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ESTIMATION OF HULL'S RESISTANCE AT PRELIMINARY PHASE OF DESIGNING

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Abstract

In this paper are presented the methodology of calculation of hull resistance components, principal parameters of a vessel, necessary for calculation of displacement in relation to vessel's type. That methodology concerns analysis of designing ways at early stage of ship's power calculation. Ship owners' preliminary assumptions for new ship consist of deadweight (for container vessel load capacity TEU), speed shipping line and others. Taking it as a base, in early stage of design one has to select propulsion type. This goal needs definition of principal dimensions of a vessel, which are the base for further calculations of hull's resistance and evaluation of necessary power of main engine (engines) to fulfil shipping requirements. In the paper, are presented major constraints for designing of new vessels coming from ship-owner assumptions such as seafaring limitations and safety of shipping regulations due to Classification Societies Rules or coming out from designing experience. In the paper are presented components of ship's resistance and methods of total resistance calculations what is a basis for power calculation and propulsion designing. Moreover, are presented results of calculations of resistance components of different types of ships, and variety of displacement and sailing velocity. It has to be assumed, that presented method concerns preliminary design stage and can vary from different ships classes and constructions of hulls.

Keywords: *seagoing ships, hull coefficient, hull dimensions parameters, hull resistance, propulsion power*

1. Introduction

The procedure of ship design has iterative character. Such way of approach is unavoidable because of the fact, that all requirements concerning a new construction can be expressed by analytic relations. It can be previously elaborated criterions of application of main dimensions coefficients of specified ship's type, block coefficients or mass coefficients for all ship or partly mass of equipment etc. Because of above, during designing process, at subsequent stages, is necessary to carry out control calculations as well as verification of obtained results. Results of approximation are used for correction of basic parameters obtained in previous steps and for specification of taken assumptions. Rules of subsequent approximations are implemented at all stages of preliminary design (conceptual stage, preliminary design, final design and workshop drawings).

Another attribute of a task of determination of general technical parameters of designed ship is fact that beside determined by ship-owner values such as speed, cargo capacity, shipping range, several random parameters must be considered. Those parameters come from experience background or Classification Societies rules.

The fact, that random parameters are included in initial equations, makes ambiguity of solutions of a task of basic parameters assumptions for new construction. It makes possible variety of fulfilling basic requirements posed by ship-owner. Ships designed according to different but possible variants may vary in main dimensions, block coefficients, power or displacement.

Any change of one amongst numerous parameters with keeping others unchanged; generally improve one group of parameters but parallel results with deteriorating others. For example, expansion of the relation of beam to draft B/T is resulting with growing initial stability, what is desirable from safety of shipping. From the other hand during sailing through rough sea, the rise of stability decrease hulls behaviour at swells and, in consequence decrease of effectiveness of transportation because loss of speed.

Similar, rise of relation between freeboard and draught improves buoyancy and stability of high list and diminish risk of a deck wash over by water. From other hand, increases displacement and major dimensions of the ship. Moreover, it causes rise of centre of gravity what generally is inconvenient.

Due to the unprecise task, necessary is distinguishing amongst big number of combinations of main parameters of a hull, one most convenient and adequate combinations of displacement, capacity, power, speed or rough sea resistance which gives lowest cost of exploitation.

2. Analysis of similarity and its implementation for propulsion system design

For purposes of designing, physical models in proper dimensional scale are constructed and tested in tanks in order to get maximum information about hulls behaviour and movement in water. All results reflect performance of real hull in proportional scale.

$$\frac{x'}{x} = \frac{y'}{y} = \frac{z'}{z} = C_l, \text{ – scale of linear dimension.} \quad (1)$$

Taking under consideration, in the equation of motion of viscous liquids – (Navier –Stokes Equation) values of the scale for two flows and comparison of that, are obtained criterion numbers describing the flow.

Criterions of hydrodynamic similarity obtained that way, can be presented in unidimensional form of four groups of variables.

$$\frac{v\rho l}{\eta} = R_n \text{ – Reynolds Number,} \quad (2)$$

$$\frac{v}{\sqrt{gl}} = F_n \text{ – Froude Number,} \quad (3)$$

$$\frac{p}{\rho v^2} = E_u \text{ – Euler Number,} \quad (4)$$

$$\frac{\tau v}{l} = S \text{ – Strouhal Number.} \quad (5)$$

Reynolds Number expresses relation between inertia forces and viscosity during flow, Froud Number is showing relation of inertia forces to the gravity, Euler Number presents relation between pressure forces and inertia forces and its relative in hydromechanics is cavity number. Strouhal Number characterizes similarity of flow in unspecified flow conditions. In general, for specified flow conditions, in ship hydrodynamics for evaluation of resistance, Froud's and Reynolds' Numbers are implemented.

Tab. 1. Scale coefficients copying with similarity according to Froud's Number criterion

Linear dimension	L, B, T	C_l	$L = C_l L_o$
time	τ	$C_\tau = C_l^{1/2}$	$\tau = C_\tau \tau_o$
force	P	$C_P = C_l^3$	$P = C_P P_0$
speed	v	$C_v = C_l^{1/2}$	$v = C_v v_0$
mas	m	$C_m = C_l^3$	$m = C_m m_0$
moment of inertia	m_b	$C_{mb} = C_l^5$	$m_b = C_{mb} m_{b0}$
torque	M	$C_M = C_l^4$	$M = C_M M_0$
power	N	$C_N = C_l^{3.5}$	$N = C_N N_0$
density	ϱ	$C_\varrho = C_l$	$\varrho = C_\varrho \varrho_0$

At preliminary stage of ship's propulsion system design, very often results of model tests are used, as well as database about groups of already made constructions, called a list of significant ships or results of prototype tests. Abode mentioned data can be useful for designing of a new unit only when are recalculated using "scale effect" i.e. estimation of scale of considered value in relation to linear dimension and its impact at characteristic parameters or performance. In Tab. 1. Influence of scale effect during recalculation of specific parameters of designed ship with sustained Froud's criterion of similarity and constant density of water are presented. Where values with index "0" refer to the model.

3. Limitations of ships' main dimensions

Main dimensions of a ship comes from ship owner's assumptions and requirements, i.e. shipping region, type of a ship, type of hull's construction, type of propulsion or classification rules. That rules gives recommendations about constructional parameters having impact at main dimensions and, subsequently affecting motional properties and ships sea prowess, buoyancy, unsinkability and economy of exploitation. Classification rules are based at theory as well as experience of ships exploitation.

In Tab. 2 are presented dimensional constraints for specified vessel class and shipping region.

Tab. 2. Some limitations of shipping routes

	B [m]	T [m]	L[m]	Max. height of freeboard [m]	Comments
Kiel Canal	40	9.5	315		
Danish Straits	48	15	260	65	
Panama Canal	32.2	12.04	289.5		5000 TEU
Post Panama Canal	54	18,29	426		13000 TEU *
Suez Canal	55	18.29	-	68	
Now Suez Canal	50 77.5	20.12 12.2		68	Wetted area limit BT to 1006 m2
St. Lawrence Seaway	23	7.6	222	57.5	
Malacca Straits	-	21	470		

**Through Post Panama Canal was crossed in 2017 container vessel 13000 TEU, L=368 m, B=48 m.*

In ship owner assumptions, load capacity (TEU) for container vessels and dead weight (DWT) for other classes, and speed are given. Those values have strong impact at necessary power of the first estimate that the Naval Architect makes is to estimate the lightweight of the new ship.

Deadweight coefficient C_D links the deadweight and the displacement. C_D depends on the ship type being considered.

Step by step, all parameters and any other important subject related to the planning of our power plant will be calculated, so that at the end of this project the complete and correctly design of it will be provided.

To have a general view of the designed ship, we will show the most important data, as main dimensions of the hull, block coefficient, deadweight or Froude Number, in following points of this project.

Values of C_D coefficient strongly affect analysis of similar (significant) ships. That coefficient gives information about similarity or, under assumption of equal fuel consumption, about similarity of the shipping range. In Tab. 3 are presented relations between major coefficients of hull shape characteristic.

Tab. 3. List of coefficients describing main dimensions of a ship

	Fn	C_D	$\frac{L}{B}$	$\frac{L}{\sqrt[3]{D}}$	C_B	$\frac{B}{T}$	$\frac{B}{H}$
General cargo	0.16 – 0.17	0.65 – 0.75	6 – 7	5.5 – 6.5	0.7 – 0.86	2 – 2.5	1.9
Large tankers	0.16 – 0.17	0.79 – 0.85	5.5 – 6.5	5.5 – 6.5	0.83	2.65	~ 1.9
Container ships	0.23 – 0.26	~ 0.6	5.5 – 6.5	6.5 – 8.5	< 0.65	2.3 – 3.6	~ 1.7

4. Hull's motion resistance

At preliminary stage of design, ship's resistance is determinate according to approximate formulas, coming from systematic model tests, analysis of similar units or basing on prototype model tank tests. Resistance of hull's motion significantly depends on ship's speed and sailing conditions, which are different from project conditions. In real conditions of operation at sea, ships speed decrease due to rise of resistance of sea water, air, deterioration of propeller effectiveness under stormy weather, shallow water in canals and streams etc. Another important factor is fouling and degradation of hull's sheet condition. Sailing under storm condition can result with speed diminish even 50-60%, when for smooth condition speed drop is at level of 7-8% for slim hulls and 9% for full body hulls i.e. for higher block coefficient values. Fouling is causing rise of surface roughness and is the reason of bigger resistance. It can be assumed that due to fouling, resistance grows 0.5% per day. Presented influence of outer conditions result with necessity of calculation of additional power redundancy for sea condition aspect – SM (sea margin) and additional power reserve for main engine safety of operation – EM (engine margin). Total power redundancy shall be calculated at level of around 25-30%.

Conceptual assumptions are verified during sea trials, when several parameters are verified, among them ship's speed, shaft torque, fuel consumption, manoeuvring properties and motional properties can be highlighted. According to the rules, sea trial has to be conducted under smooth weather conditions, when sea state is below 3. Under such conditions, ships performance is similar to the calm water situation. To transform obtained results to real conditions of ship operating must be implemented parameters of similarity and scale effect.

4.1. Total resistance

Ships resistance consist of frictional resistance, form resistance, wave making resistance, additional resistance of appendages, air resistance and wave breaking resistance. At preliminary stage of design most of attention is payed at hydrodynamic resistance of wetted area.

$$R_T = C_T \rho v^2 \, \Omega /2, \tag{6}$$

where:
C_T – coefficient of total resistance,
v – ship's speed,
ρ – sea water density,
Ω – wetted area.

Coefficient of total resistance is a sum of frictional resistance coefficient C_F, shape resistance C_K and wave making resistance C_F.

Frictional resistance makes 45-75% of total resistance. Top value is for cargo vessels having big block coefficient values and characterised by Froud Number up to 0.17. Together with Fn raising (speed), participation of frictional resistance for Fn =0.25 reaches 60% of total resistance.

For very fast war ships, passenger vessels or container vessels, sailing with speed characterised by Fn= 0.3, frictional resistance unlikely oversteps 45-50%.

Frictional resistance coefficient depends on Reynolds Number. It is described by formula ITTC-57:

$$C_F=0.075/(\log Rn -2)^2, \quad (7)$$

Moreover, frictional resistance must include correction factor due to constructional roughness of hull's sheet ΔC_F, which value according to Schoenher is 0.0004 [1].

Form resistance depends on aft part shape and has significant impact at high-block, slow ships. For Fn lower than 0.15, wave-making resistance practically can be omitted. It makes an opportunity of rough calculation of resistance coefficient as only element of additional resistance in total resistance measured during model tests. That's why form resistance is taking as additional component of frictional resistance, and its value depends on block coefficient and relation between length and beam L/B. Value of that coefficient can be quite exactly evaluated taking under consideration most of coefficients and relations between major dimensions, according to Holtrop-Mennen formula [5, 6]. Approximated value of that coefficient can be determined basing on formula [8]:

$$K_1=19(C_B L/B)^2, \quad (8)$$

That coefficient takes value, for container ships over a dozen per cent abut is much higher for high block vessels.

Wave breaking resistance is coming from transformation of part of energy of propulsion in form of energy loses due to ship's movement wave making. Created waves are surface type and one can distinguish bow waves and stern waves. In every group of waves can be distinguish transverse ones and slanting ones, wherein angles of slanting waves depends on type of ship and speed. Changes of angles of propagation can occurs in entering shallow waters, when angle is growing, also magnitude of waving goes up when depth of area diminish, and rise additional resistance. Wave making resistance because of bow waves' interference has nit monotonous character. Coefficient of wave making resistance Cw, which depends on Froud Number, can be described basing on viscous fluid formula (triple dimensional formula of Navier Stokes) in so-called computer model tanks or generated basing on classic tank test results relating on geometric similarities. In practice, model tests are carried out according to theory of models similarity, called Froud criterion, which relay on that keeping constant value of En Number for the ship and model, resistance coefficient is to be the same.

Total resistance takes form of equation:

$$R_T=[C_F(1+ K_1)+\Delta C_F+ C_W] \rho v^2 \Omega /2, \quad (9)$$

where Ω – wetted area.

In Tab. 4 are presented calculated parts of elements of individual hydrodynamic resistance for selected types of ships, sailing with different ranges of speed. In the table are also presented values of form coefficient and resistance of appendages Rap caused by installation of additional underwater equipment and air resistance Ra. While in Tab. 5. Are presented percentage of resistance elements in total resistance Ω.

Tab. 4. Elements of resistance of different ships and different sailing speed

Type of ship	D [m^3]	C_B	v [w]	R_T [kN]	R_f [kN]	R_k [kN]	R_w [kN]	R_{ap} [kN]	K_1	R_a [kN]
500 TEU	11382	0.63	16	420	284	313	48	7.3	0.11	50
1600 TEU	33300	0.65	20	997	603	78.4	138	14.7	0.13	162
2000 TEU	32195	0.55	20	866	515	93	117	7.4	0.18	134
9000 TEU	117000	0.63	25	3610	1932	580	697	12.64	0.32	336
100000 DWT	117000	0.86	15	1362	639	415	163	4.64	0.65	136

Tab. 5. Percentage of resistance elements in total resistance

	Rf	Rk	Rw	Rd	Ra
500TEU	0.67	0.07	0.12	0.02	0.12
1600TEU	0.6	0.08	0.14	0.015	0.16
200TEU	0.59	0.11	0.14	0.01	0.15
9000TEU	0.54	0.16	0.196	0.003	0.09
100000 DWT	0.47	0.30	0.12	0.0034	0.1

Presented results shows that biggest part of total resistance is made by frictional resistance. Wave making resistance, which value reaches dozen of per cent, depends mainly on sailing speed. For cargo vessels with extended above water part, air resistance is significant and together with appendages resistance can be estimated as 15%.

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