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DETERMINATION OF THE OPTIMAL CARGO OPERATIONS STRATEGY OF A BULK CARRIER VESSEL, WITH CONTINUOUS ENSURING ITS SEAWORTHINESS

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Summary

Introduction. *Maritime safety is an important aspect of the shipping industry. Ensuring that the vessel's seaworthy parameters are within acceptable limits throughout the voyage, including during cargo operations, is a key element of this safety. The International Convention for the Safety of Life at Sea (SOLAS) requires vessel personnel to plan and carry out cargo operations in such a way that the ship always meets the seaworthiness criteria. Bulk carriers are subject to more stringent seaworthiness and safety requirements, particularly with regard to stability and hull strength. The correct loading of bulk carriers is essential for their maritime safety. Inadequate loading can lead to various risks, including compromised hull strength, reduced stability and violation of the vessel's seaworthiness. Existing shipboard instruments do not allow for timely planning and real-time control of loading operations, which can lead to potential risks. Creating a cargo operations plan takes considerable time and efforts of the responsible bulk carrier personnel, and these plans will not always be the best in terms of ensuring the vessel's current seaworthiness. The high intensity of loading operations at dry bulk terminals exacerbates the problem, as there is often insufficient time to adequately prepare and verify loading plans, increasing the risk of overloading cargo holds.*

Purpose*. The article proposes the development of new methods for bulk carriers cargo operations planning. These methods would optimise the distribution of bulk cargo, taking into account factors such as port facilities, ship design and nautical restrictions of the planned voyage. The aim is to formalise the parameters that affect the ship's seaworthiness in the form of a mathematical model and to establish functional relationships between them. By analysing the relationships between different parameters, the researchers aim to determine the best strategy for cargo operations that will ensure the continuous seaworthiness of the bulk carriers. This approach would help to improve bulk carrier's safety and reduce the risks associated with incorrect loading.*

Results. *The article proposes a new approach to planning bulk carrier cargo operations. This approach allows for the optimisation of the distribution of bulk cargoes during cargo operations, taking into account factors such as port capabilities, vessel design and navigational constraints of the planned voyage. The parameters affecting a vessel's seaworthiness have been formalised and functional relationships between them established. By analysing these relationships, the researchers sought to identify a method* *for finding the best cargo operations strategy to ensure the continued seaworthiness of bulk carriers. Such a method would help to improve bulk carrier's safety and reduce the risks associated with improper loading.*

Conclusions. *The article proposes a method, based on the theories of systems analysis and operations research, as well as mathematical modelling, for optimising the cargo operations and maintaining the seaworthiness of bulk carriers. The main objective is to ensure that the vessel's seaworthiness parameters, including stability, overall longitudinal strength and local strength, remain within acceptable limits throughout the voyage, including the period of cargo operations in port. Careful management of the bulk vessel's cargo and ballast operations will ensure that these critical parameters are maintained within acceptable limits at all times, which is essential to prevent accidents and protect life and property at sea.*

Key words: *bulk carrier, maritime safety, cargo operations, optimisation, permissible loading, ship stability, the vessel strength.*

ПОШУК ОПТИМАЛЬНОЇ СТРАТЕГІЇ ВАНТАЖНИХ ОПЕРАЦІЙ НАВАЛЮВАЛЬНОГО СУДНА ЗА УМОВИ ПОСТІЙНОГО ЗБЕРЕЖЕННЯ ЙОГО МОРЕХІДНИХ ЯКОСТЕЙ

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Анотація

Вступ. *Безпека мореплавства є важливим аспектом морської індустрії. Забезпечення параметрів морехідної безпеки судна в допустимих межах протягом всього рейсу, у тому числі і під час вантажних операцій, є одним із ключових елементів цієї безпеки. Міжнародна конвенція з безпеки людей на морі (СОЛАС) вимагає, щоб судновий персонал планував і проводив вантажні операції таким чином, щоб судно завжди відповідало критеріям мореплавства. Для навалювальних суден (балкерів) існують підвищені вимоги щодо морехідної безпеки і насамперед вони стосуються їх остійності та повздоаньої міцності.*

Існуючі на навалювальних суднах документація та інструменти не охоплюють всі можливі ситуації завантаження судна, різноманітність номенклатури вантажів, специфіку майбутнього рейсу та не дозволяють своєчасно планувати і контролювати вантажні операції в режимі реального часу, що може призвести до потенційних ризиків. Створення плану вантажних операцій займає значний час і зусилля відповідального персоналу балкера, і ці плани не завжди будуть найкращими з точки зору забезпечення поточних морехідних якостей судна. Висока інтенсивність вантажних операцій на суховантажних терміналах загострює проблему, оскільки часто не вистачає часу на належну підготовку і перевірку планів навантаження, що підвищує ризик перевантаження трюмів.

Для ефективного визначення оптимальних варіантів завантаження суден повинні використовуватись методи, що дозволять автоматично моделювати вантажні операції та оцінювати параметри морехідності судна. Ці методи *повинні враховувати різноманітні фактори, такі як технічні особливості самого судна, характеристики вантажів та умови рейсу.*

Мета. *Метою статті є аналіз можливостей визначення допустимих варіантів завантаження навалювального судна, які задовольняють обмеженням, що накладаються параметрами мореxідної безпеки, а також формалізація параметрів, що впливають на мореxідність судна, та встановлення функціональних зв'язків між ними для подальшої побудови ефективної математичної моделі судна.*

Результати. *У статті запропоновано новий підхід до планування вантажних операцій балкерів. Цей підхід дозволить оптимізувати розподіл навалювальних вантажів під час вантажних операцій з урахуванням таких факторів, як портові можливості, конструкція судна та навігаційні обмеження запланованого рейсу. Проведена формалізація параметрів, що впливають на мореxідність судна, та встановлені функціональні зв'язки між ними. Аналізуючи ці взаємозв'язки, дослідники прагнули визначити метод для пошуку найкращої стратегії проведення вантажних операцій, який забезпечить безперервну мореплавність балкерів. Такий метод допоможе підвищити безпеку балкерів та зменшити ризики, пов'язані з неправильним завантаженням.*

Висновки. *У статті запропоновано метод, що базується на теоріях системного аналізу та дослідження операцій, а також математичного моделювання, для оптимізації вантажних операцій та підтримання мореxідних якостей навалювального судна. Ключова мета – забезпечити, щоб параметри мореxідності судна, зокрема остійність, загальна поздовжня і локальна міцність, залишалися в прийнятних межах протягом усього рейсу включно з періодом вантажних операцій в порту. Завдяки ретельному управлінню вантажними і баластними операціями судна можна досягти постійного дотримання цих критичних параметрів в допустимих межах, що є критичним для запобігання аваріям та збереження життя та майна на морі.*

Ключові слова: *навалювальне судно, мореxідна безпека, вантажний план, оптимізація, остійність, міцність судна.*

Introduction. Maritime safety includes maintaining the acceptable limits of a ship's seaworthiness parameters. These parameters are maintained by proper loading of the vessel during cargo operations. The stability and strength criteria apply to all categories of vessels and are defined in the conventions of the International Maritime Organisation (IMO). Cargo handling in ports has a significant impact on the safety of shipping, especially for bulk carriers.

Statement of the problem and analysis of recent research. The seaworthiness is an abstract concept used in maritime law that indicates how safe and ready a vessel is to sail. In the broadest sense, seaworthiness means the fitness of the vessel to meet the ordinary hazards contemplated for the voyage. The concept of seaworthiness also extends to the fitness of the vessel to receive, carry and care for its intended cargo. Regular inspections must be carried out to ensure that the highest standards are maintained on board the vessel at all times. If shipowners are found to be negligent, they will face severe action.

Presenting main material. In accordance with the International Convention for the Safety of Life at Sea (SOLAS), it is mandatory for a vessel's crew to carefully plan and execute loading operations to ensure that the vessel remains seaworthy throughout the process and ready to sail at any stage of port operations.

To ensure the seaworthiness of dry bulk carriers, each ship is designed by the shipbuilder with specific guidelines for loading options. These guidelines are set out in the loading manual or in specialised computer loading programs, which enable the ship's seaworthiness parameters to be assessed on the basis of the loading option selected. It is the responsibility of the ship's cargo officer to determine the most suitable loading option within the ship's allowable stability and strength parameters.

However, existing documentation for typical ship cargoes covers only a limited range of loading scenarios and may not cover all possible loading situations or the specific requirements of a particular voyage. As a result, finding the optimal cargo plan can require considerable effort on the part of the ship's personnel. In the fast-paced environment of modern dry bulk terminals, where time constraints often prevent thorough preparation and verification of new cargo plans, there is an inherent risk of overloading individual cargo holds. This can compromise the local and longitudinal strength of the hull and ultimately the seaworthiness of the ship.The use of modern computer technology makes it possible to calculate the permissible ship loading, taking into account the restrictions of the seaworthiness criteria, provided that the ship loading process is formalised and loading algorithms and programs are developed.

A method (strategy) should be developed for the optimal distribution of a given amount of dry bulk cargo, taking into account the available port cargo facilities and the design characteristics of the vessel itself, while maintaining the parameters of its draft, trim, stability and overall longitudinal strength.

The development of such a method should be based on theories of systems analysis and operations research as well as mathematical modelling tools.

To solve this problem, it is necessary to formalise the cargo operations in terms of a mathematical model of the ship and to identify the functional relationship between the parameters that affect the seaworthiness of the vessel.

Clearly, the development of this method is a relevant and promising area of scientific research aimed at ensuring the safety of bulk carriers.

The subject of maritime safety in relation to bulk carriers is examined in the next sources [1; 2; 3].

The International Maritime Organisation (IMO) has established conventions that provide guidelines for the planning and execution of bulk carrier cargo operations [4–7].

An important resource for understanding the safe operation of bulk carriers is the knowledge and experience of seafarers actively involved in this field [8–11].

Gaichenya O.V. and Klimenko E.N. proposed the application of systems analysis and operations research principles to the cargo operations of bulk carriers and multipurpose vessels [12; 13].

The authors Tsymbal M.M. and Vaskov Y.Y. [14; 15] introduce mathematical models aimed at optimising the loading processes of bulk carriers and solve this problem by applying linear programming techniques.

The study presented in [16] focuses on the selection of a specific selection of bulk carrier cargo holds for efficient loading of bulk cargoes. It outlines a method for structuring the stages of bulk carrier loading operations when dealing with non-standard loads.

The aim of this article is to examine the potential methods for determining acceptable variations in ship loading that comply with the constraints imposed by maritime safety parameters. While complying with the general requirements for maritime safety, different types of ships have additional specifications based on their design or cargo carrying technology.

Consequently, specific requirements are imposed on general cargo vessels when loading general cargo. These requirements mainly include ensuring compatibility of cargoes within a single cargo space, accommodating a large number of cargoes for transportation, adhering to a specific sequence of ports for discharge and limiting the number of cargo levels based on the strength of the cargo packaging.

Bulk carriers have more stringent loading requirements due to their considerable length. These requirements are imposed by the overall longitudinal and local strength of the ship's hull, which affects various aspects of cargo operations. In particular, bulk carriers typically carry out cargo and ballast operations simultaneously. These operations are carried out in several stages (up to twenty), depending on the number of holds to be handled simultaneously and the specific cargo volume.

Shipbuilders usually provide specific loading manuals for bulk carriers, tailored to the cargo volume and number of holds involved. These manuals focus exclusively on a single type of cargo to be loaded. Each manual outlines a sequence of loading stages, specifying which holds are to be loaded, the corresponding cargo increments and the combination of tanks used for ballast operations. At the end of each stage, the ship must be in an acceptable seaworthy condition.

Difficulties arise when dealing with non-standard loading situations not covered by the shipbuilder's instructions. The planning and execution of cargo operations in such cases becomes challenging, as it is necessary to ensure the seaworthiness of the vessel and optimise the utilisation of cargo space and deadweight capacity. Shipowners are forced to develop a series of steps that address the problem of maximising cargo placement in the holds while taking into account the simultaneous handling of the required group of ballast tanks. Compliance with numerous seaworthiness restrictions becomes a critical aspect in these scenarios.

In order to build a mathematical model for optimising the loading process of a bulk carrier, it is necessary to formalise it, which systematises complex various processes associated with cargo and ballast operations.

To describe the loading process of a vessel, it is necessary to define a set or space of its states U, and each specific loading state of a vessel u belonging to this set U should be defined as a set of parameters of the vessel's seaworthy parameters, which depend on the distribution of cargo in holds and ballast and reserves in tanks and vessel's compartments. Thus, each specific loading state of a vessel u can be accepted as a certain variant of the distribution of cargo, ballast and supplies to the respective holds, tanks and spaces.

Each vessel's condition u can be analytically expressed as follows.

$$u = \{w_{ci}, w_{bi}, w_{zi}\}, \tag{1}$$

where is w_{ci} the weight of cargo in the *i*-th cargo space;

w_{bi} – is the weight of ballast in the *i*-th ballast tank;

w_{zi} – weight of stores in the *i*-th tank or storage space;

$i = 1, 2, \dots, n$ – number of cargo spaces, ballast tanks and storage spaces, respectively.

Thus, the state of the vessel u can be represented as an n-dimensional vector, the number of elements of which is equal to the total number of cargo holds, ballast tanks and storage spaces involved in the cargo operations. The weight loads w_{ci}, w_{bi}, w_{zi} in the vessel's state vector are defined by upper limits $\overline{w_{ci}}$, $\overline{w_{bi}}$, $\overline{w_{zi}}$ determined by the cargo holds and ballast tanks capacity, as well as the local strength of the cargo spaces, and act as limiters for technological parameters.

The vessel loading process is thus a vector trajectory $u(t)$ in the space of possible states *U*. Moreover, the space of states *U* is n-dimensional with a finite value (constraints on technological parameters) along each dimension.

On the other hand, the loading of a vessel is characterized by its seaworthiness, which can be described by the vector S_u, whose components are the parameters of vessel's draught, trim, stability and strength.

Mean draught T_m, trim *t* and heel angle θ are important parameters of a vessel's seaworthiness.

The mean draught T_m is a function of the vessel's displacement *W* of the vessel and the density of the supporting water ρ, i.e:

$$T_m = f(W, \rho), \tag{2}$$

This dependence is presented in a tabular or graphical form in the 'Information on the stability and strength of the ship' (Loading manual).

The displacement of the vessel *W* is the sum of the weight of the empty vessel w_0, the weight of the vessel's stores (fuel, oil, water) w_s, including the weight of equipment, provisions and crew, the weight of cargo w_c and the weight of ballast w_b, and is expressed by the following equation:

$$W = w_0 + w_s + w_c + w_b, \tag{3}$$

The vessel's trim *t* is determined by the following anal ytical expression:

$$t = \frac{W(x_G - x_B)}{\bar{M}}, \tag{4}$$

where is:

W – the displacement of the vessel;

x_G, x_B – abscissas of the centre of gravity and the centre of buoyancy, respectively;

$\overline{M}$ – is the moment triming the vessel by 1 cm.

The difference $x_G - x_B$ represents the shoulder of the pair of forces (i.e. the equal-action forces of weight and support forces) and expresses the distance measured horizontally between the centre of gravity and the centre of buoyancy.

The value of the centre of gravity x_g abscissa is calculated using the formula:

$$x_g = \frac{M_x}{W}, \tag{5}$$

where is:

M_x – is the vessel's static moment of mass relative to the centre of gravity of the waterline plane;

W – the displacement of the vessel.

The static moment of mass of a vessel relative to the centre of gravity of the waterline plane is calculated using a formula hich takes into account the components of the moment from an empty vessel, the ship's constant, the ship's reserves, cargo and ballast:

$$M_x = w_0 x_0 + \sum_{i=1}^{n} w_{si} x_{si} + \sum_{i=1}^{n} w_{ci} x_{ci} + \sum_{i=1}^{n} w_{bi} x_{bi}, \tag{6}$$

where is:

w_0 – the weight of the empty vessel;

w_{st} – the amount of ship's stores in the i-th storage space;

w_{ei} – the amount of cargo in the i-th hold;

w_{bi} – the amount of ballast in the i-th tank;

x_0 – the abscissa of the centre of gravity of an empty vessel;

x_{si} – the abscissa of the centre of gravity of the vessel's supplies in the i-th compartment;

x_{ci} – the abscissa of the centre of gravity of the cargo in the i-th hold;

x_{bi} – the abscissa of the centre of gravity of the ballast in the i-th tank;

$i = 1, 2, ..., n$ – number of cargo spaces, ballast tanks and storage spaces respectively.

The abscissa of the centre of buoyancy x_B is a function of the mean draft, i.e. displacement W and density of the water in which the vessel is situated M:

$$x_B = f(W, \rho), \tag{7}$$

This dependency is usually presented in tabular form in the Loading manual, which is usually prepared by the shipbuilder for each particular vessel.

The value of the moment that trimming the vessel by 1 cm M also depends on the mean draft and is a function of displacement W and density of the water ρ:

$$\overline{M} = f(W, \rho), \tag{8}$$

Ship stability is the ability of a vessel to withstand external forces that disturb its equilibrium and to return to its original equilibrium position when these forces cease to act. It is one of the most important seaworthiness characteristics of a vessel.

The vessel's stability is characterised by the following parameters: initial metacentric height h, the capsizing moment of the ship M_{cap}, maximum righting lever of the static stability curve $l_{\max}$, the angle of the static stability curve maximum $\theta_{\max}$, the angle of stability curve vanishing $\theta_{\min}$.

The initial metacentric height h is determined by the following expression:

$$h = z_m - z_g + \Delta h, \tag{9}$$

where, z_m and z_g are the applicate of the transverse metacentre and the centre of gravity, respectively;

Δh – correction to the initial metacentric height in the presence of free surfaces of liquid stores and ballast.

The metacentre applicate z_m depends on the mean draft of the vessel. This dependence is expressed in a tabular form in the vessel's documents.

The centre of gravity applicate z_g depends on the static moment of mass M_z relative to the vessel's main plane and displacement and is calculated using the formula:

$$z_g = \frac{M_z}{W}, \tag{10}$$

The value of the static moment M_z is determined by the following expression:

$$M_z = w_0 z_0 + \sum_{i=1}^{n} w_{si} z_{si} + \sum_{i=1}^{n} w_{ci} z_{ci} + \sum_{i=1}^{n} w_{bi} z_{bi}, \tag{11}$$

where,

w_0 – the weight of the empty vessel;
w_{si} – the amount of ship's stores in the i-th storage space;
w_{ci} – the amount of cargo in the i-th hold;
w_{bi} – the amount of ballast in the i-th tank;
z_0 – the applicate of empty ship's centre of gravity;
z_{zi} – the applicate of ship's stores in the i-th storage space;
z_{ci} – the applicate of cargo in the i-th hold;
z_{bi} – the applicate of ballast in the i-th tank;
$i = 1, 2,\ldots, n$ – number of cargo spaces, ballast tanks and storage spaces respectively.

The parameters characterising stability can be obtained from static and dynamic stability diagrams. The static and dynamic stability curves are plotted along the static stability levers corresponding to certain heel angles of the ship. The static stability levers can be obtained either by means of a universal stability curve or by using Cross Curves of Stability (KN curves) provided in the ship's documentation.

The levers of the static stability curve, as well as the curve itself, depend on the displacement W, the density of the water supporting the vessel ρ and the static moment M_z. The values of the capsizing moment M_{cap}, the angle of the static curve vanishing $\theta_{\min}$, the maximum righting lever $l_{\max}$ and the corresponding heel angle $\theta_{\max}$ which can be obtained from the static stability curves, are also functions of displacement, water density and static moment.

The constant heel angle of the ship θ depends mainly on the static moment of the masses relative to the diametrical plane of the vessel M_y, which is given by the following expression.

$$M_y = w_0 y_0 + \sum_{i=1}^{n} w_{zi} y_{zi} + \sum_{i=1}^{n} w_{ci} y_{ci} + \sum_{i=1}^{n} w_{bi} y_{bi}, \tag{12}$$

where,

w_0 – the weight of the empty vessel;
w_{si} – the amount of ship's stores in the i-th storage space;
w_{ci} – the amount of cargo in the i-th hold;
w_{bi} – the amount of ballast in the i-th tank;
y_0 – the ordinate of the centre of gravity of an empty vessel;
y_{zi} – the ordinate of the centre of gravity of ship's stocks in the i-th storage space;
y_{ci} – the ordinate of the centre of gravity of cargo in the i-th hold;
y_{bi} – the ordinate of the centre of gravity of ballast in the i-th tank;
$i = 1, 2,\ldots, n$ – number of cargo spaces, ballast tanks and storage spaces respectively.

The following functional dependence of the heel of the vessel can be written down:

$$\theta = f\left(W, \rho, M_z, M_y\right), \tag{13}$$

The strength parameters include the shear forces SF_i and bending moments BM_i in the i-th section of the hull resulting from the vessel's loading, and the local strength P_i of the i-th cargo hold.

When calculating the strength of a vessel's hull, the vessel own weight and water support forces acting on the vessel are taken into account. The vessel's weight forces acting on the hull are represented in the form of two components – the weight forces of the hollow vessel and the weight forces from the loads that constitute the deadweight.

In this case, the bending moments BM_i and shear forces SF_i for each section of the vessel are expressed as the sum of three components:

$$BM_i = BM_0 + BM_W + BM_S, \tag{14}$$

$$SF_i = SF_0 + SF_W + SF_S\,, \tag{15}$$

where,

BM_i, SF_i – bending moments and shear forces in the i-th section of the vessel;

BM_0, SF_0 – components of bending moment and shearing force from the weight of the empty vessel;

BM_W, SF_W – components of the bending moment and shear force, respectively, from the loads included in the deadweight;

BM_S, SF_S – components of the bending moment and shear force, respectively, due to the action of support forces.

The components of the bending moment and shear force due to the weight of the empty vessel for each monitored section are constant and are given in the ship's documentation. The components of the bending moment and shear force from the loads included in the deadweight are determined by the arrangement of cargo in holds, ballast in tanks and stores in the relevant vessel spaces and tanks, and are calculated in tabular form using elementary relations.

To calculate the components of the shear force and bending moment due to support forces, the vessel's Loading manual contains information in the form of tables or graphs.

The local strength P_i is characterised by the ratio of the amount of cargo received to the area of the cargo space in which the cargo is stored. The ship's documentation specifies the permissible loads per square metre of cargo hold and upper deck.

Thus, the maritime safety vector S_u can be formally expressed as follows:

$$S_u = \left(T_m, t, \theta, h, M_{cap}, l_{\max}, \theta_{\max}, \theta_{\min}, SF_i, BM_i, P_i\right). \tag{16}$$

The vector is characterised by a range of permissible values determined by IMO or classification society requirements for the values of the landing, stability and strength parameters.

Ship cargo operations can be considered as an optimisation task. It is necessary to consider the restrictions that may be imposed when setting an optimisation task.

There are two categories of restrictions that apply to the loading of a vessel and the determination of permissible loads. The first category consists of general restrictions that are applicable to all types of vessels and are intended to ensure the seaworthiness of the vessel. The second category consists of specific restrictions that are unique to each type of vessel.

Let's focus on the first category of restrictions, which are designed to ensure the seaworthiness of the vessel. These restrictions mainly concern the draft of the vessel, which includes the mean permissible draft T_m and the permissible limits of its trim t. In most cases, restrictions on the heel θ of the vessel are also included in this category. However, it is common practice for the ship's crew to minimise the heel of the vessel during cargo operations, so separate restrictions for heel may not be necessary.

Limits on the mean permissible draft T_m arise from a number of factors, including the International Load Line Convention, shipbuilders' specifications, current voyage draft limits and the need to maintain minimum necessary forward and aft draughts to avoid slamming or propeller exposure. These considerations impose restrictions on T_m, resulting in limitations on its value.

$$T_{\min} \le T_m \le T_{\max}\,, \tag{17}$$

where $T_{\min}$ та $T_{\max}$ – respective, the lower and upper limits of the mean vessel draft T_m.

The lower limit for a vessel's trim $t_{\min}$ can be set to zero to avoid having a bow trim which would complicate ballast operations and cargo calculations. On the other hand, the upper limit $t_{\min}$ is determined by various factors such as ballast and liquid measurement tables, operational limitations of the ship's equipment and the seaworthiness of the vessel. The limitation on the vessel's trim can be defined as follows:

$$t \in [0, t_{\max}], \tag{18}$$

The limitations that ensure the necessary stability of the vessel are primarily defined by the limitation of the initial metacentric height h, as expressed in equation:

$$h_{\min} \le h \le h_{\max}\,, \tag{19}$$

In this equation $h_{\min}$ and $h_{\max}$ represent the lower and upper limits of the initial metacentric height, respectively. In addition, the minimum value of $h_{\min}$ is determined by the International Maritime Organisation (IMO) requirements for the initial stability of ships.

Several parameters related to vessel stability, such as the capsizing moment of the vessel M_{cap}, the maximum arm of the static stability curve $l_{\max}$, the angle of heel of the vessel at which the maximum arm occurs $\theta_{\max}$ and the angle of vanishing stability $\theta_{\min}$, are derived from the static stability curve. The values of these parameters are also subject to restrictions imposed by the IMO regulations for the initial stability of vessels, denoted as M_{cap}^{imo}, $l_{\max}^{imo}$, $\theta_{\max}^{imo}$ and $\theta_{\min}^{imo}$ respectively.

The third set of parameters relates to the overall longitudinal strength of the vessel and is represented by the maximum allowable values of bending moments BM_i and transverse shear forces SF_i for each control section of the vessel.

All the restricted parameters that define the seaworthiness of the vessel T_m, t, h, M_{cap}, $l_{\max}$, $\theta_{\max}$, $\theta_{\min}$ depend on the displacement, the longitudinal static moment M_x and the vertical static moment M_z of the vessel. Consequently, the longitudinal moment M_x is related to the vessel's trim t, bending moments BM_i and shear forces SF_i, while the moment M_z is related to the initial metacentric height h and the characteristics of the static stability curve M_{cap}, $l_{\max}$, $\theta_{\max}$, $\theta_{\min}$.

Taking into account the prescribed values for $t_{\max}$, $h_{\max}$, $h_{\min}$, M_{cap}^{imo}, $l_{\max}^{imo}$, $\theta_{\max}^{imo}$, $\theta_{\min}^{imo}$, BM_i, SF_i which express the requirements for the seaworthiness of the vessel, it is possible to determine the limiting values for the displacement of the vessel $W_{\max}$, the minimum $M_x^{\min}$ and maximum $M_x^{\max}$ longitudinal moments and the upper $M_z^{\min}$ and lower $M_z^{\max}$ limits of the vertical moment.

Let's consider, W', $M_x^{'}$, $M_Z^{'}$ as the displacement and static moments that occur in a selected loading configuration of the vessel. It is clear that certain loading configurations satisfy the following conditions:

$$W' \le W_{\max},\ M_x' \in \left[M_x^{\min}, M_x^{\max}\right],\ M_z' \in \left[M_z^{\min}, M_z^{\max}\right], \tag{20}$$

These loading configurations must fall within the range of permissible loads set U based on maritime safety requirements. However, it is important to note that there may be specific restrictions that are unique to a particular type of ship. These restrictions may limit the loading possibilities within the allowable set of options U.

From a maritime safety perspective, it is crucial to consider not only the seaworthiness of a vessel at the final stage of the loading process t_{fin}, but also the current state of the ship at each stage t_{cur}, from the start of loading to its completion. This requires strict adherence to a number of limitations within the system.

$$\begin{gathered} W'(t_{cur}) \le W_{\max},\ M_x'(t_{cur}) \in \left[M_x^{\min}, M_x^{\max}\right], \\ M_z'(t_{cur}) \in \left[M_z^{\min}, M_z^{\max}\right],\ t_{cur} \in \left[0, t_{fin}\right], \end{gathered} \tag{21}$$

where is t_{fin} the moment at which the ship's cargo operations are finished.

When formulating the optimisation problem for cargo operations, it is important to consider additional specific limitations that take into account the unique characteristics of different types of vessels. For example, when dealing with bulk carriers, the following constraints should be considered:

1. The number of port cargo facilities involved in handling the vessel.
2. The number of stages involved in loading and unloading the vessel.
3. The number of holds and ballast tanks used for cargo and ballast operations at each stage.
4. The amount of cargo to be handled for each hold and the amount of ballast required for each tank.
5. Cargo and ballast operations speed variations at each stage.

These limitations, together with the requirements to ensure the seaworthiness of the ship, are essential factors in formulating the optimisation problem.

Conclusions. The article presents a methodology for determining an acceptable range of vessel loads. This approach allows the selection of an optimum strategy for carrying out cargo operations, with the emphasis on maintaining the seaworthiness of the ship at all times. The key objective is to ensure that the ship's seaworthiness parameters, in particular stability, overall longitudinal and local strength, remain within acceptable limits throughout the period of cargo operations. By carefully managing the variations in cargo and ballast, it is possible to achieve continuous compliance with these critical parameters.

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