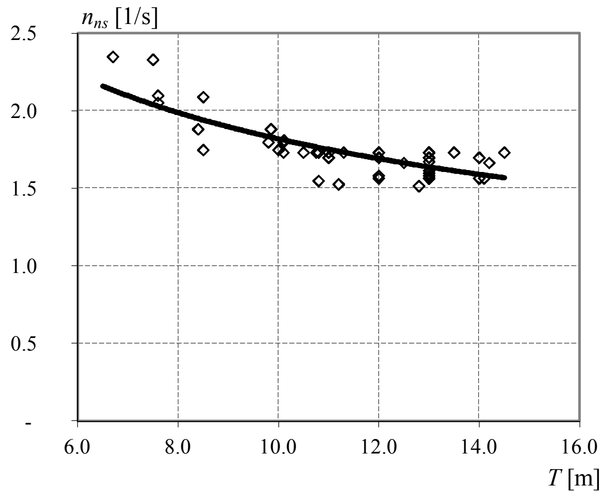


Figure 4. Approximation of the engine rated rotational speed in function of ship's draught, $n_{ns} = f(T)$, for container ships

The obtained value of the rated rotational speed, n_{ns}, estimated according to Eq. (7), was compared with the rated rotational speed specified in documentation of the existing ships. Table 8 presents illustrative results of the comparisons and the calculated accuracy (relative error) of the achieved approximations.

Table 8. Accuracy of the calculated value of the rated rotational speed n_{ns} of propulsion engine for container ships

Ship No.	Rotational speed n_{ns} [1/s] according to ship's documentation	Rotational speed n_{ns} [1/s] according to approximation Eq. (7)	Relative error [%]
K1	2.33	1.96	15.90
K2	1.88	1.83	2.90
K3	1.73	1.78	2.87

Approximation of propulsion efficiency coefficients

The relationships of the Holtrop–Mennen method were applied (Holtrop, 1984; 1988) to calculate values of the thrust deduction coefficient, t, the wake coefficient, w_T, and the rotational "efficiency," η_{RT}, for all the ships, taking into account the ship type. Because ship parameters unknown in preliminary design stage are used in the method, the values calculated on its basis were considered "reference values" for the approximations sought.

In searching for appropriate approximating functions, the thrust deduction coefficient, t, the wake coefficient, w_T, and the rotational "efficiency," η_{RT}, were determined by using the multifold regression method, and arguments for these functions were selected on the basis of parameters developed by Holtrop–Mennen (Holtrop & Mennen, 1982).

Table 9 shows the approximating functions that were obtained for the thrust deduction coefficient,

Table 9. Forms of the functions and degree of model fit for approximating the thrust deduction coefficient, t, wake coefficient, w_T, and rotational "efficiency," η_{RT}, for container ships

Ship type	Function form	R^2 – model-fit degree	Estimation standard error
Container ships	$t = 0.122934 + 0.451801\frac{B}{L} + 0.000023TB$	0.911	0.0024
	$w_T = -0.4612 - 0.000455L + 0.005854B - 0.01067T + 1.1745C_P$	0.967	0.0086
	$\eta_{RT} = 0.972764 - 0.000139L + 0.081712C_P$	0.908	0.0026

Table 10. Accuracy of calculated values of the thrust deduction coefficient t, wake coefficient w_T, and rotational "efficiency" η_{RT} for reference container ships

Ship No.	t_{wz}* [–]	t_{ap}** [–]	δt*** [%]	w_{Twz}* [–]	w_{Tap}** [–]	δw_T*** [%]	η_{RTwz}* [–]	η_{RTap}** [–]	$\delta\eta_{RT}$*** [%]
K1	0.2033	0.1991	2.09	0.2587	0.3163	–22.25	1.0071	1.0087	–0.16
K2	0.1991	0.1951	1.99	0.3265	0.3387	–3.74	1.0131	1.0068	0.62
K3	0.1979	0.2000	–1.07	0.2904	0.3115	–7.27	1.0012	0.9985	0.27

* reference values calculated by means of Holtrop-Mennen method (Holtrop, 1977; 1984; 1988; Holtrop & Mennen, 1982),
** values obtained from the approximations – Table 9,
***relative error.

the wake coefficient, and the rotational "efficiency" for container ships, as well as the value of the correlation coefficient, R^2, and the standard error of estimation.

Table 10 presents calculation results (taking accuracy into account) of the values of the thrust deduction coefficient, t, the wake coefficient, w_T, and rotational "efficiency," η_{RT}, obtained from the approximations in Table 9 and values calculated according to Holtrop-Mennen method (Holtrop, 1977; 1984; 1988; Holtrop & Mennen, 1982) for container ships.

Mean statistical value of ship service speed on a shipping line

The purpose of the work described here is the development of a method of determining the service speed of transport ships under statistical weather conditions for a designated shipping line. Because weather conditions occurring on a given shipping line are random quantities, the method to that must be developed should take into account random wind and wave parameters, and such that the ship speed estimate will constitute a statistical service speed maintained with a specified probability. The level of probability will result from the propulsion power output for the ship being designed.

The above-mentioned task was solved in two phases:

- In the first phase, an instantaneous ship's service speed was determined on the basis of the developed parametric models concerning total ship resistance (Żelazny, 2015), propeller thrust and propulsion power, for assumed parameters of wind, sea current and waving.
- In the second phase, a mean statistical service speed of transport ship was calculated on the basis of the distribution of mean statistical, long-term (seasonal) weather parameters occurring on a given shipping line.

Instantaneous ship's service speed

When a ship moves through waves, besides the still–water resistance, the ship also overcomes resistance associated with the additional forces of wind, waves, and possibly currents effects. In addition to additional total resistance, the interactions among such forces generate a lateral force and a moment turning the ship around a vertical axis (Szelangiewicz & Żelazny, 2006). The lateral force results in ship drift, and the turning moment causes a change of course, unless the rudder is deflected to keep the ship on a set course over a given sea area under the action of the external turning moment. Assuming the ship's course must be kept constant, the instantaneous speed is calculated from two sets of equations. The first of the sets consists of the following three nonlinear equations:

$$
\begin{aligned}
R_{xC}(V) &= R_x(V,P_G,P_C) + R_{xA}(V,P_G,P_A) + \\
&\quad + R_{xW}(V,P_G,P_W) + R_{xR}(V,P_G,P_R) \\
R_{yC}(V) &= R_y(V,P_G,P_C,\beta) + R_{yA}(V,P_G,P_A,\beta) + \\
&\quad + R_{yW}(V,P_G,P_W,\beta) + R_{yR}(V,P_G,P_R,\beta,\delta_R) \\
M_{zC}(V) &= M_z(V,P_G,P_C,\beta) + M_{zA}(V,P_G,P_A,\beta) + \\
&\quad + M_{zW}(V,P_G,P_W,\beta) + M_{zR}(V,P_G,P_R,\beta,\delta_R)
\end{aligned}
\tag{8}
$$

where:

$R_{xC}(V)$, $R_{yC}(V)$, $M_{zC}(V)$ – total ship resistance components and rotating moment around the "z"-axis for a ship sailing with speed V in actual, instantaneous weather conditions;

R_x, R_y, M_z – components of still-water ship resistance and moment, with sea surface current effects taken into account;

R_{xA}, R_{yA}, M_{zA} – components of additional ship resistance and moment due to wind;

R_{xW}, R_{yW}, M_{zW} – components of additional ship resistance and moment due to waves;

R_{xR}, R_{yR}, M_{zR} – components of force and moment acting onto rudder blade;

β – ship drift angle;

δ_R – rudder deflection angle;

P_G – ship geometrical parameters;

P_A – wind parameters;

P_C – sea surface current parameters;

P_W – wave parameters;

P_R – rudder blade geometrical parameters.

Particular quantities which appear in the equation set (8) (still-water ship resistance, additional ship resistance due to sea surface current, wind, waves and rudder blade action and corresponding lateral forces and moments) are described by the parametric models presented in (Żelazny, 2015) for container ships.

From the equation set (8), solved for the preliminary assumed value of ship speed V and set parameters of wind, waves and possible sea current, the following is obtained: ship drift angle β, rudder deflection angle δR, additional ship resistance due to wind, waves and passive rudder, ΔR, as well as total ship resistance R_C.

Next, a check is made on whether the ship propulsion system is capable of keeping the assumed speed V under given weather conditions and, if not, a speed value is sought for which the following is true:

- ship total resistance is balanced by propeller thrust;
- propeller torque is equal to rotational moment of propulsion engine; and the
- propulsion engine working point lies within a given working area which may be declared during a run of calculations.

The instantaneous ship's speed sought under given weather conditions is calculated in the second phase, by solving the following set of two successive nonlinear equations:

$$\begin{aligned} T(V, P_G) - \frac{R_C(V)}{1-t} &= 0 \\ Q(V, P_G) - \frac{N(V, P_G) \cdot \eta_G \eta_S \eta_{RT}}{2\pi n_p} &= 0 \end{aligned} \qquad (9)$$

where:

T, Q – approximating functions of propeller thrust and torque, in the form of Eq. (1);

R_C – total ship resistance described by the approximating function for container ships, presented in (Żelazny, 2015);

N – propulsion engine power output approximated by the function (6) appropriate for container ships;

t – thrust deduction coefficient approximated by the function appropriate for container ships, given in Table 9;

η_{RT} – rotational "efficiency" approximated by the function appropriate for container ships, given in Table 9.

The instantaneous service speed for ship propelled by a given engine under given weather conditions can be estimated by solving the equation set (9).

Because the propulsion engine working area (Szelangiewicz & Żelazny, 2007a) is confined within appropriate characteristics, only in certain cases can an assumed speed V be maintained. If the additional resistance due to wind and waves is too large, then an attainable ship speed will be estimated from one of the characteristics limiting the working area of the engine (Szelangiewicz & Żelazny, 2007a). After calculation of the instantaneous ship's speed under given weather conditions, the parameters of a ship's sea-going qualities are calculated and, if they are exceeded, the ship's speed will be reduced.

Calculation results of service speed for illustrative container ships on selected shipping lines

Equation sets (8) and (9) are solved for all weather parameters occurring on sea areas crossed by given shipping lines, and relevant calculations are performed for a set value of ship speed V and set values of course angle ψ. For each set of weather data, a definite value of instantaneous ship's service speed is obtained.

An algorithm for calculating values of instantaneous ship's service speed for all parameters of wind and waves (mean statistical values occurring on a given shipping line) is presented in Szelangiewicz and Żelazny (Szelangiewicz & Żelazny 2007b).

Illustrative calculations for container ships are presented in Figure 5.

Table 11 provides the most important results of the calculations, the mean statistical values of the ship service speed for container ships, obtained by using two different methods, given together with

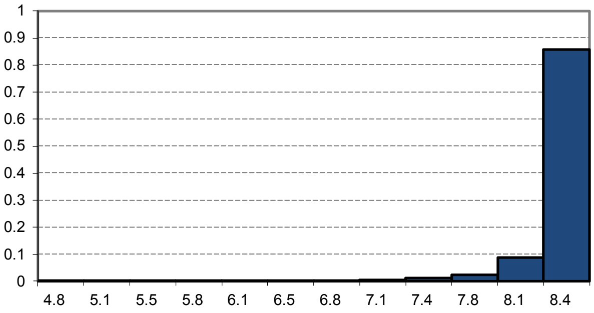
Mean statistical service speed of container ship (mean statistical seasonal weather conditions)

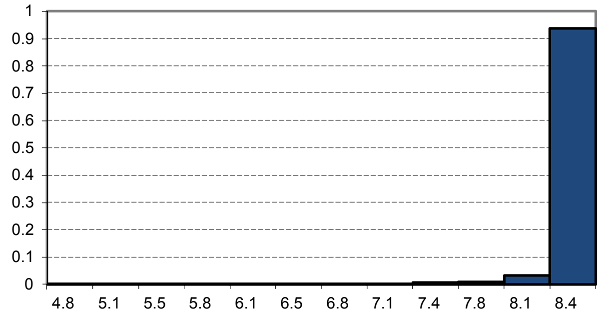
Ship: K1, Route No. 2a

Calculations acc. algorithm:
(Szelangiewicz & Żelazny, 2006; 2007a; 2007b)

Calculations based on approximation

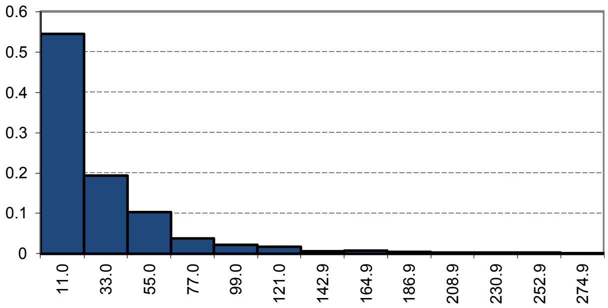
Histogram of service speed

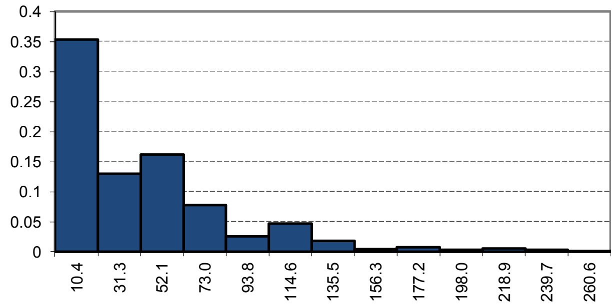




Calculations acc. algorithm			Calculations based on approximation		
Set service speed [m/s]	V_{ZE}	8.44	Set service speed [m/s]	V_{ZE}	8.44
Mean speed [m/s]	$\overline{V}_E$	8.34	Mean speed [m/s]	$\overline{V}_E$	8.38
Occurrence probability of V_{ZE} [%]	P_{VE}	86.7	Occurrence probability of V_{ZE} [%]	P_{VE}	93.8

Histogram of additional resistance





Calculations acc. algorithm			Calculations based on approximation		
Still-water resistance for ship speed V_K [kN]	R	462.0	Still-water resistance for ship speed V_K [kN]	R	437.9
Mean additional resistance [kN]	$\Delta\overline{R}$	32.58	Mean additional resistance [kN]	$\Delta\overline{R}$	46.75
Resistance increase [%]		7.05	Resistance increase [%]		10.68

Figure 5. Histograms of ship service speed and additional ship resistance obtained from the "reference" calculations, as well as those based on approximation, for K1 ship sailing on route No. 2a

Table 11. The relative calculation error (δV_E) of mean statistical values of the ship service speed $\overline{V}_E$ obtained from approximating formulae in relation to the "reference" calculation results (Szelangiewicz & Żelazny, 2006; 2007a; 2007b) for existing container ships on selected shipping routes

Container ships (Żelazny, 2015)	Shipping route (Szelangiewicz & Żelazny, 2007b)											
	2a			2b			9a			9b		
	$\overline{V}_E$ [m/s] refer.	$\overline{V}_E$ [m/s] appr.	δV_E[%]	$\overline{V}_E$ [m/s] refer.	$\overline{V}_E$ [m/s] appr.	δV_E[%]	$\overline{V}_E$ [m/s] refer.	$\overline{V}_E$ [m/s] appr.	δV_E[%]	$\overline{V}_E$ [m/s] refer.	$\overline{V}_E$ [m/s] appr.	δV_E[%]
K1	8.34	8.38	0.5	8.21	8.30	1.1	8.35	8.38	0.4	8.33	8.37	0.5
K3	11.3	11.34	0.4	11.21	11.30	0.8	11.36	11.35	0.1	11.31	11.5	0.4

Route No. 2a – East USA – West Europe; Route No. 2b – West Europe – East USA;
Route No. 9a – Persian Gulf – Africa – West Europe; Route No. 9b – West Europe – Africa – Persian Gulf

relative error between results achieved from the developed parametric methods and from calculations according to the algorithms presented in Szelangiewicz and Żelazny (Szelangiewicz & Żelazny, 2006; 2007a; 2007b).

Conclusions

On the basis of the analysis described above, the following conclusions may be offered:

- The relative calculation error of the mean statistical value of a ship's service speed is in the range of 0.1% to 2.0%, depending on the ship and route examined; thus, the accuracy of service speeds estimated by using the parametric developed here is quite high;
- When calculating the service speed with the parametric methods developed in this paper, the same trend is observed as if exact methods (the

"reference" calculations acc. of Szelangiewicz & Żelazny, 2006; 2007a; 2007b) are used. Specifically, whenever reference calculations estimated a service speed for a "less difficult" route that were greater than for a "more difficult" route, the same ordinal ranking was seen between the comparable vales estimated by the parametric model;

- The results of calculations shown here indicate that not all analyzed ships, have been properly designed, particularly in regard to their propulsion system. This is evident from a comparison of calm-water contract speeds with their service speeds on a given shipping line assuming mean statistical weather conditions.

Żelazny's monograph (Żelazny, 2015) provides service speed estimates for bulk carriers, oil tankers and LNG tankers assuming mean statistical weather conditions.

The method developed here may be also applied to optimizing design parameters as early as the preliminary design stage, especially for maximizing a ship owner's profits from future operation of a ship built for a particular route (Abramowski, 2011). It can be also used to plan a ship's route (Szelangiewicz, Wiśniewski & Żelazny, 2014a; 2014b).

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