

A METHOD FOR PRELIMINARY ESTIMATION OF THE LENGTH OF MIDSHIP BODY BLOCK TO BE INSERTED DURING SHIP'S CONVERSION

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ABSTRACT

The paper presents a method for preliminary estimation of the length of the midship body block, which inserted in the original hull, increases the deadweight of the ship in line with a required quantity. The method may be useful for establishing the scope of conversion to better adjust the ship for transportation tasks. The problem is formulated by using a mathematical model so selected that its solution, under set of assumptions, is obtained in a closed analytical form. The presented method can be useful for application to pre-investment analysis of the ship conversion costs and functional profits.

Keywords: ship design, ship conversion, increase of ship deadweight, lengthening of ships

FORMULATION OF THE PROBLEM, ASSUMPTIONS AND AIM OF THE WORK

Profitability of the maritime transport depends on adjusting functional features of the ship to its operation in given sea navigation and market conditions. The functional adjustment of the ship consists in the appropriate selecting of both its functional type and technical parameters, that can be made either by commissioning the building of a new ship of required features or purchasing of an existing ship which satisfies the given requirements or by the commissioning of an appropriate conversion of owned ship. In many cases such conversion is capable of satisfying given requirements to an acceptable degree and it usually represents the cheapest solution. Decision on purposefulness of ship's conversion may result e.g. from necessity of increasing the following ship parameters:

- ship deadweight;
- ship speed;
- capacity of ship holds or cargo tanks;
- number of shipped containers;
- length of cargo trails;
- under-deck space volume.

To satisfy the requirements it is usually enough to perform conversion of the ship, which consists in its lengthening by inserting a hull block into midship zone.

In the available subject-matter literature any description of a parametric method for a simple assessment of an extent of lengthening the ship in order to reach a required increase in deadweight of the ship after its conversion, is still lacking. In shipyard's realconditions [1], [2] the issue in question is solved by iterative increasing the block length, determining its structure and weight in order to obtain a proper length of the hull block, which is rather very labour – and - time consuming.

The assumed cognitive aim of this work consists in elaborating an original parametric method suitable for preliminary estimation of length of hull block to be inserted within midship zone in order to increase deadweight of the ship and (optionally) its speed (by replacing the existing propulsion engine with a new one of a greater output and mass) by a quantity required by ship owner, as well as preliminary estimation of mass of the block in question. The utilitarian aim consists in providing a solution useful for application in real shipbuilding conditions.

The considered range of conversion concerns the case when ship draught, breadth and depth would not be changed after conversion. The solution of the issue is presented analytically in the form of a relation which *explicite* expresses dependence of the cylindrical block length ΔL on the required deadweight increase ΔP_n and (optionally) the required speed increase Δv as well as the ship parameters before conversion. Also,

is presented evaluation of the method's error in case of linearization of the issue, as well as a determined relation which introduces correction into linear expression and significantly improves accuracy of the method.

Usefulness of the presented method may deal with its application for analyzing relations between profits and expenditures – depending on the assumed parameters of ship conversion, i.e. the method useful for pre-investment considerations in ship owner offices, consulting offices and also in ship design offices. The issue in question may be considered important in the light of the opinion expressed by the consulting agency *Clarkson's*, stating that the world market of ship conversion orders is estimated to be worth about 3 mld Euro [3] of investment per year, in which the lengthening of ships by inserting cylindrical block for increasing ship deadweight, takes a significant share.

MATHEMATICAL MODEL OF THE ISSUE

Parametric description of the ship before conversion is defined by a vector of its significant technical parameters, \bar{x} , of known numerical values:

$$\bar{x} \equiv (x_1, x_2, \dots, x_n) \equiv (L, B, T, CB, CM, H, Pn, v, Ne) \quad (1)$$

where the following notation is used :

- L – ship length between perpendiculars;
- B – ship breadth;
- H – ship hull depth;
- T – ship constructional draught;
- CB – ship hull block coefficient;
- CM – midship section coefficient;
- Pn – ship deadweight;
- V – ship speed;
- Ne – main engine output.

Changeability of ship mass components can be expressed in an approximate way by using approximate module functions such e.g. as given in [4], [5], which determine dependence of ship mass components on its main dimensions and speed:

$$M_1(\bar{x}) = c_1 \cdot L \cdot B \cdot H \quad M_2(\bar{x}) = c_2 \cdot (L \cdot B \cdot H)^{2/3} \quad (2)$$

$$M_3(\bar{x}) = c_3 \cdot Ne^{1/2} = c_3 \cdot \left(\frac{D(\bar{x})^{2/3} \cdot v^3}{CA} \right)^{1/2} \quad M_4(\bar{x}) = \text{const}$$

gdzie:

- M_1 – hull mass;
- M_2 – outfit mass;
- M_3 – power plant mass;
- M_4 – superstructure mass;
- CA – factor stands for proportionality coefficient, and
- D – ship displacement.

Proportionality coefficients of the module functions are determined on the basis of ship parameters before its conversion:

$$c_1 = \frac{M_1}{L \cdot B \cdot H} \quad c_2 = \frac{M_2}{(L \cdot B \cdot H)^{2/3}} \quad c_3 = \frac{M_3}{Ne^{1/2}} \quad CA = \frac{D^{2/3} \cdot v^3}{Ne} \quad (3)$$

As ship hull longitudinal bending moment increases along with square of ship length, therefore, in case of lengthening the ship, its hull section modulus W in bending should be so increased, within the range of the inserted block, as not to impair overall hull strength.

In accordance with the relation for the required value of the hull section modulus W in bending, given e.g. in [6]:

$$W \sim \frac{Cw_o}{k} \cdot L^2 \cdot B \cdot (CB + 0,7) \quad (4)$$

the unit mass of the inserted block structure is adjusted by the factor b which increases hull section area within the range of the inserted block :

$$\beta = \left(\frac{L + \Delta L}{L} \right)^2 \quad (5)$$

with not taking into account a rather low influence of change of the block coefficient CB resulting from inserting the block into ship hull.

Ship length extension affects value of convention freeboard. Its preliminary, simplified estimation with taking into account the following [7]:

- change of table value of freeboard;
 - correction which covers change of the coefficient CB ;
 - correction connected with the required bow height;
- leads to the relation which expresses change of the minimum value of the summer freeboard $MSFB$:

$$\Delta MSFB \sim \Delta L \cdot \left[\frac{15 \cdot (CM - CB)}{1.36 \cdot \left(\frac{L}{\Delta L} + 1 \right)} - \frac{250}{15} \right] [\text{mm}] \quad (6)$$

where $L, \Delta L$ are given in[m].

As the estimation provides a negative value it is not necessary to account for any increase of $MSFB$.

The issue in question has two interesting utilitarian aspects consisting in determination of:

- the length, ΔL , of the cylindrical insertion block, which corresponds with the assumed increase of the ship deadweight ΔPn and (optionally) of the ship speed Δv ;
- the deadweight increase ΔPn resulting from the insertion of the ΔL – long block, e.g. an additional hold of the required length ΔL .

The insertion of the cylindrical block of the length ΔL is associated with the change of:

- the initial hull block coefficient – by the value of ΔCB ;
- the initial ship displacement – by the value ΔD ;
- the initial ship mass – by the value of ΔM .

Moreover, it was used to increase the insertion block mass ΔM by adding the technological margin of mass R – proportional to mass of the block.

Buoyancy equation expressed by balance of displacement and mass components after conversion of the ship can be written as follows:

$$D(\bar{x}) + \Delta D(\bar{x}) = Pn + \Delta Pn + M(\bar{x}) + \Delta M(\bar{x}) + R(\bar{x}) \quad (7)$$

where: Pn , D and M stand for deadweight, displacement and mass of the ship before conversion, respectively, and ΔPn , ΔD and ΔM are values of the same parameters of the ship after its conversion; $R = (\lambda - 1) \cdot (\Delta M_1 + \Delta M_3)$ is the technological margin of ship mass. Value of the mass margin is usually contained within the range $\lambda \in (1,02 \div 1,03)$, and depends on applied shipyard's standards.

Solution of the issue in question is presented in the form of the closed formula which expresses the cylindrical insertion length depending on a required ship deadweight increase and speed, together with the formula for estimating the insertion block mass.

NON-LINEAR MODEL

If the ship conversion has to concern both the ship deadweight change $\Delta Pn > 0$ and its speed $\Delta v > 0$ which leads to replacement of existing main engine by other one of a greater output and similar rated rotational speed, then, under taken assumptions, the buoyancy equation of the ship after its conversion (7) can be expressed as follows:

$$D \cdot \left(1 + \frac{CM \cdot \Delta L}{CB \cdot L}\right) = Pn + \Delta Pn + c_1 \cdot (L + \lambda \cdot \beta \cdot \Delta L) \cdot B \cdot H + c_2 \cdot [(L + \Delta L) \cdot B \cdot H]^{2/3} + c_3 \cdot \left[\frac{D^{2/3} \cdot (v + \lambda \cdot \Delta v)^3}{CA}\right]^{1/2} + M_4 \quad (8)$$

By substituting the factor β which adjusts the hull section modulus in vertical bending it is possible to express the buoyancy equation as follows:

$$D \cdot \left(1 + \frac{\Delta L \cdot CM}{L \cdot CB}\right) = Pn + \Delta Pn + \left[1 + \frac{\lambda \cdot \Delta L}{L} \cdot \left(\frac{L + \Delta L}{L}\right)^2\right] \cdot M_1 + c_2 \cdot [(L + \Delta L) \cdot B \cdot H]^{2/3} + c_3 \cdot \left[\frac{D^{2/3} \cdot (v + \lambda \cdot \Delta v)^3}{CA}\right]^{1/2} + M_4 \quad (9)$$

The insertion block length ΔL can be determined by solving the above given non-linear equation with the use of numerical methods, that is rather not very convenient in practice. It is much more useful to have a formula for determining ΔL – value *explicite*. To obtain such relation the non-linear segments of the buoyancy equation (9) was linearized providing this way the formula for determining ΔL – value. Applicability merits of the determined formula was verified by evaluating value

of the error resulting from the linearization; the error value was then assessed with taking into account the aspect of applications in engineering.

LINEARIZED MODEL

By taking into account only the linear parts of the increases of the ship mass $M_i(\bar{x})$ and ship displacement $D(\bar{x})$, which result from the changes Δx_i in ship parameters, the balance of mass increases after conversion can be expressed by the general linear relations as follows :

$$\Delta D(\bar{x}) = \Delta Pn + \Delta M(\bar{x}) \quad (10)$$

$$\sum_{i=1}^4 \frac{\partial D(\bar{x})}{\partial x_i} \cdot \Delta x_i = \Delta Pn + \sum_{j=1}^4 \sum_{i=1}^4 \frac{\partial M_j(\bar{x})}{\partial x_i} \cdot \Delta x_i \quad (11)$$

On substitution, into Eq. (11), of the linear mass increases resulting from the modular formulae as well as the displacement increase, the buoyancy equation of ship after conversion takes the following form:

$$\frac{D}{L} \cdot \frac{CM}{CB} \cdot \Delta L = \Delta Pn + \left[\lambda \cdot \frac{\Delta L}{L} \cdot M_1 + \frac{2 \cdot \Delta L}{3 \cdot L} \cdot M_2 + \lambda \cdot \frac{3 \cdot \Delta v}{2 \cdot v} \cdot M_3 \right] \quad (12)$$

On determination the value ΔL from Eq. (12), the searched formula is reached as follows:

$$\Delta L = \frac{\Delta Pn + \lambda \cdot \frac{3 \cdot \Delta v}{2 \cdot v} \cdot M_3}{D \cdot \frac{CM}{CB} - \lambda \cdot M_1 - \frac{2}{3} \cdot M_2} \cdot L \quad (13)$$

VERIFICATION OF THE METHOD

On the basis of the set of the data dealing with built ships (of known values of \bar{x} and M_i) was conducted a series of calculations consisting in comparison of the results obtained from the linear formula (13) with the results of solving the non-linear equation (9). From the performed investigations can be concluded that linearization error value depends on values of the relative increases: $\Delta Pn/Pn$ and $\Delta v/v$. In the range of the increases from 5 % up to 30% the relative percentage error of the ΔL is contained in the interval from about 1% to about 7%, that is illustrated by the results given in Tab. 1.

Tab. 1

Δv [%]	The mean relative percentage error ΔPn [%]					
	5	10	15	20	25	30
0	0.73	1.54	2.38	3.26	4.18	5.15
5	0.92	1.68	2.50	3.37	4.29	5.26
10	1.28	1.92	2.70	3.55	4.45	5.41
15	1.78	2.24	2.95	3.77	4.65	5.60

CONCLUDING PART – EXAMPLE OF APPLICATION OF THE METHOD

The presented question consists in preliminary estimation of insertion block length and mass as well as power plant mass (in advance of designing the block structure) in case when the required increase of ship deadweight is equal to 3500 t, and the main engine should be replaced with other one of a greater output so selected as to increase ship speed by 1.50 knots. The parameters of the considered ship before conversion are given in Tab. 3.

Tab. 3.

Deadweight	12450	t
Speed	16.80	knots
Length	143.12	m
Breadth	20.20	m
Draught (max)	8.92	m
Depth	11.80	m
Main Engine Power output	5740	kW
Mass of Steel Hull	2917	t
Mass of Superstructure	308	t
Mass of Outfit	1524	t
Mass of Machinery	774	t
Block Coefficient	0.680	-
Midship Section Coefficient	0.983	-

Length of the insertion block:

The length of the block is obtained by substituting the values of ship parameters into Eq. (15):

$$\Delta L = \frac{\left(1.002645 - 0.160408 \cdot \frac{3500}{12450} - 0.055994 \cdot \frac{1.50}{16.80}\right)^{-1} \cdot \left(3500 + 774 \cdot \lambda \cdot \frac{3 \cdot 1.50}{2 \cdot 16.80}\right) \cdot 143.12}{17974 \cdot \frac{0.983}{0.680} - 1.02 \cdot 2917 - \frac{2}{3} \cdot 1524} \approx 24.63 \text{ m}$$

Mass of the insertion block together with its technological margin:

$$M_B = \left[\lambda \cdot \frac{\Delta L}{L} \cdot \left(\frac{L + \Delta L}{L} \right)^2 \right] \cdot M_1 + c_2 \cdot \left[(L + \Delta L) \cdot B \cdot H \right]^{2/3} - M_2 = \left[\frac{1.02 \cdot 24.63}{143.12} \cdot \left(\frac{167.75}{143.12} \right)^2 \right] \cdot 2917 + 1.449 \cdot \left[167.75 \cdot 20.20 \cdot 11.80 \right]^{2/3} - 1524 = 704 + 170 = 874 \text{ t}$$

Mass of the ship's power plant:

$$M_M = c_3 \cdot \left[\frac{D^{2/3} \cdot (v + \lambda \cdot \Delta v)^3}{CA} \right]^{1/2} \approx 10.216 \cdot \left[\frac{17974^{2/3} \cdot (16.80 + 1.02 \cdot 1.50)^3}{566.82} \right]^{1/2} = 882 \text{ t}$$

Mass of the empty ship after conversion:

$$M_S = M_1 + \Delta M_1 + M_2 + \Delta M_2 + M_3 + \Delta M_3 + M_4 = 2917 + 704 + 1524 + 170 + 774 + 108 + 308 = 6505 \text{ t}$$

Δv [%]	The mean relative percentage error ΔPn [%]					
	5	10	15	20	25	30
20	2.38	2.64	3.27	4.03	4.89	5.82
25	3.05	3.10	3.63	4.34	5.17	6.08
30	3.78	3.61	4.03	4.69	5.47	6.36

It was concluded that in the considered issue the accuracy of the results obtained from Eq. (12) does not satisfy demands of engineering applications especially in case of greater values of the relative increases ΔPn and Δv . To improve the accuracy of the formula, the function $Fc(\bar{x})$ for correcting Eq. 13 was formed; the ΔL – values corrected this way more better approximate the results from the non-linear model. The function $Fc(\bar{x})$ was determined from the condition of minimizing value of the linearization error. The correcting function in question was obtained by applying the method of least squares of deviations. As a result it reached the following form :

$$Fc(\bar{x}) = \left(1.002645 - 0.160408 \cdot \frac{\Delta Pn}{Pn} - 0.055994 \cdot \frac{\Delta v}{v} \right)^{-1} \quad (14)$$

The corrected formula (13) took finally the form as follows:

$$\Delta Lc = Fc(\bar{x}) \cdot \frac{\Delta Pn + \lambda \cdot \frac{3 \cdot \Delta v}{2 \cdot v} \cdot M_3}{D \cdot \frac{CM}{CB} - \lambda \cdot M_1 - \frac{2}{3} \cdot M_2} \cdot L \quad (15)$$

Eq. (15), on inversion, may serve to estimate value of ship deadweight increase after inserting the block of the required length ΔLc , e.g. one-hold block :

$$\Delta Pn = \frac{\Delta Lc \cdot \left(D \cdot \frac{CM}{CB} - \lambda \cdot M_1 - \frac{2}{3} \cdot M_2 \right)}{Fc(\bar{x}) \cdot L} - \lambda \cdot \frac{3 \cdot \Delta v}{2 \cdot v} \cdot M_3 \quad (16)$$

The calculations analogous to those included in Tab. 1, performed by means of the corrected formula, show much lower values of error of the method (see Tab. 2).

Tab. 2.

Δv [%]	The mean relative percentage error after correction ΔPn [%]					
	5	10	15	20	25	30
0	0.19	0.21	0.25	0.33	0.45	0.63
5	0.10	0.06	0.08	0.16	0.28	0.45
10	0.19	0.02	-0.01	0.04	0.15	0.32
15	0.41	0.06	-0.03	-0.02	0.07	0.23
20	0.74	0.19	0.00	-0.03	0.03	0.17
25	1.14	0.37	0.09	0.00	0.02	0.14
30	1.60	0.61	0.22	0.07	0.05	0.14

Displacement of the ship after conversion:

$$D_s = D + \rho \cdot CM \cdot \Delta L \cdot B \cdot T \cong 17974 + 1.025 \cdot 0.983 \cdot 24.63 \cdot 20.20 \cdot 8.92 = 22446 \text{ t}$$

Deadweight of the ship after conversion:

$$Pn_s \cong Pn - M_s = 22446 - 6505 = 15941 \text{ t}$$

The required ship deadweight after conversion is equal to 15950 t, hence in the considered case the total error in estimating ship mass is equal to 9 t and results from linearization of the issue (in this example the assumed technological mass margin amounts to about 19.7 t).

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