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Numerical Model of the Large Carrying Capacity Crane Ship with the Fully Revolving Topside

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Abstract

A numerical model of the large carrying capacity crane ship with the fully revolving topside is represented in the article. The model provides a way of determining the main crane ship's elements using version design approach with further system optimization. The principal analytical equations are set up in the article to solve that problem. Relationship between ship characteristics and elements is established from the point of view of providing initial stability. Once the model has been verified, an investigation of the influence of relative breadth and block coefficient on the displacement of the large carrying capacity crane ship in operating condition is performed. Based on the results of that investigation, the conclusions as to insufficiency of the condition of providing initial stability for system optimization of crane ships are made.

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Keywords: numerical model; design of crane ships; systems analysis; crane ship; crane topside;

1. Introduction

The most typical feature of the ship design process is the search for compromise solutions enabling designers to reach the highest efficiency of the ship and meet numerous and mutually contradictory performance requirements, which is the main principle of system optimization of ships. As a matter of fact, optimization is the essential

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condition for any ship development, and optimization problems are solved at all stages and levels of the ship design [1].

The ship design theory deals with a selection of design solutions for the ship as a whole. A version optimization approach is the main method of the ship design theory. The version optimization approach is based on a selection of the best ship version out of a set of previously designed versions with systematically varying elements. Such sets allow plotting the graphs of parameters characterizing various qualities of the ship and her effectiveness as a function of elements being optimized. The complete implementation into the design of those system approach principles, which require that the design of any sub-systems and facilities should be performed in compliance with the unified requirements of optimization of the ship as a whole, can be achieved only in case of simultaneous optimization of ship's elements and sub-systems as a single problem. Let's denote the set of ship's elements defined at the initial stage of design development as a vector of elements $x=\{x_i\}$, $i \in I$, where I is the set of elements. We will include into it such parameters as principal dimensions, block coefficients, amounts of solid and liquid ballast, etc. Similarly, let's introduce vector $x_k=\{x_{kj}\}$ as a vector of variables characterizing the *k-th* ship sub-system (with $k \in K$, where K is the set of sub-systems, and $j \in J_k$, where J_k is the set of variables of the *k-th* sub-system). Examples of sub-systems are as follows: the hull, power plant and electric-power plant, hydrodynamic facilities, ship arrangements, systems, etc.

If the function $f(x, x_k)$ is available for quantitative estimation of the efficiency of the ship being designed, and qualities of the ship (i.e. buoyancy, storage capacity, stability, etc.) and those of her sub-systems and facilities can be estimated with the use of functions $g_S(x, x_k)$ and $g_{Sk}(x, x_k)$, respectively, then the optimal ship design problem can be formulated in the following way: determine such x and x_k, which satisfy the below conditions:

$$f(x, x_k) \rightarrow \min(\max) \tag{1}$$

$$g_S(x, x_k) \geq b_S, \quad \forall s \in S, \tag{2}$$

$$g_{Sk}(x, x_k) \geq b_{Sk}, \quad \forall s \in S_k, \quad k \in K, \tag{3}$$

$$x_{\max} \geq x \geq x_{\min}, \tag{4}$$

$$x_{k\max} \geq x_k \geq x_{k\min}, \quad \forall k \in K. \tag{5}$$

Where b_S, b_{Sk} = normal levels of allowable values of a specific quality; S, S_k = sets of requirements for qualities of the ship and those of her sub-systems.

It is not feasible to solve the set (1) through (5) as a single problem [1]. Instead, as indicated by experience of designing ships and other complicated objects, the sub-systems should be designed separately. In [1] the actual solution of the problem of obtaining x is defined as follows:

$$f(x) \rightarrow \min(\max), \tag{6}$$

$$g_S(x) \geq b_S, \quad \forall s \in S_1, \tag{7}$$

$$g_S(x) \geq b_S, \quad \forall s \in S_2, \tag{8}$$

$$x_{\max} \geq x \geq x_{\min}. \tag{9}$$

S_1, S_2 = sub-sets of restrictions represented by strict equations and in equations $(S_1 \cup S_2 = S)$. In [2], [3], the following equations are applied to the analysis of crane ships (hereinafter abbreviated as CS).

$$s \in S_1 : \Delta - \sum_i P_i = 0\,; \tag{10}$$

$$s \in S_2 : M + M_Q - g\Delta h[\theta] = 0\,. \tag{11}$$

Where Δ = the total displacement of the crane vessel in operational condition; $\sum P_i$ = a sum of weight loads of mass groups; M = a design heeling moment [4]; M_Q = a maximal loading moment created by cargo on the main hoist hook of the crane being in operation, [2], [4]; g = acceleration due to gravity; h = the corrected metacentric height (i.e. with consideration of correction for free surfaces); $[\theta]$ = the critical value of heeling angle, [4].

Considering the equation $\Delta = \rho C_B LBd$, the conditions (10), (11) can be re-written as

$$s \in S_1 : \gamma C_B LBd - \sum_i P_i = 0\,, \tag{12}$$

$$s \in S_2 : M + M_Q - \gamma C_B LBdh[\theta] = 0\,. \tag{13}$$

At early stages, the unknowns are $x = \{L, B, d, D, C_B\}$. γ = specific gravity of sea water; ρ = sea water density, C_B = block coefficient corresponding to the operational state of the crane ship; L, B, d, D = design length, breadth, draft and depth of the ship, respectively.

Thus, according to [1], [2], and [3], the mathematical representation satisfying conditions (12) and (13) is necessary to develop to solve the main problem of crane ship design theory, considering system optimization of that CS. In doing so, certain reliable relations between the main CS's elements and a number of design parameters such as $\{L, B, d, D, C_B\} = f(Q, R, A_{LD}, H_{LD}, \theta)$ should be established as a means of performing practical calculations.

The aim of this article is to build a mathematical representation of the CS based on a number of equations which relate the main ship's elements to her design parameters. In addition, the representation should satisfy conditions (12) and (13).

When deriving the analytical relations of the main ship's elements, commonly known relations of ship statics are used in the left-hand side of equations, while some empirical relations specified in Rules [4] are used in the right-hand side of the same equations. When determining coefficients, statistical methods are used. That allows leaving certainly unsuitable candidate solutions out of consideration.

2. Literature – critical overview

A review of the existing approaches, such as [3], [5], [6], [7], [8], indicates that problems of ship theory and hull structure, including some specific issues, are generally solved in designing of vessels under consideration. There are scarcely any publications to reveal the relation between main ship's elements and principal performances of the CS in terms of solving optimization problems of ship design theory. In addition, many publications have become out of date.

The following drawbacks of the existing publications should be brought to attention:

1. Most comprehensive methods of the determination of CS main elements are intended only for the earliest design stages.

2. In developing general methods (i.e. methods not associated with any highly specialized type of vessel) of the determination of CS main elements, CS's were being split into no more than two groups, each with its own general and specific features, which were then allowed for in the principal equations of the method to obtain vessel's

dimensions. Analyses of those methods, particularly those performed by A.A. Aliseichik [10], V.G. Zinkovsky-Gorbatenko & Ye.A. Kravtsov [9], have demonstrated insufficient accuracy or a wide range of variation of the sought quantities, which renders those methods unsuitable for optimization design.

3. It is only in publications by N.F. Voyevodin [2], where the complete cycle of CS designing and determination of her main elements, considering CS classification for the purpose, intended, is provided. Even though the groundwork laid by Voyevodin (i.e. ensuring stability in operational conditions, the proper selection of counterweights, etc.) remains unchanged, the following arguments against it should be highlighted: a) the method developed by Voyevodin for the determination of mass measures and weight/overall dimensions, was based on historical data dated back to his time (i.e. the 50th of the previous century), b) progress in science and technology has brought about considerable modifications of CS topsides, c) new types of CS's have been developed to perform new functions (voyages to open sea, oil/gas offshore operations), d) Voyevodin method was applicable for CS's with topsides lifting capacity lower than 250 t.

3. Determination of analytical relations

Let's obtain relations between variables (13) and principal ship's elements. According to [4], the corrected metacentric height can be described as

$$h = z_{\mathrm{C}} + r_{\mathrm{i}} - z_g - m_{\mathrm{h}} \, . \qquad (14)$$

Where z_{C}, r_{i}, z_{g} are respectively, CS vertical center of buoyancy, transverse metacentric radius, and vertical center of gravity at a specified design load of the ship; m_{h} is a total maximal correction for free surfaces, according to [4]:

$$m_{\mathrm{h}} = \Delta^{-1} \sum_i \rho_i i_{xi} \, . \qquad (15)$$

In formula (15), ρ_{i} is the density of liquid in the i-th tank with free surface; i_{xi} is a transverse moment of inertia of free surface area at θ=0 in the i-th tank with free surface. The combination of tanks with free surfaces shall be selected based on their worst effect on the initial stability of the ship. At initial design stages, it is allowable to assume $\rho_{\mathrm{i}} \approx 1$. The analysis of general arrangement options results in an approximate estimation of i_{xi} in the following range:

$$\sum_i i_{xi} = k_{\mathrm{MH}} L B^3 , \qquad (16)$$

where $k_{\mathrm{MH}} = (1.65\ldots2.47)\cdot10^{-3}$ for CS equipped with the Heeling Compensation System (HCS); and k_{MH} can be assumed to be zero for CS without the HCS. At operational drafts of the CS, the quantity z_{C} is linear with d. For convenience purposes, it can be re-written using the coefficient:

$$z_{\mathrm{C}} = k_{\mathrm{C}} d = k_{\mathrm{C}} k_{\mathrm{dB}} B, \qquad (17)$$

$$k_{\mathrm{dB}} = \frac{d}{B} \, . \qquad (18)$$

According to [11], the transverse metacentric radius can be represented as

$$r_{\mathrm{i}} = k_{\mathrm{I}} \frac{LB^3}{C_{\mathrm{B}} LBd} , \qquad (19)$$

where k_I = coefficient to fit the transverse moment of inertia of design waterline area to the product LB^3; product $C_B LBd$ is the volume displacement at a specified load of the CS. Considering (17), formula (18) can be re-written as follows:

$$r_i = \frac{k_I}{k_{dB} C_B} B. \tag{20}$$

The mass displacement of the CS can be represented as

$$\Delta = \rho k_{dB} C_B L B^2 . \tag{21}$$

Ship's vertical CoG, z_g (in ship-based coordinates [2], [11]) can be determined as

$$z_g = \frac{z_H \left[g\Delta - \left(P_{UC} + gQ \right) \right] + z_{UC} P_{UC} + z_Q g Q}{g\Delta}, \tag{22}$$

where z_H = ship's vertical CoG without consideration of the topside (TS) and the cargo on hook; z_{UC}, P_{UC} = vertical CoG and weight, respectively, of the revolving part of the CS; z_{gQ}, Q = vertical CoG and weight of the cargo on hook, respectively. Let's assume that $z_Q \cong (H_{LD}+d)$ and represent z_H, z_{UC}, z_Q in the following format:

$$z_H = k_H D , \tag{23}$$

$$z_{UC} = k_{UCZ} \left(H_{LD} - D + d \right) + D , \tag{24}$$

$$z_Q \cong H_{LD} + d , \tag{25}$$

$$P_{UC} = k_{UC} Q . \tag{26}$$

Cargo lifting height above the free water surface H_{LD}, is specified in the design basis of the CS. If the ship depth is represented as a sum of operational draft and some normalized freeboard h_n, as specified in the design basis or determined based on condition of the main deck unfloodability at specified operational conditions, i.e.

$$D = d + h_n , \tag{27}$$

then (23) and (24) will respectively become

$$z_H = k_H \left(d + h_n \right), \tag{28}$$

$$z_{UC} = k_{UCZ} \left(H_{LD} + h_n \right) + d + h_n . \tag{29}$$

Now that, considering (18), (25), (26), (28) and (29), and having variables re-grouped with respect to CS's elements and characteristics, formula (22) will take the form:

$$z_g = k_{B1} B + \left(k_{H1} H_{LD} - k_{\Delta 1} \right) \frac{Q}{\Delta} + k_H h_n . \tag{30}$$

The following notations are used in (30):

$$k_{B1} = k_H k_{dB} + \left(k_{dB} k_{UC} + k_{dB}\right)\frac{Q}{\Delta}\,, \tag{31}$$

$$k_{H1} = k_{UCZ} k_{UC} + 1\,, \tag{32}$$

$$k_{\Delta 1} = k_H k_{UC} + k_H + \left(k_{UCZ} k_{UC} - k_{UC}\right)h_n\,. \tag{33}$$

The loading moment M_Q will be taken as suggested in [2], and with due regard for requirements of Part IV of the Rules [4]

$$M_Q = \left(1 - \varphi + k_{UCY} k_{UC}\right)\left(k_P B + A_{LD}\right)Qg\,. \tag{34}$$

In (34), φ is a balancing factor, [2]; k_{UCY} = a coefficient to account for the distance of transverse center of gravity of the topside's revolving part from the crane rotation axis (positive at the direction of lifting the cargo), which represents the ratio of topside's transverse center of gravity y_g (considering the sign) to the expression $\left(0.5B + A_{LD}\right)$; k_P = a coefficient to account for the distance of transverse center of gravity of the topside's rotation axis from the ship's Center Line Plane (CLP). $k_P = 0.5$ for TS located in the CLP; $k_P = 0$ for TS located at side (at the distance of $0.5B$ from the CLP); A_{LD} = useful outreach of the cargo from the CS side for the crane being operated perpendicular to the CLP.

After substitution to (13) (17), (20), (30) and (34), and appropriate re-arrangements, the condition takes on the below form:

$$M + \left(1 - \varphi + k_{UCY} k_{UC}\right)\left(k_P B + A_{LD}\right)Qg - \left[k_{B3} LB^3 - k_{B2} LB^2 - \left(k_{H1} H_{LD} - k_{\Delta 1}\right)Q\right]\left[\theta\right] = 0\,, \tag{35}$$

where

$$k_{B2} = \gamma k_H k_{dB} C_B h_n\,, \tag{36}$$

$$k_{B3} = \gamma\left(k_C k_{dB} + \frac{k_I}{k_{dB} C_B} - k_{B1}\right)k_{dB} C_B - k_{MN}\,. \tag{37}$$

Condition (35) is a modified CS initial stability equation as a function of ship's principal dimensions. That equation is impossible to solve in an explicit form. In order to solve (35) by use of successive approximations method with respect to B, the following parameters should be specified: Q, A_{LD}, H_{LD}, h_n, k_P, $[\theta]$, which are initially known as specified in the design basis; M, which is taken by close prototypes at early design stages; $L=f(B)$, which is determined by close prototypes or statistical relationships, or can be resulted from solution of the optimization problem; k_{MH}, k_C, k_I, k_H, k_{UCZ}, k_{UCY}, k_{UC}, which are are coefficients which are determined by close prototypes or statistical relationships. k_{UCZ}, k_{UCY}, k_{UC} are known for a specific crane; k_{dB}, C_B, which are specified by the designer as sub-sets limiting ranges of optimal values to be sought for; φ, which is a factor that can be specified in the design basis or by prototype, or can be obtained from solution of the optimization problem. [2] includes the justification of the condition $\varphi \leq 0.5$.

4. Verification of initial stability equation

The verification of the CS initial stability equation as a function of the ship's principal dimensions is performed by comparison of numerical calculation results obtained in solving (35), with the principal dimensions of built CS's, [3], [12], [13], [14], [15].

All the parameters required for solving the equation have been calculated based on characteristics of the corresponding prototypes, except for coefficients k_{MH}, k_C, k_I, k_H. The value of 0.78 was assumed for C_B, unless the value of block coefficient was provided in the source. The values of 0.00412; 0.525; 0.0671; and 0.550 were assumed for coefficients k_{MH}, k_C, k_I, k_H, respectively, for all design cases to be verified.

The results of comparative calculations are represented in Tables 1 through 3. Principal dimensions and elements of the built ships are listed in Table 1, those calculated by (35) are listed in Table 2, percentage errors of ship's elements calculated by (35) are given in Table 3.

Table 1. Prototype's elements.

Ship name	Q, t	L, m	B, m	D, m	d, m	C_B
Toisa Perseus	150	98.32	22.00	9.50	6.75	-
KS350	350	116.00	25.00	7.40	4.40	0.782
Toisa Proteus	400	117.70	22.00	9.50	6.75	-
KS600	600	138.00	32.00	9.20	5.20	0.829
Saibos FDS	600	152.00	30.00	12.40	8.00	-
Toisa OCV	900	144.00	32.00	13.30	7.50	-
Azerbaidjan	2,000	121.00	34.50	7.50	6.50	0.730
Sapura 3000	1,996	144.40	37.80	15.00	6.50	-
Stanislav Yudin	2,500	173.20	36.00	13.00	8.91	0.865
Lan Jiang	2,500	153.50	48.00	12.50	8.00	0.855
Oleg Strashnov	5,000	171.60	47.00	19.20	13.84	0.699

Table 2. Prototype's calculated elements.

Ship name	Q, t	L, m	B, m	D, m	d, m	C_B
Toisa Perseus	150	111.61	23.79	10.05	7.30	0.780
KS350	350	127.19	26.11	7.60	4.60	0.782
Toisa Proteus	400	107.57	21.14	9.23	6.48	0.780
KS600	600	149.27	32.97	9.36	5.36	0.829
Saibos FDS	600	158.94	30.51	12.54	8.14	0.780
Toisa OCV	900	136.61	31.48	13.18	7.38	0.780
Azerbaidjan	2,000	116.64	34.25	7.45	6.45	0.730
Sapura 3000	1,996	149.69	38.08	15.05	6.55	0.780
Stanislav Yudin	2,500	167.20	35.78	12.94	8.85	0.865
Lan Jiang	2,500	145.22	47.53	12.42	7.92	0.855
Oleg Strashnov	5,000	170.89	46.94	19.38	14.02	0.699

Table 3. Percentage errors of ship elements calculated.

Ship name	Q, t	δL, %	δB, %	δD, %	δd, %	C_B
Toisa Perseus	150	13.51%	8.12%	5.77%	8.12%	0.780
KS350	350	9.65%	4.43%	2.64%	4.43%	0.782
Toisa Proteus	400	-8.60%	-3.93%	-2.79%	-3.93%	0.780
KS600	600	8.17%	3.02%	1.71%	3.02%	0.829
Saibos FDS	600	4.56%	1.70%	1.10%	1.70%	0.780
Toisa OCV	900	-5.13%	-1.61%	-0.91%	-1.61%	0.780

Azerbaidjan	2,000	-3.61%	-0.74%	-0.64%	-0.74%	0.730
Sapura 3000	1,996	3.66%	0.74%	0.32%	0.74%	0.780
Stanislav Yudin	2,500	-3.46%	-0.62%	-0.43%	-0.62%	0.865
Lan Jiang	2,500	-5.40%	-0.97%	-0.62%	-0.97%	0.855
Oleg Strashnov	5,000	-0.41%	-0.13%	0.91%	1.26%	0.699

5. The influence of the relative breadth and block coefficient on the displacement (new results)

Let's consider the problems of searching for the optimal values of the sub-set *x,* (6) through (9), for the operational mode illustrated by the example of a crane vessel rated for maximal carrying capacity of 500 metric tons. Sub-sets of k_{dB} and C_B values are bounded from below and from above by the limiting values which are used for ships of the type under consideration. The minimum of total ship's displacement in operational state, Δ, is assumed as a target function:

$$\Delta(x) \to \min \ , \tag{38}$$

$$s \in S_1 : \gamma C_B LBd - \sum_i P_i = 0 \, , \tag{39}$$

$$s \in S_2 : M + (1 - \varphi + k_{\mathrm{UCY}} k_{\mathrm{UC}})(k_P B + A_{\mathrm{LD}}) Qg - \left[k_{\mathrm{B3}} LB^3 - k_{\mathrm{B2}} LB^2 - (k_{\mathrm{H1}} H_{\mathrm{LD}} - k_{\Delta 1}) Q \right] [\theta] = 0 \, ,$$
(40)

$$0.18 \le k_{\mathrm{dB}} \le 0.30 \ , \tag{40}$$

$$0.60 \le C_{\mathrm{B}} \le 0.85 \ . \tag{41}$$

Initial data for calculation are: Q = 5000 tons; A_{LD} = 10 m; H_{LD} = 130 m; M = 30744 kN x m; h_n = 6 m; k_P = 0.5; φ = 0.5; $[\theta]$ = 0.08727; k_{MH} = 0.00412; k_I,= 0.0671; k_{UCZ} = 0.5; k_{UCY} = -0.3; k_{UC} = 1.30;

The below statistic relations obtained by the author have been used:

$$\sum_i P_i = 0.135 \gamma C_B LBd + k_{\mathrm{UC}} gQ + 25000 \, , \ kN;$$

$$L = k_P B + 2.92(k_P B + A_{\mathrm{LD}}) + 50 \, , \ m;$$

$$k_{\mathrm{C}} = k_{\mathrm{H}} = 0.96(1 + 1{,}13 C_{\mathrm{B}}).$$

Since liquid ballast of the HCS makes a major contribution to the deadweight of the large carrying capacity CS being in operational state (generally greater than 30% of the total ship's displacement, [3], [6]), it is feasible to represent the condition (39) in the following form:

$$\gamma C_B LBd - \sum_i P_i \ge 0{,}3 \gamma C_B LBd \ . \tag{42}$$

Calculation results are listed in Table 4 as relations of Δ to varied values of k_{dB} (*B/d*) and C_B, and in Figure 1 as well.

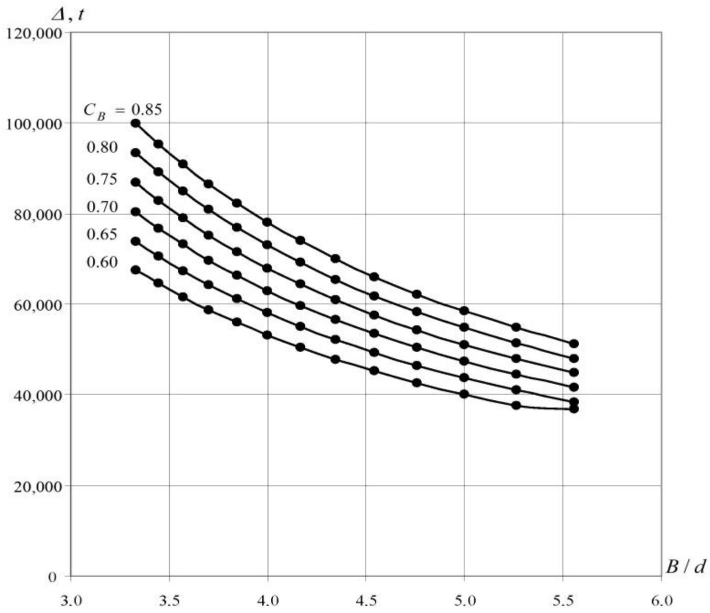

Fig. 1. Relations of Δ to varied values of k_{dB} (B/d) and C_B.

Table 4 $\Delta = f(k_{dB}, B/d, C_B)$, tons.

k_{dB}	B/d	C_B					
		0.60	0.65	0.70	0.75	0.80	0.85
0.18	5.56	36,749	38,416	41,598	44,798	48,016	51,251
0.19	5.26	37,653	41,042	44,454	47,889	51,343	54,815
0.20	5.00	40,100	43,724	47,374	51,049	54,746	58,464
0.21	4.76	42,600	46,464	50,359	54,281	58,228	62,199
0.22	4.55	45,151	49,263	53,409	57,586	61,790	66,021
0.23	4.35	47,755	52,122	56,526	60,964	65,433	69,932
0.24	4.17	50,412	55,041	59,710	64,417	69,159	73,933
0.25	4.00	53,124	58,021	62,962	67,946	72,967	78,025
0.26	3.85	55,891	61,063	66,284	71,552	76,861	82,210
0.27	3.70	58,714	64,168	69,677	75,236	80,841	86,490
0.28	3.57	61,593	67,337	73,141	78,999	84,909	90,866
0.29	3.45	64,529	70,571	76,677	82,844	89,066	95,340
0.30	3.33	67,524	73,870	80,287	86,770	93,313	99,912

The figures show that the target function does not reach its extreme value within the range of x under investigation. Actually, ship's displacement function is monotonically decreasing with decrease in k_{dB} and C_B. Therefore, two restricting conditions imposed on large carrying capacity CS, as suggested earlier in [1], [2], are not sufficient from the point of view of solving problems based on the system optimization approach for the ship.

6. Conclusion

In order to solve main problems of CS design theory with system optimization of those CS's, and to solve the problem settled in this article, we have established relations $\{B, d, D, \Delta\} = f(Q, R, A_{LD}, H_{LD}, \theta)$. That makes possible to solve the initial set of equations (12) and (13) for the case where ships elements to be determined differ from the prototype elements in their design characteristics, e.g. TS carrying capacity. A mathematical representation of large carrying capacity CS with the fully revolving topside, based on providing initial stability of the CS in operating condition, is built.

The verification has shown that this model allows determining values of the main ship's elements with a good accuracy, provided that prototype data are available. For comparison, models represented in [9] provide the accuracy of determining ship's elements $\{B, d, D, \Delta\}$ which is 20 to 25% lower than the accuracy ensured by the model built herein. When used for "exact re-calculation" from a close prototype, the principal dimensions determination method described in [10] yields close values of B and Δ (accuracy up to 5%). However, unlike the model proposed by us, that method is restricted by maximal characteristics of the CS TS and renders unsuitable for system optimization. The investigation of the influence of relative breadth and block coefficient on the displacement of the large carrying capacity crane ship in operating condition has shown that some additional restricting conditions are required to introduce for CS system optimization. In other words, conditions (12) and (13) are necessary for the determination of the CS satisfying requirements of Rules [4] only with respect to stability, but some additional conditions are needed to determine the elements with respect to system optimization. This important issue has never been addressed in any of the previous studies.

Further investigation to be carried out by the author will be focused on introducing that condition in terms of a requirement for restriction of initial metacentric height as one of the governing parameters of stability in cargo-break-away condition, [4].

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