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Form Factor Determination of the Full, Large Breadth and Shallow Draught Ship Series

Original scientific paper

By using the traditional approach, the total resistance can be broken down into Froude and Reynolds number dependent components. These are then scaled according to their respective scaling laws. The common practical method of separating the resistance components is by the use of a form factor to estimate the total viscous component. This paper presents the form factor determination of the full ships with large breadth and shallow draught for full load and ballast conditions using Prohaska's method. Form factors have been determined from the results of resistance tests carried out in *Brodarski institute* with ship models of the *Jelsa* series. Since full ships with block coefficients C_B > 0.8 are concerned, higher powers of the Froude number, *n* = 4 ÷ 6, have been used in the expression for the wave resistance. Obtained values for the total resistance have been compared with measured ones. It has been shown that all three powers give satisfactory agreement of results.

Keywords: *form factor, Prohaska's method, total resistance, viscous resistance, wave resistance.*

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Određivanje faktora forme serije punih brodova velike širine i malog gaza

Izvorni znanstveni rad

Primjenom tradicionalnog pristupa ukupni otpor se može razložiti na komponente ovisne o Froudeovom i Reynoldsovom broju, koje se prenose s modela na brod prema odgovarajućim zakonima sličnosti. Uobičajena praktična metoda razdvajanja komponenti otpora je primjenom faktora forme kako bi se procijenila komponenta ukupnog viskoznog otpora. U radu je prikazano određivanje faktora forme punih brodova velike širine i malog gaza za puno opterećenje i balast metodom Prohaske. Faktori forme određeni su na temelju rezultata modelskih ispitivanja serije *Jelsa* provedenih u *Brodarskom institutu*. Budući da se radi o punim brodovima s koeficijentima punoće C_B > 0,8, upotrebljene su više potencije Froudeovog broja, *n* = 4 ÷ 6, u izrazu za otpor valova. Dobivene vrijednosti ukupnog otpora uspoređene su sa izmjerenim vrijednostima i pokazano je da sve tri potencije daju zadovoljavajuće slaganje rezultata.

Ključne riječi: *faktor forme, otpor valova, Prohaskina metoda, ukupni otpor, viskozni otpor.*

Nomenclature

a	coefficient / koeficijent
B_{WL}	breadth on waterline, *m* / širina na vodnoj liniji
C_F	frictional resistance coefficient / koeficijent otpora trenja
C_T	total resistance coefficient / koeficijent ukupnog otpora
C_V	viscous resistance coefficient / koeficijent viskoznog otpora
C_W	wave resistance coefficient / koeficijent otpora valova
Fn	Froude number / Froudeov broj
g	acceleration of gravity, m/s^2 / gravitacija
k	form factor / faktor forme
L_{PP}	length between perpendiculars, m / duljina broda između okomica
L_{WL}	length on waterline, m / duljina broda na vodnoj liniji
n	power of Froude number / potencija Froudeovog broja
R_F	frictional resistance, N / otpor trenja
R_T	total resistance, N / ukupni otpor
R_V	viscous resistance, N / viskozni otpor
R_W	wave resistance, N / otpor valova
Rn	Reynolds number / Reynoldsov broj
T	draught mean, m / srednji gaz broda
S	wetted surface of bare hull, m / oplakana površina golog trupa
x_{CB}	longitudinal distance of centre of buoyancy abaft amidship, m / uzdužni položaj težišta istisnine od sredine broda
∇	displacement volume, m^3 / volumen istisnine
v	ship speed, m/s / brzina broda
ρ	water density, kg/m^3 / gustoća vode
C_B	block coefficient (on the basis of L_{PP}) / koeficijent punoće (na temelju L_{PP})
C_{BWL}	block coefficient / koeficijent punoće
C_{WP}	load waterline coefficient / koeficijent punoće vodne linije

C_P	prismatic coefficient / prizmatički koeficijent
C_X	maximum transverse section area coefficient / koeficijent punoće najvećeg poprečnog presjeka
B_{WL}/T	breadth on waterline-draught ratio / omjer širine na vodnoj liniji i gaza
L_{WL}/B_{WL}	length on waterline-breadth on waterline ratio / omjer duljine na vodnoj liniji i širine na vodnoj liniji
(M)	length-displacement ratio / omjer duljine i istisnine
(S)	wetted surface coefficient / koeficijent oplakane površine

1 Introduction

In recent years, the development of full form ships has taken a specific direction because of the demand for an increase in ship economics and limitations of main dimensions. These limitations are conditioned by the depth of ports and waterways, and length of cargo quays. The economics is expressed by the ship-owner's requirement for the transport of maximum possible cargo quantity with minimum fuel consumption. This, together with the previously mentioned limitations, leads to the conclusion that ship breadth has the maximum possibility of enlargement. This has resulted in the development of full ships with something smaller L_{WL}/B_{WL} ratio, but with considerably increased B_{WL}/T ratio which can now achieve a value of up to 5.0. Block coefficient C_{BWL} has remained within the same limits ($C_{BWL} = 0.8 \div 0.85$).

Time limitation of the project drafting conditioned the calculation of the ship resistance and the required power by approximate methods based on multiannual analysis of the model test results and trials. However, approximate methods of resistance determination applied till now have not given exact results for the before mentioned form parameters. Therefore, the need for testing a new systematic model series of full, large breadth and shallow draught ships has arisen. The *Jelsa* series has been developed within the scope of the research program dealing with the development of new hulls and methods for the optimization of hydrodynamic performances of actual and perspective ship types. The research was performed in *Brodarski institute* in Zagreb, [1], in cooperation with shipyards *3. maj*, *Brodosplit* and *Uljanik*.

As the resistance of the full-scale ship can not be measured directly, it is determined from model tests. The measured calm water resistance is usually decomposed into various components, [2], although all these components interact mutually and most of them can not be measured individually.

The calm water resistance of a ship is a result of shear and normal stresses acting on the wetted surface of a ship. The shear stress is due to the viscosity of the fluid, while the normal stress can be divided into two components: wave making and a viscous pressure component. The first one is due to the generation of free surface gravity waves and the second one is caused by a pressure deficit at the stern due to the presence of the boundary layer.

The standard procedure is to break down the total resistance into viscous and wave resistance components. The wave resistance can be decomposed into wave pattern and wave breaking resistance components, where the latter is present for ships with high block coefficient. The viscous resistance includes the resistance due to shear stress (friction resistance) and the viscous pressure resistance (form resistance). Viscous resistance is usually estimated by using "ITTC-57 model-ship correlation line" for C_F and appropriate form factor. C_F is an approximation for the skin friction of a flat plate and the form factor accounts for the three-dimensional nature of the ship hull. This includes the effect of the hull shape on the boundary layer growth and also on the viscous pressure resistance component. The ITTC-57 correlation line is an empirical fit and some form effect is included. Thus it can be written as:

$$R_T(Rn, Fn) = R_V(Rn) + R_W(Fn) = (1+k)\,R_F(Rn) + R_W(Fn) \quad (1)$$

The form factor can be determined by different methods: direct measurement of viscous and/or wave pattern resistance, Prohaska's method from slow speed data, Huges' method based on geosim data and full scale thrust measurements.

2 Basic Form and the *Jelsa* Series Geometry

The *Jelsa* systematic series is a series of full ships with large breadth and shallow draught, consisting of thirteen models and one control model. This series has arisen from the need to estimate the resistance of full ships with large breadth-draught ratio because approximate methods for resistance determination for such form parameters do not give satisfactory results. The basic form, the M-938 ship model, Figure 1, is formed by slight modification of the main dimensions of the ship type *Argosy*, which was constructed in the *3. maj* shipyard in Rijeka.

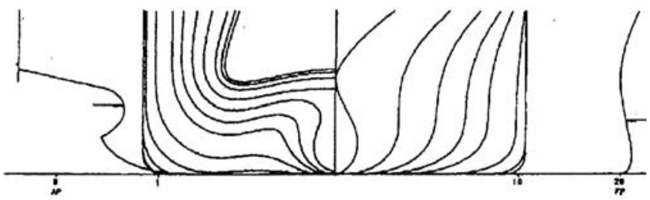
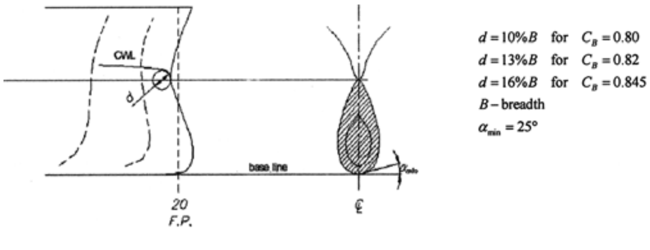


Figure 1 **Body plan, fore and aft contour of the basic form, the M-938 ship model**
Slika 1 **Nacrt rebara, pramčana i krmena kontura osnovne forme, model M-938**

Previous model tests of full ship type *Argosy* have shown that the combination of VHC-bulb bow and butterfly stern with bulb is the best possible solution of the hull form for ships of these characteristics. Consequently, the same form of the bow and stern is adopted for all models of the *Jelsa* series. VHC-bulb bow (V-vertical, H-horizontal, C-cylinder), Figure 2, [3], developed at *Brodarski institute* in Zagreb, is suitable for ships with fuller waterlines for the purpose of transition moderation between bow taper and bow shoulder. Also, such bow lowers the height of the bow wave, which results in a decrease in the required power for wave resistance overcome. Butterfly stern with bulb, Figure 3, [3], has also been developed in *Brodarski institute* in Zagreb for ships with limited draught, i.e. with large breadth-draught ratio.

Figure 2 **VHC – bulb bow**
Slika 2 **VHC – bulb forma pramca**



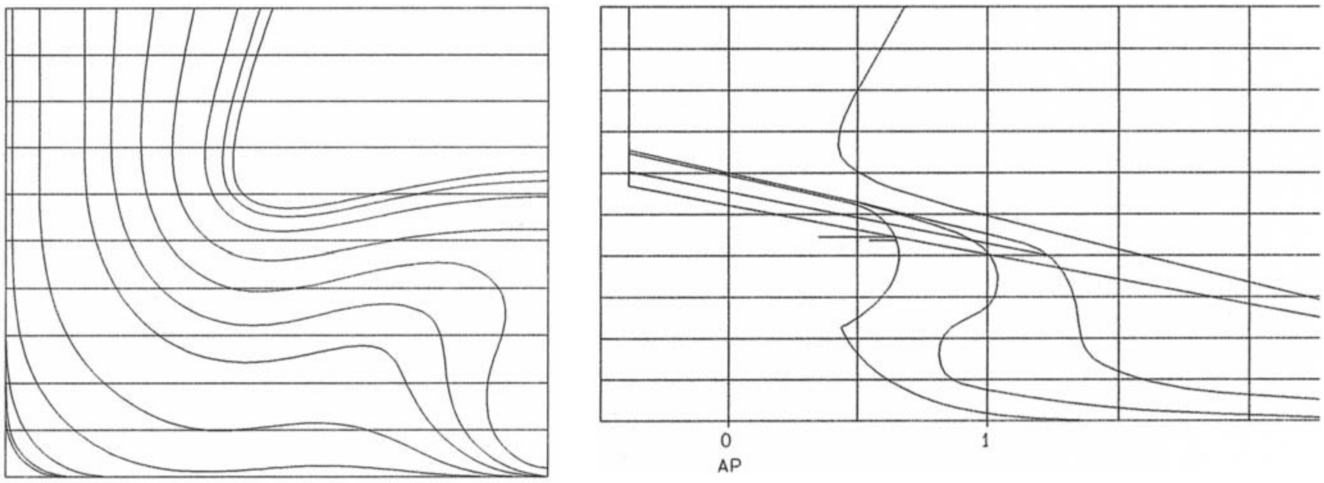


Figure 3 **Butterfly stern with bulb**
Slika 3 **Leptir krma s bulbom**

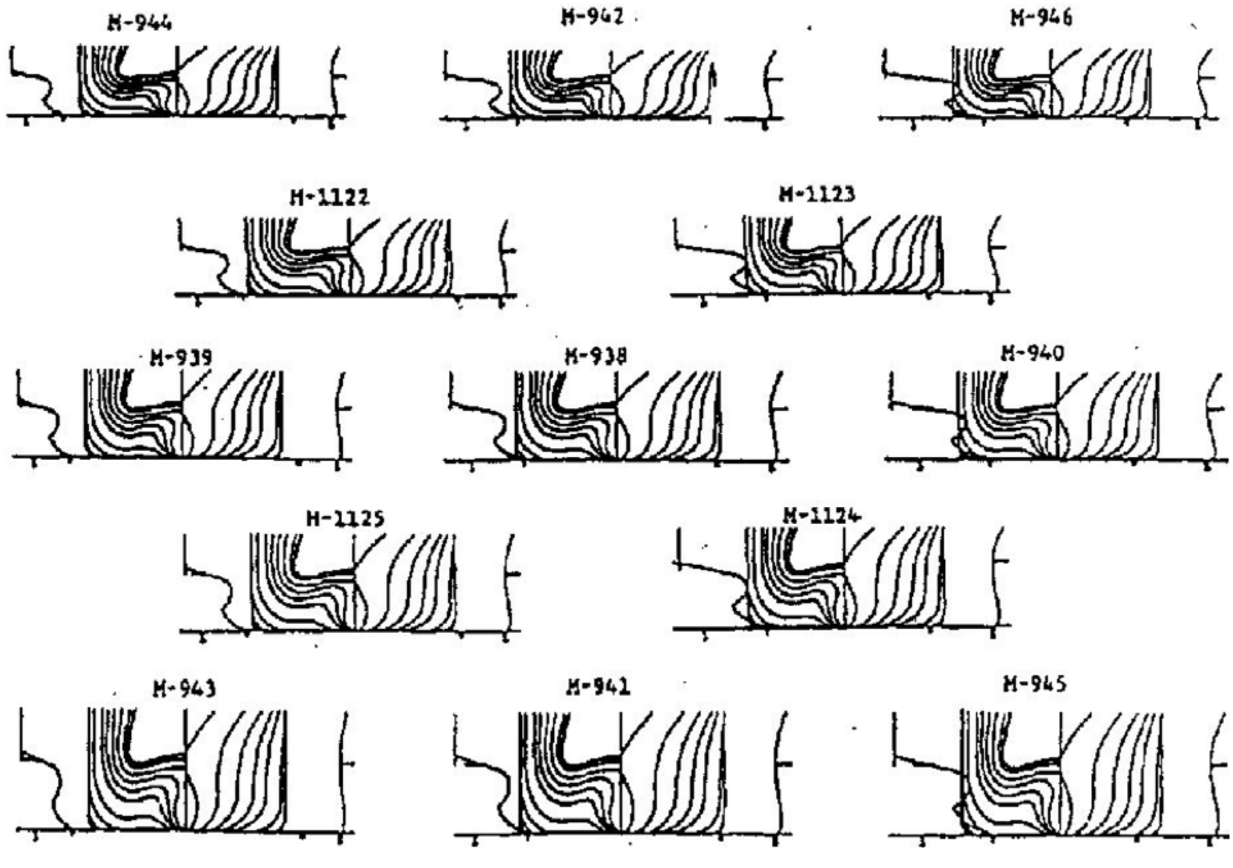


Figure 4 **Geometry of the *Jelsa* series ship models**
Slika 4 **Geometrija modela serije *Jelsa***

The stern form has been faired along buttocks because the flow around the form takes place approximately along these curves. In that way the streamline curvature decreases, so this stern form results in a more uniform wake distribution (circular form of the equal wake curves) and a higher water flow velocity in the upper part of the propeller disc. Although the average nominal wake across the propeller disc is considerably lower than for classic forms, this stern form enables a propeller arrangement of a bigger diameter with higher efficiency. The stern taper on the sides is made as smooth as possible, which decreases the viscous pressure resistance component. The butterfly form of the stern withstands bigger displacement and enables sharper bow, resulting in the shift of the centre of buoyancy towards stern. The geometry of the *Jelsa* series ship models is shown in Figure 4, [4].

2.1 Overview of the *Jelsa* series for full load condition

In the analysis of Prohaska's method suitability it is necessary to distinguish different ship load conditions, i.e. full load and ballast conditions.

Ship models of the series have different ratios L_{WL} / B_{WL}, B_{WL} / T, and a constant block coefficient and displacement volume. For full load condition, the following values apply:

$$\frac{L_{WL}}{B_{WL}} = 3.75 \div 7.25$$

$$\frac{B_{WL}}{T} = 3.0 \div 5.0$$

$$C_{BWL} = 0.835$$

A scheme of the *Jelsa* series for full load condition is shown in Figure 5. Main characteristics of ship models for full load condition are given in Table 1.

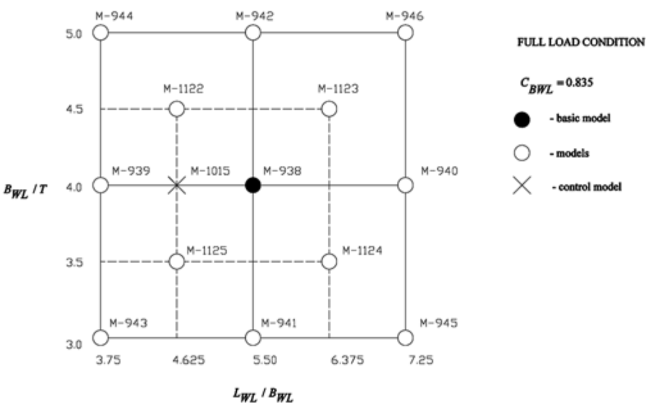


Figure 5 **Scheme of the *Jelsa* series for full load condition**
Slika 5 **Shema serije *Jelsa* za puno opterećenje**

2.2 Overview of the *Jelsa* series for ballast condition

Ship models of the series have different ratios L_{WL} / B_{WL}, B_{WL}/T, and a constant block coefficient and displacement volume. For ballast condition, the following values apply:

$$\frac{L_{WL}}{B_{WL}} = 3.56 \div 6.89$$

$$\frac{B_{WL}}{T} = 4.58 \div 7.74$$

$$C_{BWL} = 0.787$$

A Scheme of the *Jelsa* series for ballast condition is shown in Figure 6. Main characteristics of ship models for ballast condition are given in Table 2.

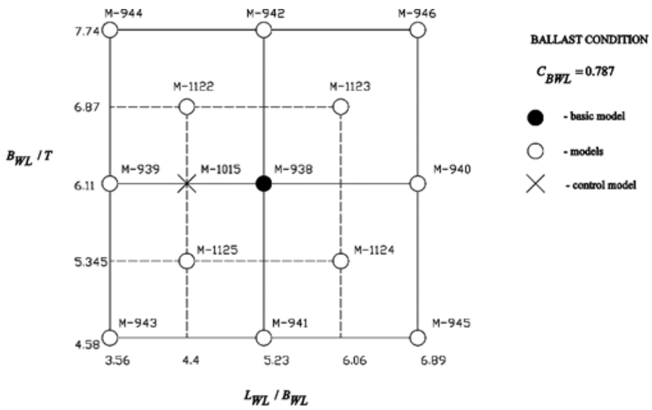


Figure 6 **Scheme of the *Jelsa* series for ballast condition**
Slika 6 **Shema serije *Jelsa* za balast**

Table 1 **Main characteristics of ship models, full load condition**
Tablica 1 **Glavne značajke modela, puno opterećenje**

MODEL	M-938	M-939	M-940	M-941	M-942	M-943	M-944	M-945	M-946	M-1015	M-1122	M-1123	M-1124	M-1125
∇ (m^3)	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283	1.283
x_{CB} (%L_{PP})	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862	1.862
L_{WL}/B_{WL}	5.500	3.750	7.250	5.500	5.500	3.750	3.750	7.250	7.250	4.625	4.625	6.375	6.375	4.625
B_{WL}/T	4.000	4.000	4.000	3.000	5.000	3.000	5.000	3.000	5.000	4.000	4.500	4.500	3.500	3.500
L_{PP}/L_{WL}	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
$\textcircled{M}$	5.191	4.021	6.240	4.716	5.591	3.654	4.332	5.670	6.723	4.625	4.810	5.959	5.480	4.424
$\textcircled{S}$	6.564	5.782	7.194	6.039	7.107	5.322	6.260	6.617	7.791	6.198	6.452	7.179	6.614	5.945
C_{BWL}	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835	0.835
C_B	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832	0.832
C_P	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836
C_X	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995
C_{WP}	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898	0.898

Table 2 **Main characteristics of ship models, ballast condition**
Tablica 2 **Glavne značajke modela, balast**

MODEL	M-938	M-939	M-940	M-941	M-942	M-943	M-944	M-945	M-946	M-1015	M-1122	M-1123	M-1124	M-1125
∇ (m^3)	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809	0.809
x_{CB} (%L_{PP})	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870	0.870
L_{WL}/B_{WL}	5.230	3.560	6.890	5.230	5.230	3.560	3.560	6.890	6.890	6.400	4.400	6.060	6.060	4.400
B_{WL}/T	6.110	6.110	6.110	4.580	7.740	4.580	7.640	4.580	7.740	6.110	6.870	6.870	5.340	5.340
L_{PP}/L_{WL}	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031	1.031
Ⓜ	6.052	4.690	7.278	5.500	6.554	4.261	5.052	6.612	7.840	5.394	5.609	6.950	6.390	5.158
Ⓢ	7.522	6.617	8.253	6.733	8.360	5.919	7.307	7.385	9.110	7.100	7.466	8.319	7.490	6.720
C_{BWL}	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0.787
C_B	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.750	0.758
C_P	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769	0.769
C_X	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
C_{WP}	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899	0.899

The *Jelsa* series has arisen from the basic form M-938 with the development of thirteen models with the same block coefficient and same displacement volume for the same loading condition. The development of the series is based on three essential equations:

$$\nabla = C_{BWL} \cdot L_{WL} \cdot B_{WL} \cdot T = \text{const}$$
$$L_{WL} / B_{WL} = \text{const}$$
$$B_{WL} / T = \text{const}$$

Model tests of the *Jelsa* series were carried out within the project "Investigation of optimal forms of wide ships with shallow draught", [1]. Ship models were made of paraffin wax in the scale 1:45. Trip wire of 1mm in diameter placed at the station No. 19 was used as a turbulence stimulator. The surface of all models was technically smooth. Displacement volumes of all models for full load and ballast conditions were ∇ = 1.283 m^3 and ∇ = 0.809 m^3, respectively.

The following tests were carried out: resistance tests, self propulsion tests, open water tests, measurements of wake field and streamline tests with paint.

During tests the models were towed by a horizontal force at different speeds. The point of application of the towing force was in the centre of buoyancy. Ship models had all degrees of freedom except the deflection from the line in the horizontal plane.

3 Prohaska's method

Prohaska's method, [5], is based on the Hughes' method, [6], but the two methods differ in the definition of the form factor. Prohaska defines the three-dimensional form factor as follows:

$$k = \frac{C_V - C_F}{C_F} = \frac{C_V}{C_F} - 1 \tag{2}$$

$$\frac{C_V}{C_F} = 1 + k \tag{3}$$

where C_V is the viscous resistance coefficient and C_F is the friction resistance coefficient in two-dimensional flow.

If no separation is present, the total resistance coefficient can be written as:

$$C_T = (1+k) \cdot C_F + C_W \tag{4}$$

with the wave resistance coefficient C_W assumed in the following form:

$$C_W = a \cdot Fn^n \tag{5}$$

where a is a coefficient and Fn is the Froude number.

Power n varies, depending on the block coefficient C_B, between 4 and 6.

Dividing the expression (4) for the total resistance coefficient by the friction resistance coefficient results in the following equation:

$$\frac{C_T}{C_F} = (1+k) + \frac{C_W}{C_F} = (1+k) + a \cdot \frac{Fn^n}{C_F} \tag{6}$$

If the wave resistance component in a low speed region is assumed to be a function of Fn^n, the straight line plot of C_T/C_F versus Fn^n/C_F will intersect the ordinate (Fn = 0) at (1 + k), enabling the form factor to be determined. For drawing such straight line it is necessary to measure about ten points in the Froude number range $Fn = 0.1 \div 0.2(0.22)$, because in that range the wave resistance is negligible. The uncertainty of measuring resistance at very low speed is relatively large, which means that it is difficult to determine the "run-in-point" exactly. Friction resistance coefficient is calculated according to the "ITTC-57 model-ship correlation line":

$$C_F = \frac{0.075}{(\log Rn - 2)^2} \tag{7}$$

For full hull forms, $C_B > 0.8$, the points may plot on concave curves indicating that either (1 + k) or a, or both, are speed dependent. It is more appropriate for full ships to use a power of Fn between 4 and 6 instead of 4, [2].

A regression method is used to determine the magnitude of form factors. When experimental information is represented by a regression, there are two kinds of uncertainties. One is uncertainty due to the uncertainty in the original experimental results; the other is introduced if the wrong regression model is used. ITTC recommended Prohaska's method for experimental evaluation of the form factor, [7].

Viscous resistance is then calculated according to the following equation:

$$R_V = \frac{1}{2}\rho v^2 S\left(C_F\left(1+k\right)\right) \qquad (8)$$

4 Results

4.1 Full load condition

The results for full load condition, [8], are shown in Figures 7-13 and Table 3. Only the results for the central model and models with extreme values of L_{WL} / B_{WL} and B_{WL} / T are presented in this paper. Other experimental results are available on request.

Relative error between measured and calculated values of the total resistance coefficient can be determined by:

$$\text{Relative error}\left(\%\right) = \frac{C_{T,\text{measured}} - C_{T,\text{Prohaska}}}{C_{T,\text{Prohaska}}} \cdot 100 \qquad (9)$$

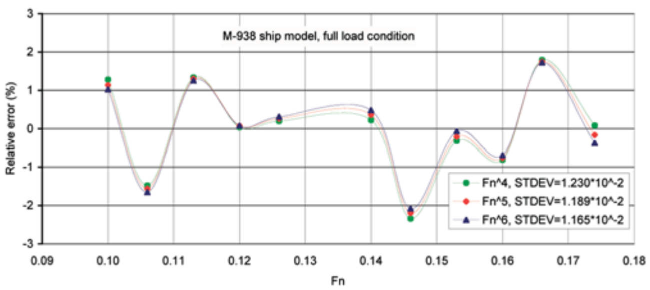
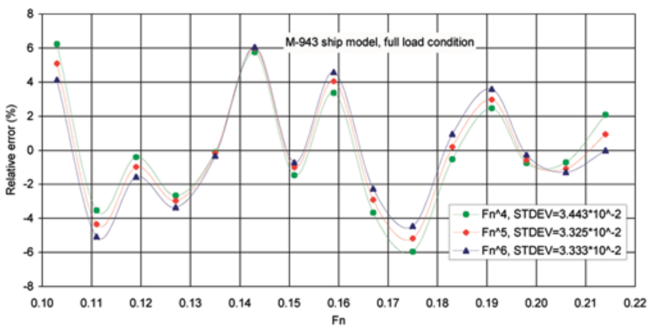


Figure 7 **Relative error comparison for the M-938 ship model, full load condition**
Slika 7 **Usporedba relativne pogreške za model M-938, puno opterećenje**

Figure 8 **Relative error comparison for the M-943 ship model, full load condition**
Slika 8 **Usporedba relativne pogreške za model M-943, puno opterećenje**



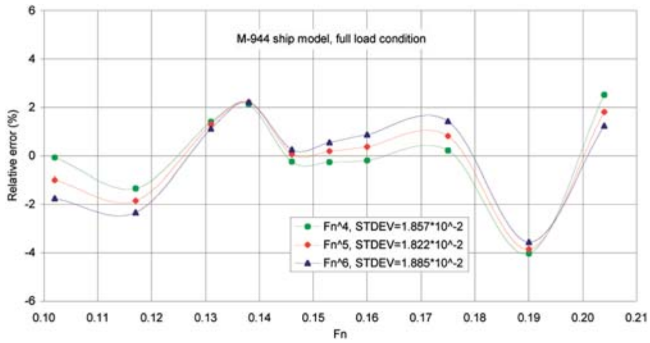


Figure 9 **Relative error comparison for the M-944 ship model, full load condition**
Slika 9 **Usporedba relativne pogreške za model M-944, puno opterećenje**

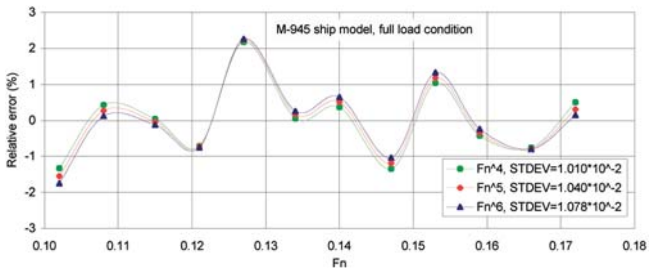


Figure 10 **Relative error comparison for the M-945 ship model, full load condition**
Slika 10 **Usporedba relativne pogreške za model M-945, puno opterećenje**

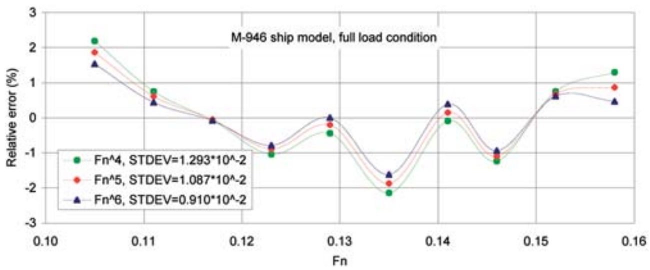


Figure 11 **Relative error comparison for the M-946 ship model, full load condition**
Slika 11 **Usporedba relativne pogreške za model M-946, puno opterećenje**

Figure 12 **Form factor as a function of the L_{WL} / B_{WL} ratio, full load condition**
Slika 12 **Faktor forme u ovisnosti o omjeru L_{WL} / B_{WL}, puno opterećenje**

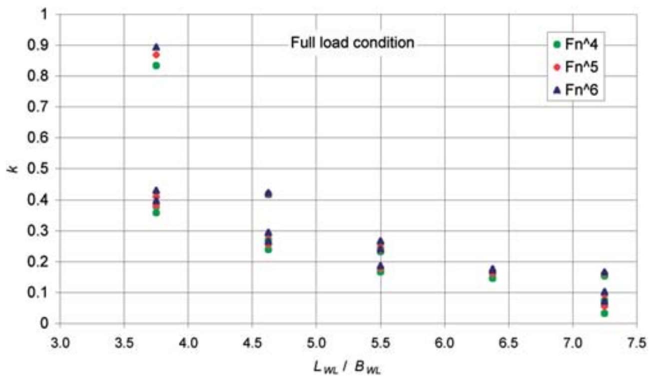


Table 3 **Form factor and maximum relative error for full load condition**
Tablica 3 **Faktor forme i maksimalna relativna pogreška za puno opterećenje**

			Fn^4		Fn^5		Fn^6	
Model	L_{WL}/B_{WL}	B_{WL}/T	Form factor, *k*	Maximum relative error, %	Form factor, *k*	Maximum relative error, %	Form factor, *k*	Maximum relative error, %
M-938	5.500	4.000	0.232	2.341	0.238	2.198	0.241	2.081
M-939	3.750	4.000	0.379	2.088	0.409	2.878	0.429	3.754
M-940	7.250	4.000	0.032	2.275	0.055	2.615	0.071	3.144
M-941	5.500	3.000	0.241	4.743	0.256	3.776	0.267	3.435
M-942	5.500	5.000	0.166	1.607	0.178	1.701	0.187	1.964
M-943	3.750	3.000	0.833	6.228	0.868	5.998	0.893	6.059
M-944	3.750	5.000	0.358	4.036	0.381	3.852	0.397	3.557
M-945	7.250	3.000	0.154	2.174	0.162	2.224	0.166	2.256
M-946	7.250	5.000	0.074	2.192	0.092	1.871	0.103	1.616
M-1015	4.625	4.000	0.27	3.746	0.285	3.435	0.295	3.192
M-1122	4.625	4.500	0.239	2.764	0.255	2.992	0.266	3.149
M-1123	6.375	4.500	0.146	6.077	0.161	5.871	0.172	5.713
M-1124	6.375	3.500	0.161	3.581	0.17	3.525	0.177	3.444
M-1125	4.625	3.500	0.417	5.532	0.419	5.463	0.421	5.433

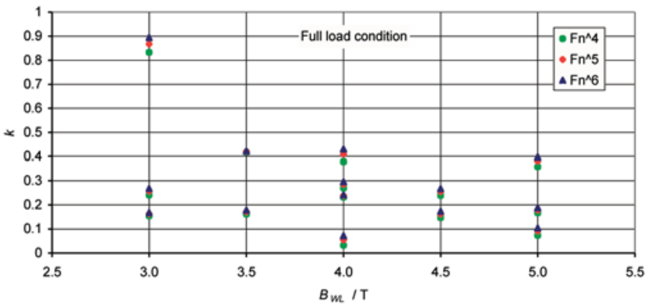
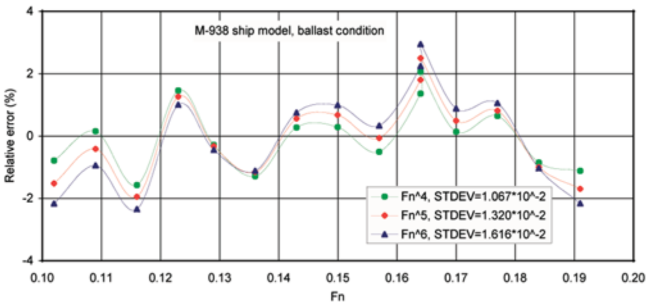


Figure 13 **Form factor as a function of the B_{WL} / *T* ratio, full load condition**
Slika 13 **Faktor forme u ovisnosti o omjeru B_{WL} / *T*, puno opterećenje**

4.2 Ballast condition

The results for ballast condition, [8], are shown in Figures 14-20 and Table 4. Only the results for the central model and models with extreme values of L_{WL} / B_{WL} and B_{WL} / *T* are presented in this paper. Other experimental results are available on request.

Figure 14 **Relative error comparison for the M-938 ship model, ballast condition**
Slika 14 **Usporedba relativne pogreške za model M-938, balast**



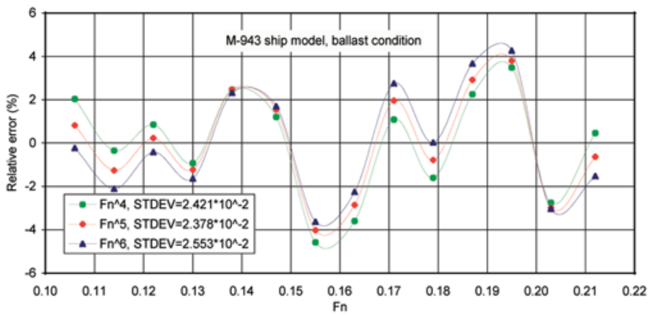
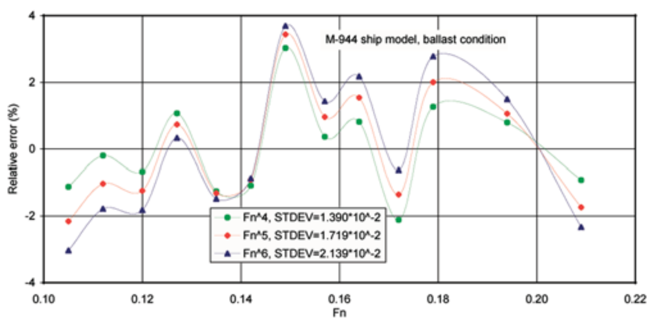


Figure 15 **Relative error comparison for the M-943 ship model, ballast condition**
Slika 15 **Usporedba relativne pogreške za model M-943, balast**

Figure 16 **Relative error comparison for the M-944 ship model, ballast condition**
Slika 16 **Usporedba relativne pogreške za model M-944, balast**



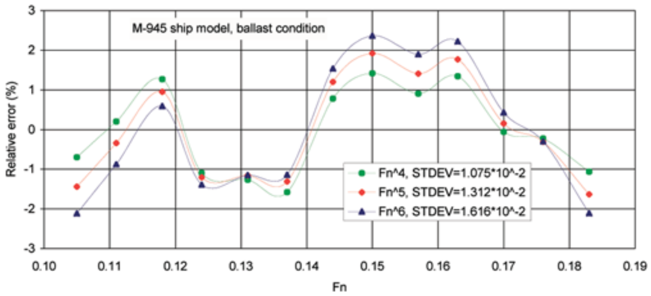


Figure 17 **Relative error comparison for the M-945 ship model, ballast condition**
Slika 17 **Usporedba relativne pogreške za model M-945, balast**

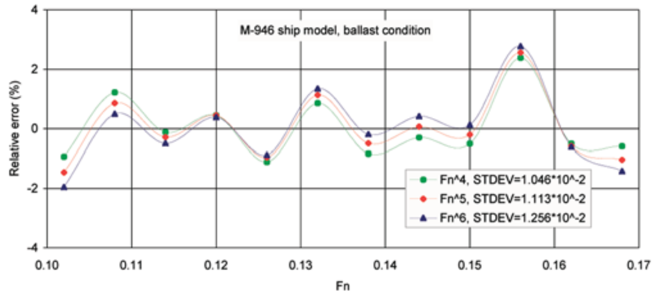


Figure 18 **Relative error comparison for the M-946 ship model, ballast condition**
Slika 18 **Usporedba relativne pogreške za model M-946, balast**

Each curve in Figures 7-11 and Figures 14-18 is identified by the standard deviation.

Table 4 **Form factor and maximum relative error for ballast condition**
Tablica 4 **Faktor forme i maksimalna relativna pogreška za balast**

			Fn^4		Fn^5		Fn^6	
Model	L_{WL} / B_{WL}	B_{WL}/T	Form factor, k	Maximum relative error, %	Form factor, k	Maximum relative error, %	Form factor, k	Maximum relative error, %
M-938	5.230	6.110	0.219	2.059	0.237	2.499	0.25	2.941
M-939	3.560	6.110	0.437	5.213	0.461	4.735	0.477	4.754
M-940	6.890	6.110	0.084	3.173	0.115	3.203	0.136	3.119
M-941	5.230	4.580	0.25	2.373	0.273	1.808	0.29	2.388
M-942	5.230	7.740	0.169	1.694	0.194	1.903	0.21	2.41
M-943	3.560	4.580	0.61	4.583	0.647	4.024	0.673	4.264
M-944	3.560	7.740	0.336	3.028	0.363	3.435	0.381	3.688
M-945	6.890	4.580	0.123	1.578	0.145	1.92	0.16	2.362
M-946	6.890	7.740	0.127	2.385	0.145	2.558	0.158	2.773
M-1015	4.400	6.110	0.288	2.173	0.308	2.049	0.322	2.347
M-1122	4.400	6.870	0.22	0.867	0.242	1.106	0.258	1.455
M-1123	6.060	6.870	0.116	4.439	0.133	4.002	0.145	3.575
M-1124	6.060	5.345	0.113	2.543	0.127	3.028	0.131	2.929
M-1125	4.400	5.345	0.304	3.161	0.324	2.592	0.337	2.528

Figure 19 **Form factor as a function of the L_{WL} / B_{WL} ratio, ballast condition**
Slika 19 **Faktor forme u ovisnosti o omjeru L_{WL} / B_{WL}, balast**

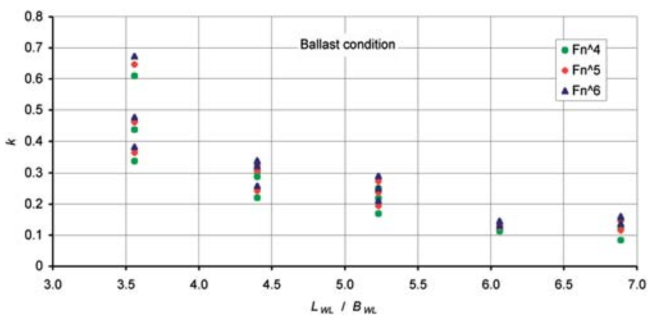
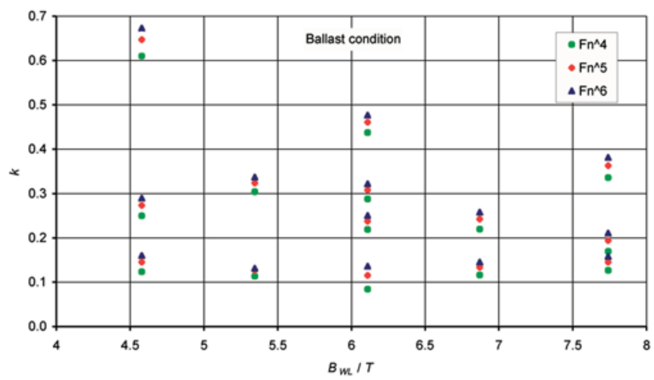


Figure 20 **Form factor as a function of the B_{WL} / T ratio, ballast condition**
Slika 20 **Faktor forme u ovisnosti o omjeru B_{WL} / T, balast**



5 Conclusions

Based on the results of resistance tests performed with fourteen models of the *Jelsa* series, (full, large breadth and shallow draught ships), the form factors for full load and ballast conditions have been determined and presented in the paper. The tests were carried out in *Brodarski institute*, Zagreb. For the form factor determination, Prohaska's method has been applied. Since full ships are concerned, greater powers of the Froude number in the wave resistance expression have been used.

In the process of the form factor determination using linear regression analysis, the values of the determination coefficient for full load condition are within the range $0.6978<R^2<0.9819$, except for the M-1125 ship model for which the range is $0.1508<R^2<0.1927$. Form factor values are within the range $0.055<k<0.893$.

In the process of the form factor determination using linear regression analysis, the values of the determination coefficient for ballast condition are within the range $0.8904<R^2<0.9927$. Form factor values are within the range $0.084<k<0.673$.

As far as the dependency of the form factor value on variable characteristics of the *Jelsa* series is concerned, the following can be concluded:

- as the L_{WL} / B_{WL} ratio gets larger, the value of the form factor k is smaller for the both tested conditions, i.e. full load and ballast conditions,
- dependency on the B_{WL} / T ratio is not significant.

Such results are in accordance with expectations because the form factor value represents a portion of the form resistance in the total viscous resistance, which is lower for finer hulls.

Maximum value of k for ballast and full load conditions occurs when the values of both ratios, L_{WL} / B_{WL} and B_{WL} / T, are minimum in the tested range. The minimum value of k for the full load condition occurs when the values of the ratios L_{WL} / B_{WL} and B_{WL} / T are maximum, and for the ballast condition when L_{WL} / B_{WL} is maximum, and B_{WL} / T is in the middle of the tested range. Values of the form factors for the ballast condition are smaller and more equable than for the full load condition. That is also according to expectations because C_B has a smaller value for the ballast condition.

But, similar conclusions cannot be drawn about the dependency of the relative error on the variable characteristics of the *Jelsa* series. Dependency of the relative error on L_{WL} / B_{WL} and B_{WL} / T ratios is not significantly pronounced. For the ballast condition it can be noted that the influence of the L_{WL} / B_{WL} ratio is present, but the influence of B_{WL} / T is not significant at all. Ship models with the highest and lowest values of of the determination coefficients have, for example, the same B_{WL} / T ratio. Ship models with the lowest values of L_{WL} / B_{WL} have lower values of the determination coefficients compared to other models. On the other hand, at the full load condition the dependency on the L_{WL} / B_{WL} ratio is not evident. When the values of the B_{WL} / T ratio are equal to 3 and 3.5 for the full load condition (which are the lowest values for the tested range), the values of the determination coefficients are mainly lower than for the other values of this ratio.

The connection of a particular ship model and relative errors for the full load and ballast conditions, respectively, is also not present. For example: for the M-1123 ship model maximum relative errors are among the greatest for both conditions, on the other hand, for the M-939 ship model the maximum relative error for the ballast condition is the greatest for the tested models, and for the full load condition the maximum relative error is among the lowest.

Obtained values point out to the fact that total resistance measurements in this Froude number range represent a particular problem and impose strict requirements on the equipment for total resistance measurement.

Results of the analysis have shown that all three powers give fairly good agreement with measured values since maximum relative error amounts to 6.23% for full load condition, and to 5.21% for ballast condition. The average value of the maximum relative error for all models amounts to 3.49% for the full load condition and to 2.84% for the ballast condition.

Since the form factor is used for the calculation of the viscous resistance (see equation 8), it can be said that the relative error of the viscous resistance calculation, due to the relative error of form factor value for the tested *Jelsa* series, has the maximum value of 2.83% for the full load condition and of 1.59% for the ballast condition. That means that Prohaska's method is quite appropriate for the determination of the form factor of the tested ship series.

The best results for most models at full load condition are obtained by applying power $n = 6$ in the wave resistance expression, and by applying power $n = 4$ at ballast condition. It is important to emphasize that the difference of the maximum relative errors of the results obtained with the powers 4, 5 and 6 is not large. No connection between a particular model and the power of the Froude number has been noted.

In the future work the values of the form factors should be compared with the same values obtained by applying Hughes' and Shirose's methods, [9], and the method proposed by Zotti [10].

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