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Superposition and interchangeability of design characteristics of the multipurpose ice-going ship in determining their optimum values

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Abstract: [**Objectives**] This paper aims to propose an approach for optimization of the multipurpose ice-going ship characteristics and design particulars, considering methodological interdependence among these values. The ship particulars do not appear to be independent in the systemic sense, and any of the characteristics of the size could be predetermined by the definite approximation. [**Methods**] The methodological approach means the selecting an independent characteristic which is varied in the next for searching its optimal value on the criteria used. It is taken into account the methodological property of superposition of design characteristics as to find the optimal values of the independent design characteristics, the associated balance proportions with the rest of the ship size characteristics and the associated parametric dependences with the design particulars, that means as well determining in the initial approximation of the rest characteristics of ship size and design particulars. Since in the subsequent design stages the refinement are carried out in the narrow intervals of their variation of the approximate values of rest ship size characteristics and design particulars, which were found approximately at the initial stage, corresponding to definite inaccuracy of their approximate determination at the initial stage. The improvement of the originally found values within the inaccuracy does not exert the noticeable influence on the optimum value of the independent design characteristic, determined at the initial stage, serving as the design constraint in the improving of the values of the rest characteristics, as well as its design particulars, found approximately in determining of optimal value of independent design characteristic. [**Results**] The property of superposition in finding optimal design characteristics and particulars means the possibility of their independent sequential determination if the characteristics found in the previous design stages and particulars are used as the design constraints in subsequent stages. [**Conclusions**] Initially the characteristics of ship size are determined with the allowance of design constraints, and then the design particulars are sought, while the design constraints are found for ship characteristics.

Key words: multipurpose ice-going ship; design optimization; optimality criteria; objective function; design constraint; ship characteristics; ship particulars

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0 Introduction

The research field involves the improvement of the methodological approaches utilized to determine the characteristics and particulars determined during the initial steps of multipurpose ice-going ship (herein refered to as "the ship") design with the application of objective functions and optimization within the frames of the definite constraints. This is critical, as the construction of the merchant ships of this class are expensive, thus causing the level of the requirements for the logic and quality of design-characteris-

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tic finding. This article is based on previous author research [1-10] and the known works from colleagues in the field of ship design methodology[11-12].

However, the well-known works usually do not correspond sufficiently to the determination of the design characteristics and particulars of the ship of the considered class due to the specific selection of criteria, constraints, and the set of variables that will be used. The goal of the article is to cover the determination of recommendations, which correspond with the choice of variables of the objective function- the characteristics and particulars of the ship sought at design.

The characteristic sequence of the design optimization of merchant ice-going ship and its use consists of the following steps:

1) The definition of the concept of a multipurpose ice-going ship as the subject of design methodology, as well as the object in the merchant ship classification system.

2) The formulation of the issue of finding optimal characteristics and design particulars of the multipurpose ice-going ship in the hierarchy system of objects linked to the ship being designed, particularly: the concept of the object definition, which works for the ice-going ship as the general complex system. This also considers the option variation of this general system and the definition of the option concept comparability in the optimization.

3) According to the decision made in the first and second tasks regarding finding design constraints and the initial data set for the determination of the optimal ship characteristics and design particulars.

4) Considering the decision of the first and the second tasks, the subsystems' [1] definition of the multipurpose ice-going ship and is represented as the complex system, consisting of subsystems.

Design constraints are considered in the form of the equations or data that are characteristics of the complex general system, part of which is the multipurpose ice-going ship being designed.

5) The composition definition (vector) of ship design characteristics in the total set of numerical values characterizing the ship by identifying the following value classes: the array of constraints, which work as data for design optimization, and are determined by solving the second and third of the above tasks; the vector of the design particulars of the ship, defined by solving the fourth task.

6) Formulation of the balance assumptions of characteristics of the multipurpose ice-going ship, particularly, the creation of the displacement balance equation possesses a probabilistic nature, showing the ratios of these characteristics.

7) The finding of functional and parametrical dependences between the characteristics and design particulars, as well as dependences between the particulars on their relative sizes.

8) Analysis of ship capabilities in ice of particular intensities, depending on engine power and propulsive characteristics according to the design requirements specified in the form of design constraints by the features of the ship in icy conditions. Also considering the size of the vessel and the strength of the hull, depending on the structural elements of the ship.

9) The calculating of the functional dependences of economic indexes regarding multipurpose ice-going ship characteristics on the starting data (design constraints) and the parameters; the formalization of utility functions, economic criteria, and the creation of the objective functions to discover optimal characteristics and the design particulars.

10) The multisided quality control of the multipurpose ice-going ship characteristics uncovered and the sustainability of the characteristics' optimality. Determining the factors of the optimal characteristics and design particulars' sustainability.

11) The assent of the mathematical models in the calculations made to find the optimal characteristics and design particulars for the specified constraints, also involving the investment constraints of the subsidies in ship construction and the specified technical requirements of seakeeping and strength of the ship in ice.

The tasks outlined above will be decided during the initial design stages, specifically at the stages of: working out the technical specifications and development of the technical proposal and, to a lesser degree, at the point of calculating the particulars of the ship at the preliminary design or technical stage.

Each of the outlined tasks, from the second to the fifth, is subordinate systematically to the first, and their solutions serve as a foundation for forming the methods that will be utilized to discover the effective design characteristics of the multipurpose ice-going ship.

Thus, the accurate solution for the first task is critical -the formalization of the multipurpose ice-going ship definition, which emphasizes the functional and structural characteristics of the ships of this type, and which allows further definition of the criterion in the form of objective function and that of design constraints (the set of initial data). This is the characteristics range sought, as well as the design particulars, and generally, this leads to the solution of tasks involving finding the optimal characteristics of the multipurpose ice-going ship.

1 Interchangeability concept of ship design characteristics

Interchangeability involves the methodological property of the values of different types within the mathematical model utilized to decide these characteristics and particulars optimum when designing the multipurpose ice-going ship. The characteristics and particulars' interchangeability within the mathematical model means the connection between the characteristics and the design particulars of the ship, which possess the balance equations form of characteristics as well as the form of the parametric dependencies of particulars at the primary design stages.

Optimal behavior characteristics occuring at the early design stages of multipurpose ice-going ship in the framework of the systematic approach, it is necessary to take into account the feature of superposition of ship characteristics and design particulars pertaining to the independent determining of the characteristics and the particulars successively at different stages, or the feature of superposition of ship characteristics and their extension. And at each individual design stage, these values could be considered independent because of the disparity of their variation intervals, or because of the existing parametric dependencies among these values.

As the variable of the required values, one or another characteristic of the size of the projected multipurpose ice-going ship is used, then, as a rule, the other ship size characteristics e.g, displacement (D), deadweight (DW), cargo capacity(PG), gross registered tonnage (GRT), net registered tonnage (NRT), are with the specified characteristic in balance ratios. In other words, the possible intervals for their variation are substantially shorter than the range of values in which the independent size characteristic selected from this set can vary, and as it can be recommended that the characteristic of the design deadweight of multipurpose ice-going ship be used.

The intervals of variability of the other characteristics associated with the balance ratios with the independent characteristic of ship, and the variability intervals of the design particulars of the multipurpose ice-going ship, meaning the characteristics of its subsystems are proportionate with the approximation inaccuracies of the balance ratios used in the constraints at the early design stages, and the approximation inaccuracies of parametric dependencies, by which the design particulars are correlated with the ship varied characteristics required for their optimal values at the preliminary design stages.

Considering that the design particulars of the multipurpose ice-going ship are determined as a result of these characteristics, and are further specified (in subsequent design stages, when the object is the subsystems of ship), the variation intervals in the determination of design particulars correspond with the approximation inaccuracy of the parametric formulas used, and in view of the fact that the generalized variable characteristics of the ship are governed by balance equation and in consequent design stages, when looking for particulars functioning as the characteristics of the ship subsystems, the generalized variable characteristics of ship are refined and their variation intervals are proportional with the errors of the balance ratios used, then, in arriving at the optimum design characteristics of the ship, the corresponding reserve of ship size is required, in particular, the design reserve of the displacement, or the reserve of the projected deadweight, which in the subsequent design stages in determining design particulars and the other corresponding characteristics of the ship, could be used to compensate for the indicated ship size adjustments, depending on the calculation taken from design particulars.

It should be noted that, despite the variety of design particulars of the multipurpose ice-going ship, established at the various stages as the characteristics of ship subsystems, there is no need for unnecessary design reserves of ship size, as the displacement reserve, or the deadweight, or the other size characteristic, used as the required independent variable at the early design stages , since the impact on the ship size of each of the design particulars, indicated in the corresponding intervals of variation at following stages, can be categorized probabilistically as factors increasing or decreasing of size of multipurpose ice-going ship under design.

Thus, the cumulative effect of the design particulars on the size of the multipurpose ice-going ship planned in the next stages is less in the general case than the influence of certain design particulars determined in the order of their improvement. Therefore, the project reserve of the size of the multipurpose ice-going ship, for example the displacement reserve, or the deadweight, or the other characteristic of ship size acquired as independent at the initial design stages, would act as the slight relative helpful correction to the characteristic of ship size required in a linear corresponding ratio to ship size characteristic, in particular as the summand of the balance equation of displacement, depending on the displacement (or on the design deadweight) in the linear corresponding degree.

In the examples presented, the superposition, that is the ability of determining the independent characteristic of ship and the other characteristics and the design particulars, becomes visible as the systemic property, taking into consideration the disparity of the intervals of the variability of the independently determined characteristics and of design particulars, since the independent design characteristic of the ship, when determining its optimal value at the initial design stage, varies in the interval in proportion to its own value, and the remaining characteristics and design particulars are formed at further stages of designing into essentially smaller intervals in keeping with the inaccuracies of the balance proportions between the characteristics of ship and corresponding with errors in the parametric dependencies between the characteristics and the design particulars.

2 Superposition of factors: payload and displacement

It is possible to give another illustration of using the system property of superposition in discovering the design characteristics connected with the result of the balance equation of displacement of the multipurpose ice-going ship. The displacement of a vessel of this type can be considered consequently the given design deadweight $D(DW)$ and on the rise in the level of displacement $\Delta p(h)$ due to an inherent predetermined load increment $\Delta D_{p(h)}$, contingent in this case, on the specified design limitations on the maximal thickness h of advancing ice, meaning in the general case on operational capabilities of the ship in ice or on a given ice category (arctic, polar, icebreaking, etc.) specified in the technical assignment.

The superposition, meaning the calculable occurrence of independent estimates of these components of displacement, also paired with the disparity of intervals of variation of the design deadweight and the rising levels of displacement due to the specified naturally occurring increase of load of the multipurpose ice-going ship being designed, results from the manner of displacement being the sum of specified summands employing balance equations of displacement in the finite form or in the derivative form.

The defining of displacement D at the design stage of the multipurpose ice-going vessel as part of the order of dependencies in the mathematical model is arrived at using the balance equation of displacement in the finite form and in the increments, depending on data; in other words, on the design parameters of the ship which serve as characteristics of more general systems, which to the ship belongs to as a subsystem:

1) on design deadweight DW, including not just the maximal load of the variable cargoes, but also the combined load of all systems, machinery and gears specified directly or indirectly within the design parameters in keeping with the task of the ship, i.e., the total load entering the zero degree of dependence on displacement in an equation of its balance;

2) on icebreaker function, characterized in particular by thickness h of the continuous solid ice field with the assumption that the remaining criteria of seaworthiness in ice conditions to some extent depend on the ability of the ship to move in continuous ice field of specified or known thickness.

It can be recommended that it takes into account the effect of the icebreaker function in the form of increment of displacement dD_P using the balance equation of ship displacement in the form of rising values (Norman factor, Fig. 1).

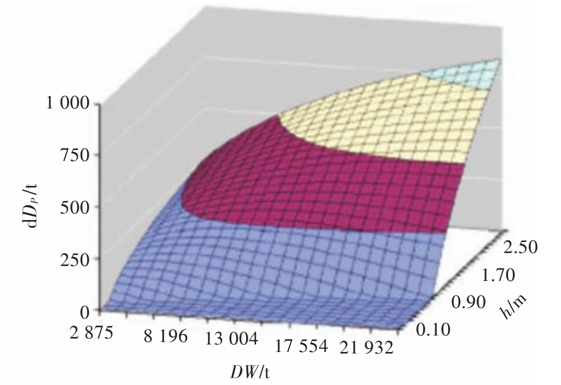
Thus, when determining the displacement D of the multipurpose ice-going ship at the design stage, taking into account two listed data groups having an impact on different orders on the resulting index, one can adopt the superposition concept of the influence of these data groups and successively find both terms in the derivative equation of displacement balance:

$$D(DW,h) = D(DW) + dD_{p(h)} \qquad (1)$$

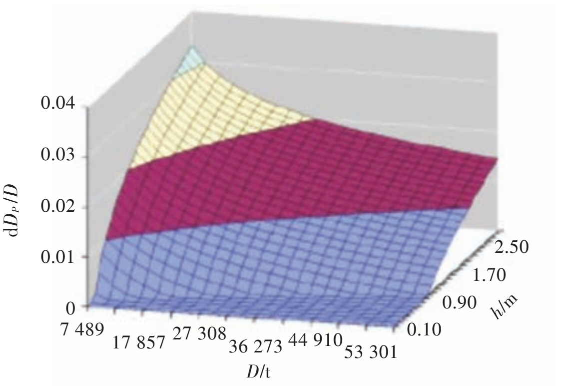
3 Interchangeability of effect indices

The utility function exemplifies the impact of the multipurpose ice-going ship and serves as an integral part of the economic criterion used to determine the optimal characteristics of the ship. The effect can be as a navigational service in conditions of ice of ships that do not have an ice category or have an insignificant ice category, and also itself cargo transportation or other work in the ice of the ship under design.

As variations of the utility function, meaning, the



(a) Displacement dD_P in absolute value



(b) Relative valued D_P/D

Fig.1 The dependence of displacement dD_P in absolute value and dD_P/D in relative value

dependence of the index of the beneficial effect on variables and on design parameters: the initial data and the particulars, the characteristic of the transport function of the ship, that is to say, its cargo transportation capacity would be considered, including the singular capacity in ice conditions, and the characteristic of the size of the multipurpose ice-going ship, which at the same time shows the capability of the ship to maintain equipment and personnel, as well as for the provision of secondary navigational services in ice conditions, including the ability to lay fairways in ice fields.

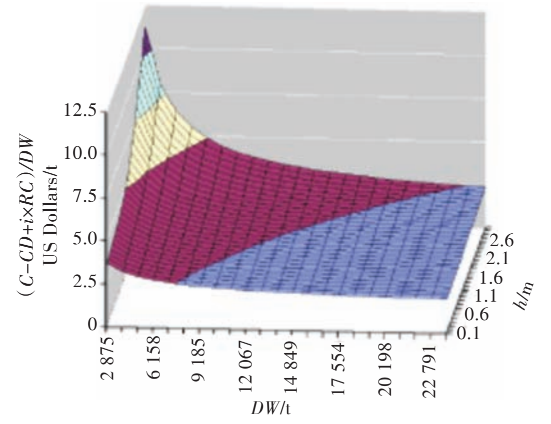
The function of the criterion of specific present worth (without taking into account the financial limits of the investor in the form of an adjustment to the criterion) per unit of the utility function, if it considers the design deadweight DW, is shown in the form of a graphic surface (Fig. 2(a)). As an alternative to the characteristic of the effect E, it is used to indicate annual capacity Q_{CG} (Fig. 2(b)), and it would be the usual indicator of a cargo ship planned for batch construction.

Non-uniform smoothness of the surface of the objective function (Fig. 1(b)), coupled with the physical prerequisites in determining the effective power of the ship's engine and the ship's velocity in open water, of small ice categories ships, does not importantly influence the general agreement about the preference for a larger ship size when assessing efficiency per unit of transported cargo according to specified reduced costs (PW/Q_G).

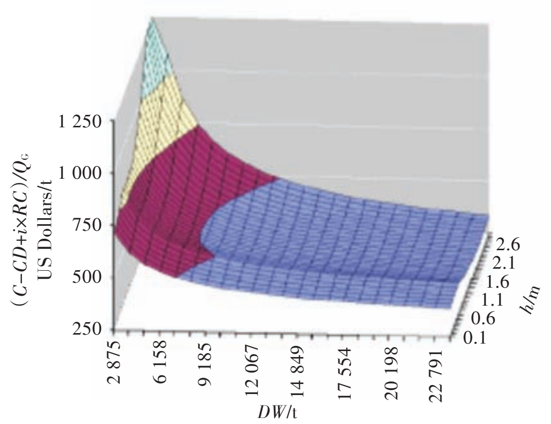
A similar conclusion about the preference of a ship of the largest size can be made from the analysis of the graph (Fig. 2(a)) per unit size (of design deadweight) of the ship's objective function in the form of the present value per unit of the deadweight PW/DW.

It transpired that the size of a multipurpose ice-going ship is roughly proportional to its index of cargo transportation capacity, and these functional characteristics (the size of the ship and its transportation capacity) in the wide range of data are interchangeable as part of the criterion when deciding optimum design characteristics of the ship.

In a wide range of variation of ship size to its annual cargo transportation capacity Q_G, for each given design limit of the thickness h of continuously encroaching ice, proportional to the size of the ship (DW or etc.), at the initial design stages it can be con-



(a) The dependence of specific present worth PW/DW



(b) The dependence of specific present value PW/Q_G

Fig.2 The dependence of specific present worth PW/DW per unit of the utility function and the specific present value PW/Q_G per unit of cargo transportation capacity of ship Q_G

sidered.

Replacing one of the utility functions with any other of the two options considered (Q_G and DW) in the denominator of the economic criterion practically, cannot affect the position of the optimal extremes of the objective function along the axis of the required characteristic of ship size.

4 Interchangeability of design characteristics of ship size

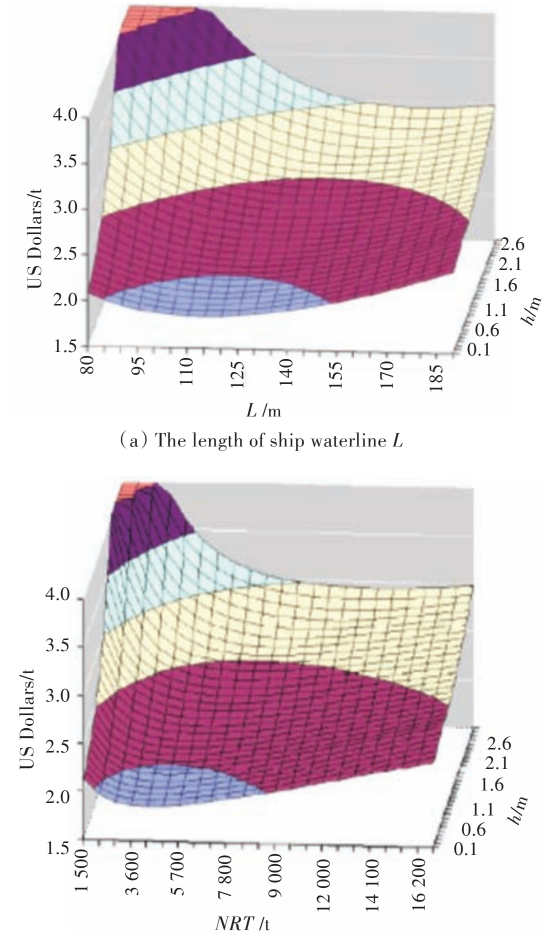
The other variable characteristic of the size of the multipurpose ice-going ship, for example, the cargo displacement D, the cargo capacity PG, the gross register tonnage GRT or the net tonnage NRT, etc., as well as some of these, which usually are referred to as the design particulars of a ship, meaning the characteristics of it subsystems can be used as variable characteristics of ship size besides its design deadweight DW. In particular, the length of ship waterline as a variable characteristic of size, can be used and is normally attributable to its design particulars.

The examples of using the other characteristics of ship size as the variable characteristic required at the early design stages are shown on the graphical functional surfaces of the objective function f, dependent on the design limits on the maximum thickness of the forced ice h and on the variable required for design optimization, represented by the characteristic of ship waterline length L (Fig. 3(a)) or by the net tonnage NRT (Fig. 3(b)).

The use as examples of the variable required characteristics of the multipurpose ice-going ship of its waterline length L or its net tonnage NRT, means the reference of the deadweight DW and the other characteristics of ship size, in such cases depending on length or capacity, to the number of design particulars, serving as the parameters dependent on the variable of required ship size characteristic.

5 The replacing of the design limitation by ship characteristic when determining the velocity of the ship under design

The characteristic of ship operation velocity v_S, together with the characteristic of ship size (for example, with the characteristic of load line displacement, D_l) in the most general approximation, determines the effective power Ne, associated with propulsive power N_{ICE}, required for forcing of ice field, and simultaneously determines the particular level of the operational features of the ship in the ice.



(a) The length of ship waterline L

(b) The net register tonnage NRT

Fig.3 The dependences of objective function f on design constraint of the maximal thickness of forced ice h and on the variable characteristic sought in the variants of that characteristic

This signifies that for non-essential ice categories, the level of performance of a ship in ice can be calculated depending on the operating velocity v_S of ship in the open water, using the operating velocity in open water as the ship's characteristic required, instead of the set design limit of the ice category of ship under design, by the specified thickness h of forced continuous ice field or the other related index.

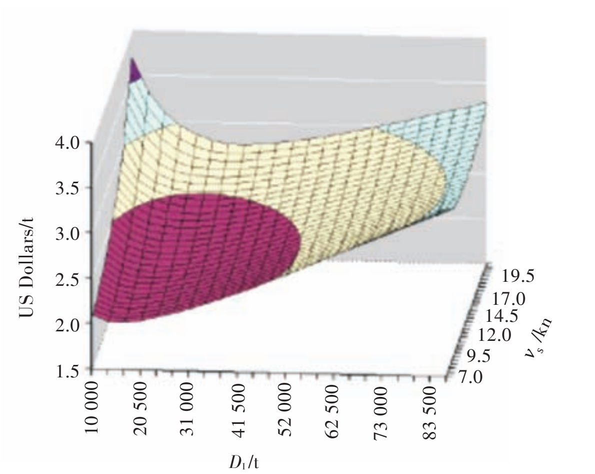
In order to find optimum design characteristics for an insignificant ice category of ship, it would be possible to replace used, in determining the objective function of the design limits of the maximal thickness of forced continuous solid ice field h (or the other specified characteristic of ship operation properties in ice in the assignment), which serves simultaneously as the design characteristic of the ship, to the required variable characteristic of the ship's operating velocity v_S in open water.

On the graph, functional surfaces are presented: the example of the dependence (Fig. 4(a)) of objective function f on ship load line displacement D_l (that is the mass of the loaded ship) and the dependence of ship operating velocity v_S (that is the specified value of velocity, Fig. 4(b)) in open water.

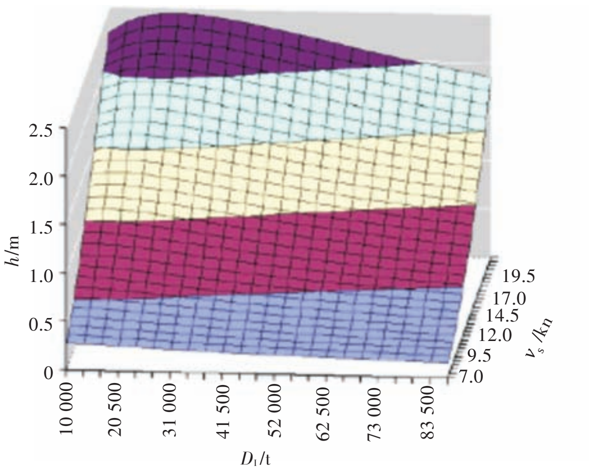
On the analysis of graphical functional surfaces, one can surmise that the limits of the operating velocity of ship v_S in open water, logical from an economic point of view, and the limits of ship size D_l, connected to the specified restrictions of the subsidies for ship construction, accounted for in the form of penalty (or premium) amendment to the objective function f (Fig. 4(a)), parallel the insignificant operational properties of the ship in ice, estimated in the specified example as the maximal thickness of the forced continuous solid ice h (Fig. 4(b)).

6 Conclusions

1) The interchangeability of the characteristics



(a) The objective function f on variables



(b) Characteristics of icebreaking features of ship

Fig.4 The dependence of objective function f on variables and the characteristics of icebreaking features of ship

and particulars in the mathematical model means that the interdependence among the characteristics and among the design particulars of the ship, have the form of the balance equations of characteristics and the form of the parametric dependencies.

2) The factor of the superposition of payload and displacement as well covers the directly and indirectly indicated increments of ship displacement value, as the volume of cargo and the body weight corresponding to the ship's ice-breaking function associated with the disparity of intervals of variation of these increments.

3) The interchangeability of indexes of effect on the objective function for ship designing optimization is characteristic because the effect indexes for each of specified functions -as cargoes transportation so as the ice-forcing are dependent on the ship size characteristic unilaterally.

4) The impact of the ice category, specified in the data, on to the superposition of the ship's design characteristic required, is that at the small or the insufficient ice-category, the targeted design characteristic could be the operation velocity of ship-not the ship size, which is the characteristic variable for the great ice categories, and these two characteristics are not variable simultaneously.

5) When the variable design characteristic or particular is found, the rest, which are in the superpose relation to the discovered values, are determined with the use of ship balance equations and the parametric dependences.

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确定多用途冰区航行船舶设计特性最优值的叠加性和互换性方法

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摘　要：[**目的**] 研究冰区船设计参数之间的相互关联性，旨在提出一种多用途冰区航行船舶性能与设计参数之间的优化方法。冰区船作为一个整体系统，其性能指标不是独立的，通过任何一个技术指标能够近似确定其他的技术指标。[**方法**] 采用的方法是在满足设计要求的前提下，选取冰区船各项性能指标的最优值，并采用冰区船单项设计指标最优值的叠加性特性方法，因为每一项船舶技术指标既与其他的技术指标相关，也与船舶的设计参数相关，从而可以初步估算船舶其他尺度指标和设计参数的初始近似值。在初步设计阶段，确定技术指标和设计参数近似值的大致范围会有一定的误差，这些参数在后续设计阶段将进一步细化。在误差范围内对初始值进行调整不会对某个性能指标的最优值产生较大影响，初步设计阶段确定的最优值可作为进一步改善其余船舶技术指标的约束条件，从而可以进一步确定该技术指标的最优值。[**结果**] 采用叠加性优化设计性能指标和参数时，若将初始设计阶段确定的特征参数作为后续设计阶段的设计约束，可以逐次迭代确定目标船的性能指标和参数值。[**结论**] 首先确定船舶参数的设计范围，然后以该确定的船型参数为约束条件，可以进一步细化冰区船的设计指标。

关键词：多用途冰区航行船；设计优化；优化准则；目标函数；设计约束；船舶技术指标；船舶参数