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DEVELOPMENT OF CONTROL MODEL FOR LOADING OPERATIONS ON HEAVY LIFT VESSELS BASED ON INVERSE ALGORITHM

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The aim of the work is to develop a method for optimal control of handling operations with heavy lift cargo on sea vessels. Based on the review of scientific research in the field of loading heavy lift cargo, priority directions for improving the automated control systems for cargo handling operations on ships have been determined. Within a scientific hypothesis, it was proposed to synchronize solutions to the problem of ship propulsion control and automated control of heavy lift onboard cranes in order to improve the accuracy of loading processes.

The paper analyzes the dynamic model of the "vessel-crane-cargo" system and the criteria of optimality in the problem of ship regulation-stabilization under minimization of loading time.

An inverse loading algorithm has been developed, based on the principles of the loading control optimization with limiting the choice of motion by linear displacements and turns of the vessel. When executing the inverse algorithm, restrictions associated with the minimization of heeling moments in the "vessel-crane-cargo" system and restrictions associated with the maximum and minimum boom outreach are applied. The study determined the technical feasibility of achieving invariance in the cargo stabilization system with the inverse loading algorithm on heavy lift vessels.

On the basis of the proposed method, simulation modeling of the ship loading process was carried out on simulators at the Kherson State Maritime Academy.

The simulation modeling has shown that the use of the inverse algorithm will reduce the time of cargo operations by 50–70 percent and, as a result, reduce the risk of emergencies when loading the ship. It was also determined that the use of the inverse algorithm is appropriate for cargo of more than 100 tons

Keywords: optimal control, PID controller, heavy lift cargo, inverse algorithm, loading modeling

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1. Introduction

Modern information technologies in maritime transport undergo a number of innovative transformations due to the constantly expanding production and logistics. For example, over the past few years, the volume of overseas transportation has increased significantly, especially transportation of heavy lift cargo for the needs of the energy industry, the offshore industry [1]. The crisis of 2020, caused by the SARS-CoV-2 pandemic and fall of the world's marine economy greatly motivates scientists to develop the most appropriate information tools for the safe and efficient loading of vessels.

To solve the current situation and level the possible risks, shipping companies are increasingly using specialized heavy lift vessels. This circumstance is caused, on the one hand, by cost estimates due to the transportation of oversized cargo, and, on the other hand, by the possibility of using high-capacity onboard cranes [2].

Experience demonstrates that the most dangerous situations during the operation of Heavy Lift vessels are the immediate loading-unloading of oversized cargo on the vessel and the control of its maneuvering process [3].

Problems of safety enhancement during loading operations are given special attention in the major shipping companies, such as Jambo Shipping (Netherlands), BigLift Shipping (Netherlands), Hansa Heavy Lift (Germany), BBC Chartering (Germany), Intermarine (Netherlands), SAL (Schiffahrskontor Alles Land) (Netherlands), Harren & Partner (Germany).

A large number of theoretical and practical works are devoted to the problem of ensuring the safety of cargo handling operations on Heavy Lift vessels. The analysis of the presented works states that an increase in the safety of cargo operations on Heavy Lift vessels can be ensured by the available integrated software to control the loading of the vessel. Currently, the software products are intensively developing, the most fully functional of which are the following: COLOS Computer-Loading-System by DatentechnikRostockGmbH (Germany); Seacos MACS3 Loading Computer System by INTERSCHALT maritime systems AG (Germany); LOCOPIAS by SARC BV (Netherlands).

A common disadvantage of the existing software is that it only solves the direct task, in which the parameters of the seaworthiness are estimated for a given load. However, the existing theoretical researches and modern computer technologies allow developing the programs that are able to find the best option of loading under the given valid parameters of vessel sitting, stability and overall longitudinal strength, as well as the cargo to be transported.

2. Literature review and problem statement

A number of works [4, 5] investigate the procedures for carrying out cargo operations with heavy lift cargo (Guideline for Project Cargo Operations). These procedures are developed in accordance with the requirements of the regulations of the International Maritime Organization (IMO), for example, the IMO Code of Safe Practice for Cargo Stowage and Securing [6, 7].

Observations have shown that two processes have the greatest impact on safety assurance:

1) stabilization of the vessel position, which in turn depends on many factors of environmental disturbance;

2) ensuring the safety of cargo operations while minimizing time and power resources.

The modeling results in the researches [8–10] showed that there is a real problem with the inaccuracy of modules for optimizing loading processes in existing systems and control algorithms. External uncontrollable disturbances in the movement of cargo destabilize the loading process as well as create precedents for the negative influence of the human factor.

Some works [11–15] present the results on improving mathematical modeling when controlling the vessel movement by automated systems.

It is shown that various mathematical methods of analysis and synthesis for control systems are known, each of which is applicable for a certain class of systems and problems.

But there are still unsolved issues related to the classification of the types of ship control during vessel positioning. Actually, different tasks of dynamic positioning are distinguished when controlling the pitch, lateral, rolling motions of the ship's hull. These are Dynamic Positioning (DP), Dynamic Position's Alteration (DA), Dynamic Tracking (DT) [11, 13].

This may be due to objective difficulties associated with the fact that the tasks of the dynamic positioning of the vessel differ from other tasks of motion control. This difference is that the vessel has minor own-ship speeds, and hydrodynamic forces on the hull and rudder affect the dynamics of control processes.

Thus, the complex task of building control systems affects the basic issues of ship automatic control systems. In addition, one should take into account that the operation of the main engines in the slow speed modes is insufficient to compensate for the main external disturbances: wind forces, currents, wave motions and control means [16, 17].

The option to overcome these difficulties can be the construction of more efficient regulators than PID controllers [18]. In this case, the solution of the regulation problem, as the task of stabilization of the loading process parameters, requires identifying an adequate control law by known methods.

This is the approach applied in some researches [11, 12, 19], but the problem of loading Heavy Lift vessels involves a significant increase in safety requirements for operations, and necessitates the synthesis of movement control laws in the "vessel-crane-cargo" system. So, the methodology based on the synthesis of control laws involves regulation compliance at risk and time constraints.

Thus, it is expedient to conduct a study based on the combined principle of choosing a control law ranging from regulation by one-dimensional objects to optimal systems with multidimensional objects. In this regard, studies that allowed narrowing the range of control law synthesizing methods for vessel positioning were analyzed [13, 14, 17].

3. The aim and objectives of the study

The aim of the study is to solve the problem of modeling and developing a method for optimal control of cargo handling operations with heavy lift cargo on seagoing vessels, taking into account the effect of cargo weight. This will enable to reduce the level of risk with the existing equipment, increase the safety of these operations, reduce economic costs by cutting down the time of cargo operations, and reduce the influence of the so-called "human factor" on the process of their performance.

To achieve the aim of the study, it is necessary to complete a number of tasks:

– to analyze the dynamic model of the "vessel-crane-cargo" system and the main criteria of optimality in the problem of vessel regulation-stabilization in sea space;

– to carry out simulation modeling of the loading processes in conditions of external disturbances;

– to develop an inverse algorithm for loading a vessel, based on optimization of the loading process with limiting the choice of movement by linear displacements and turns of the vessel.

4. Materials and methods of analysis of the "vessel-crane-cargo" dynamic model

The dynamic model of the "vessel-cargo" system is a problem with a model, comprising a system of differential equations describing the crane load (k) and vessel (c), which the crane is mounted on, moving on a given trajectory x^*, (1)

$$\left.\begin{aligned} &\ddot{x}_k + a_k\dot{x}_k + b_k x_k = u_k\left(x^*, x_c, x_k\right), \\ &\ddot{x}_c + a_c\dot{x}_c = u_c + q_k, \end{aligned}\right\} \qquad (1)$$

$$x \in x^*,$$

where x – the coordinate (for the crane and the vessel, respectively); a, b – coefficients (for the crane and the vessel, respectively), u – control; q – disturbance.

In this problem, the objective function (J_k – the objective functional) is the minimum time (t) for performing the loading operation with minimal impact on the object [20, 21]. For heavy lift cargo, it is necessary to avoid overloads in the system, which limits the control (u) and the problem takes the following form:

$$\left.\begin{aligned} &u_k=\arg\min J_k,\\ &J_k=\int_{t_0}^{t_1}\mathrm{d}t,\\ &\ddot{x}_k+a_k\dot{x}_k+b_kx_k=u_k;\ |u|\le\frac{1}{2}u_m.\end{aligned}\right\}\qquad(2)$$

For speed-optimal control at sign-constant intervals, the control is maximal and equal in modulus $u_m/2$, which guarantees that there is no going out beyond the permissible limits when the control sign changes [21]. Thus, the larger the load, the stricter the control restriction and the longer the loading process, even the optimal one in speed terms.

On the other hand, the dynamics of the vessel is simpler and the maneuvering speed is limited by the control margin, so the problem of vessel stabilization is solved theoretically as follows:

$$\left.\begin{aligned} &u_c^*=\arg\min J_c,\\ &J_c=\int_{t_0}^{t_1}(x_c-x_{c0})\mathrm{d}t,\\ &\ddot{x}_c+a_c\dot{x}_c=u_c,\end{aligned}\right\}\qquad(3)$$

where u_c – control for the ship; J_c – target functional for the vessel; t – time; x_c – vessel coordinate; a – coefficient.

Thus, the "optimality" of control in the problem (2) of cargo movement is reduced to a slow movement of the cargo, which ensures minimal efforts in the power elements of the cranes and minimal damage in case of operator error.

On the other hand, by associating the cargo with a fixed coordinate system, we obtain the inverse problem (3), where the cargo is stable in space, and the vessel performs the necessary evolutions. Naturally, this does not complicate the cargo trajectory in ship coordinates, but completely changes the control task. Now the task of regulation-stabilization in space is performed for the cargo:

$$\left.\begin{aligned} &u^*_k=\arg\min J_k,\\ &J_k=\int_{t_0}^{t_1}(x_k-x_{k0})^2\mathrm{d}t,\\ &\ddot{x}_k+a_k\dot{x}_k+b_kx_k=u_k.\end{aligned}\right\}\qquad(4)$$

In the task (4), there are no strict control restrictions, since the cargo movements are small, and, as a consequence, the corrective efforts are small.

The vessel movements are described by the problem of optimal performance of a linear system [21, 22]:

$$\left.\begin{aligned} &u_c^*=\arg\min J_c,\\ &J_c=\int_{t_0}^{t_1}\mathrm{d}t,\\ &\ddot{x}_c+a_c\dot{x}_c=u_c;\ x_c\in x^*.\end{aligned}\right\}\qquad(5)$$

Given that the control is linearly related to the speed for small deviations from the linear dynamic object control, the system (5) is written as:

$$\ddot{x}+b\dot{x}+\mathrm{d}x=u\xrightarrow[\substack{t\in[0,\Delta t];\\ x(0)=0}]{}b\dot{x}\approx u\to a_{\substack{\dot{x};\\ t\in[0,\Delta t];\\ x(0)=0}}\approx ku.\qquad(6)$$

Therefore, the force on the cables at the start of movement is presented as $F\approx ku$. Then the comparison of transients in a static system and system with low dissipation $a_1>>a_2$ was conducted:

$$\left.\begin{aligned}&\ddot{x}_1+a_1\dot{x}_1+bx_1=u\\ &\ddot{x}_2+a_2\dot{x}_2+bx_2=u\end{aligned}\right\}\xrightarrow[a_1>>a_2]{}\varepsilon=$$
$$=x_1-x_2\to\ddot{\varepsilon}+(a_1-a_2)\dot{\varepsilon}+b\varepsilon=0.\qquad(7)$$

Since the coefficient a has changed little due to the smallness of a_2, the convergent process with increased vibrations is obtained. There is a visual modeling diagram for the process assessment in Fig. 1.

Actually, the object with low dissipation (oscillatory object) is more difficult to control [23], since the elimination of vibrations requires energy dissipation, which is rather difficult when working with heavy lift cargo.

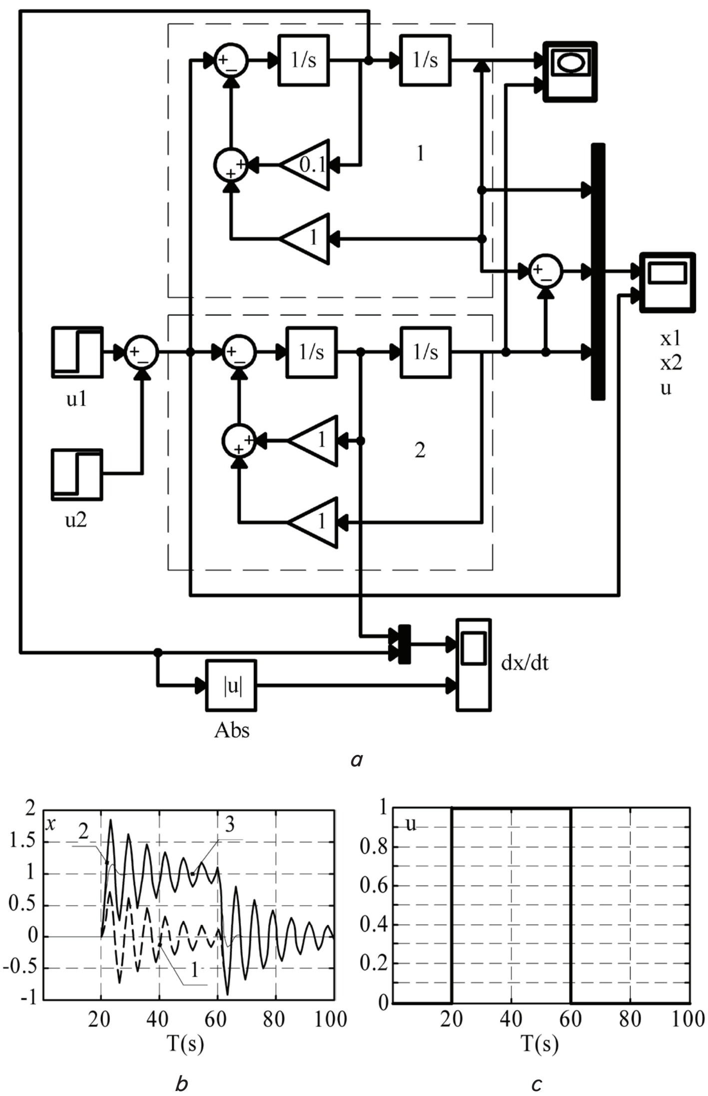

Fig. 1. Transient processes with different oscillability: *a* – 1 – model of an object with low dissipation; 2 – model of an object with high dissipation; *b* – 1 – transient process for the ε system; 2 – transient process with low dissipation; 3 – transient process with significant dissipation

In the study, the use of PID controller for both systems is considered. The cargo modeling scheme is shown in Fig. 2.

The transients obtained in the simulation modeling of both systems are shown in Fig. 3.

Thus, to control the vessel as the object with dissipation is much easier than to control the cargo. The desire to keep the cargo from swaying when moving is possible only for small weights. It is very difficult to keep the weight of hundreds of tons from swaying with slings, and you will have to sharply slow down the movement of the cargo, reducing control.

However, if the fixed coordinate system is combined with the cargo, the problem is greatly simplified [24]. If the cargo is fixed in space and control is reduced to eliminating errors in the dynamic positioning of the cargo, then the control efforts are minimal. So, it becomes possible to achieve invariance, since the disturbances associated with the movement of the vessel are known, and it is possible to compensate them [25].

There is a simulation modeling layout for an invariant disturbance system of cargo stabilization coordinates in Fig. 4.

If the cargo is fixed in space and control is reduced to eliminating errors in the dynamic positioning of the cargo, then the control efforts are minimal.

The estimate for the problem is an effect assessment of the vessel displacement under a given control. Naturally, this is a fairly well-known process, but to assess the quality of the stabilization algorithm, a random process that simulates the measurement error is introduced in the estimating system.

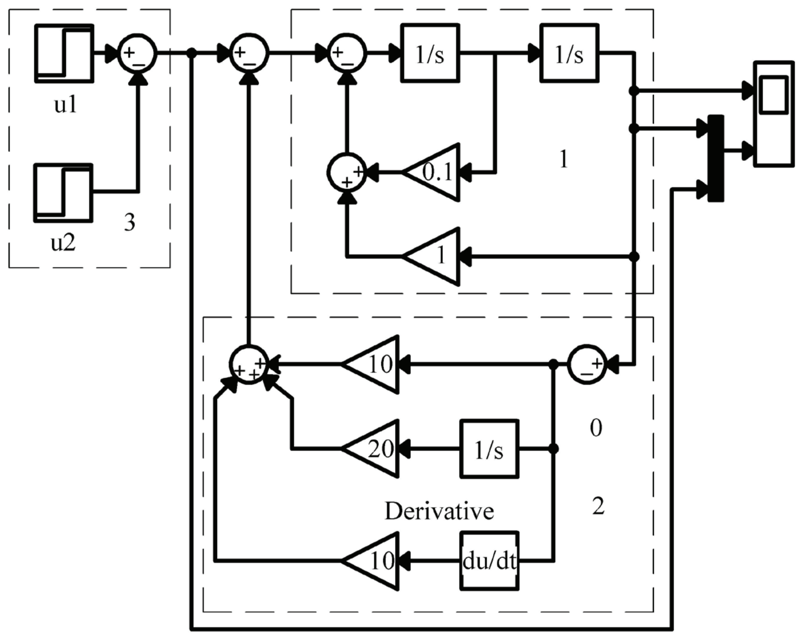

Fig. 2. Modeling of the cargo stabilization channel with a PID controller: 1 — model of cargo dynamics; 2 — PID controller model; 3 — control

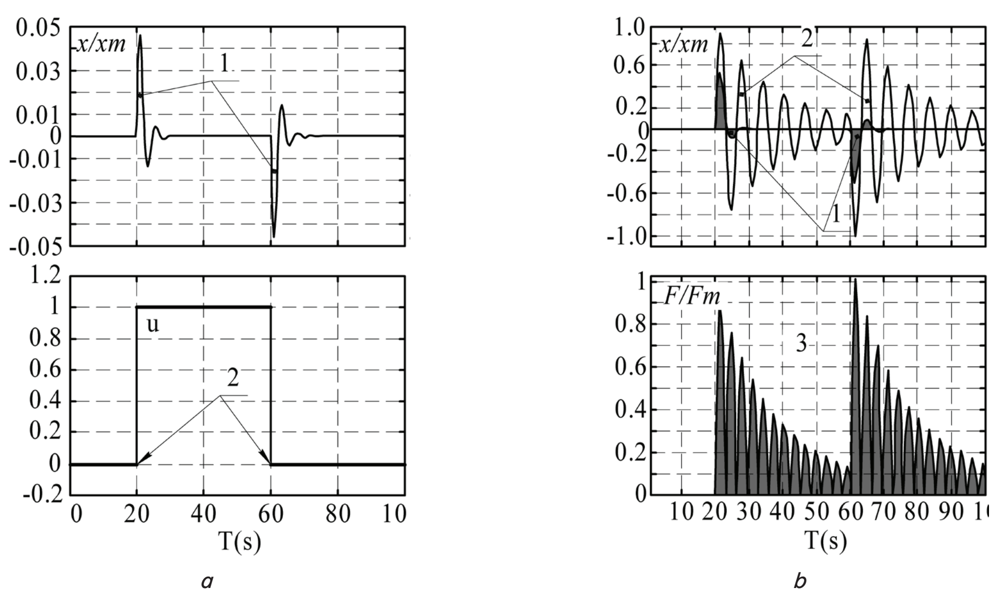

Fig. 3. Results of modeling the vessel and cargo dynamics with a PID controller: *a* — 1 — transient characteristics of the vessel disturbance; 2 — control; *b* — 1 — transient characteristics of the vessel; 2 — transient characteristics of the cargo; 3 — module of the cargo transient characteristics; *T* — time

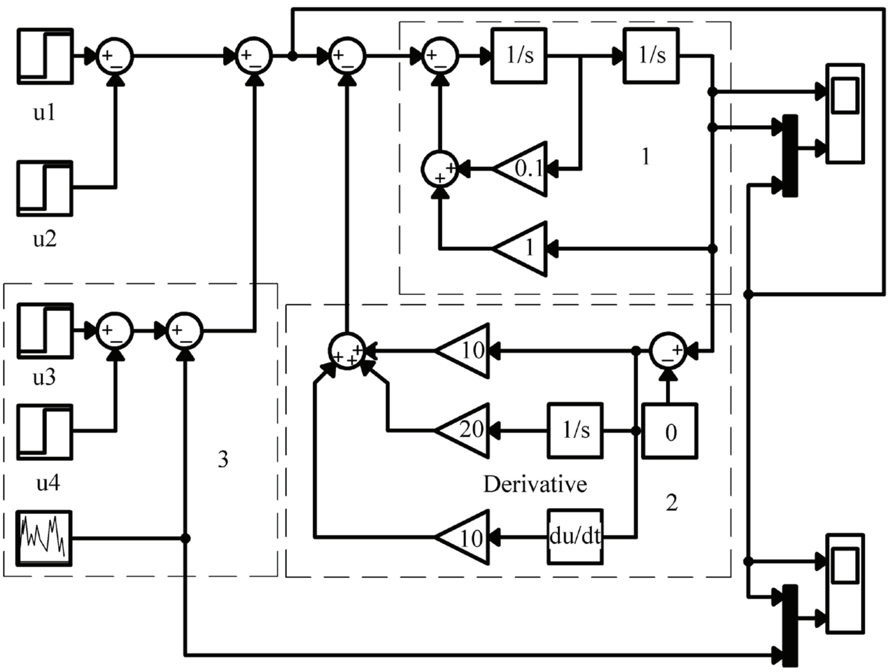

Fig. 4. Simulation modeling of the cargo stabilization system dynamics with the estimate of disturbances: 1 – object model; 2 – PID controller model; 3 – estimating system model with regard to measurement errors

In this case, the positioning error is small, which made it possible to consider the task of cargo stabilizing much simpler than the task of moving it. This is especially important for operations with heavy lift cargo.

Thus, the task was set opposite to the movement of heavy lift cargo on the vessel. In this case, the vessel with an additional stabilizing pontoon lifts the cargo and removes it from the wall at a distance, sufficient for maneuvers. Then the operation of transferring the vessel with the cargo to a position where its evolution is possible takes a lot of time, since the movements of the vessel should not cause overloads in the crane system. After reaching the position, the cargo is stabilized due to the control of the cranes. In this case, the vessel performs evolutions, which transfer it to the position of receiving cargo, Fig. 5.

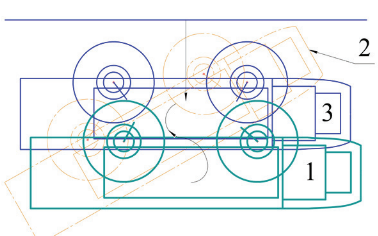

Fig. 5. Trajectory of the vessel movement in the inverse loading task: 1 – initial position; 2 – intermediate position; 3 – completion of the operation

In this case, the speed of the vessel evolutions is limited only by the speeds of the cranes and the speeds of anti-heeling systems.

5. Results of the loading process modeling

Based on the results, modeling was carried out in the dynamic positioning laboratory at the Kherson State Maritime Academy (KSMA), Ukraine.

Modeling of the automated control process for heavy lift cargo was carried out on the example of VANESSA ABB Heavy Lift vessel (Panama). The cargo is the fractional column (the length is 49 meters, the diameter is 6 meters, the weight is 280 tons).

In this case, the cargo weight is limited to the capabilities of the vessel's crane equipment [26]. Since the geometric dimensions of the cargo do not allow a simple motion to perform loading, the inverse loading algorithm has been considered.

At the stage of planning the loading operation, the target function is the heeling moment from the side of the cargo, and the task is to determine the trajectory of the vessel from the initial position to the installation of the cargo, which ensures the minimum heeling moments. The limitation is the boom outreach of the crane, on which the lifting capacity depends. To determine the allowable outreach, the dependence of crane capacity (SWL) on the boom outreach was built, Table 1.

Table 1

Dependence of crane capacity (SWL) on the boom outreach

No.	Minimum boom outreach (m)	Maximum boom outreach (m)	SWL (t)
1	5	13	180
2	4.5	16	150
3	4.5	19	120
4	4.0	24	95
5	4. 0	33	70

Based on the crane characteristics (Table 1), the maximum boom outreach is found for a given cargo. Checking the conditions for the feasibility of loading with on-board cranes indicated the limiting capabilities of the vessel, both in terms of the lifting capacity of the cranes and the geometric parameters of the vessel and cargo. Obviously, in this case, loading based on the direct algorithm will take a lot of time.

Therefore, the inverse algorithm of loading was considered (Fig. 6) where the movements are performed with a fixed-in-space cargo. Moreover, in this case, the restrictions on the maneuvering speed of the vessel are related only to the speed of the anti-heeling system.

a *b*

Fig. 6. Layout of the inverse loading algorithm, ABB VANESSA vessel: *a* — the initial position of the cargo; *b* — the final position of the cargo

Construction of the optimal plan of operation considers, firstly, the need to minimize heeling moments resulting from the motion in the "vessel-crane-cargo" system, and secondly, limits of the minimum and maximum boom outreach. The principle of simple movements was used for developing the algorithm calculating the operation plan. Actually, there are no limitations, requiring strict use of simple movements only, as in the direct algorithm, but the execution of such movements is easier, which determined the use of this principle in the development of the movements of the algorithm in the "vessel-crane-cargo" system.

The algorithm for calculating the program for performing the operation is shown in Fig. 7.

The algorithm for calculating the optimal plan is based on the task of choosing a trajectory that minimizes heeling moments, with restrictions on the geometry of the vessel and cargo. To implement the optimization procedure, a gradient method was used, which is determined by the convexity of the goal function.

The process simulation software was executed in MATLAB 6.5 environment. Thus, the algorithm is based on an optimization procedure with the restriction of the choice of motion to only simple linear displacements and turns.

Table 2 shows the plan for the operation of loading the fractional column on the ABB VANESSA Heavy Lift vessel.

Table 2 contains the points of the trajectories of the cranes hooks; the actual evolution of the vessel with the inverse algorithm is performed according to the types of movement.

One of the essential points in the fulfillment of the loading plan is to compensate for heeling moments using an outside pontoon. The assessment of the pontoon capacity ΔV_p is made according to the displacement of the center of the cargo gravity and the center of the pontoon gravity, taking into account the density of water:

$$\frac{\Delta l_g \cdot m_g}{x_p \rho} = \Delta V_p, \tag{8}$$

where Δl_g – displacement of the center of gravity of the cargo during the period of the loading operation; m_g – the mass of the cargo; x_p – center of gravity of the pontoon in ship coordinates; ρ – the weight density of water.

For a given cargo weight and plan data (Table 2), an estimate of the compensation pontoon capacity was obtained ΔV_p=490 m^3. Thus, at a pontoon filling rate of 10 m^3 per minute, the operation is limited to 49 minutes, since with the inverse algorithm there are no restrictions on the speed of movement in the vessel-cargo system.

For the inverse algorithm, the anti-heeling system is a limitation and the vessel cannot move until the anti-heeling system compensates for the vessel's heel. Thus, the speed of movements with the inverse algorithm is determined not by the mass of the cargo, but by the performance of the pumps in the system of heeling tanks and pontoon.

Based on relation (9), the time of performing operations was estimated by the direct method:

$$T_o \approx \frac{S_g}{v_g} = \frac{S_g m_g}{F_{\max} T_d} + nT_f, \tag{9}$$

where S_g – the length of the cargo trajectory; v_g – permissible speed of cargo movement; m_g – the mass of the cargo; $F_{\max}$ – the maximum allowable effort to move the cargo; T_d – the time of accelerated movement of the cargo; n – the number of movements in the operation plan; T_f – the time of cargo settling.

The time of loading operations using the inverse algorithm is determined by the capacity of pumps servicing the pontoon and estimated by the relation (8):

$$T_o \approx \frac{\Delta l_{g\max} \cdot m_g}{x_p \rho v_n}, \tag{10}$$

where Δl_g – displacement of the gravity center of the cargo for the period of loading operation; m_g – the mass of the cargo; x_p – the gravity center of the pontoon in ship coordinates; ρ – the weight density of water; V_n – pump capacity.

The efficiency of the suggested method was determined by the relation of the operation time with the direct algorithm to operation time with the inverse algorithm. So, for the ABB VANESSA vessel, it is advisable to consider the inverse algorithm, starting with a cargo of 100 tons. The inverse algorithm is preferable for cargo of more than one hundred tons, since the loading time is reduced significantly, which, taking into account the freight cost, saves tens of thousands of dollars. The calculations have shown that the efficiency of the inverse algorithm grows linearly with the increase of cargo weight.

Table 2

Loading plan of the fractional column on the ABB VANESSA Heavy Lift vessel (in the absolute coordinate system)

Movement	Crane center coordinates (m)				Crane hook coordinates (m)			
	x_1	y_1	x_2	y_2	x_1	y_1	x_2	y_2
1 – shift	–23.04	7.2	23.04	7.2	–24.5	15.6	24.5	15.6
2 – shift	–20.48	18.14	25.63	18.14	–24.5	11.23	24.5	11.23
3 – turn	–27.36	11.08	18.2	18.14	–24.5	11.23	24.5	11.23
4 – shift	–27.07	14.68	18.43	7.5	–24.5	11.23	2 4.5	11.23
5 – turn	–16.42	14.68	29.1	7.5	–24.5	11.23	24.5	11.23
6 – shift	–19.1	14.68	27.01	14.68	–24.5	11.23	24.5	11.23

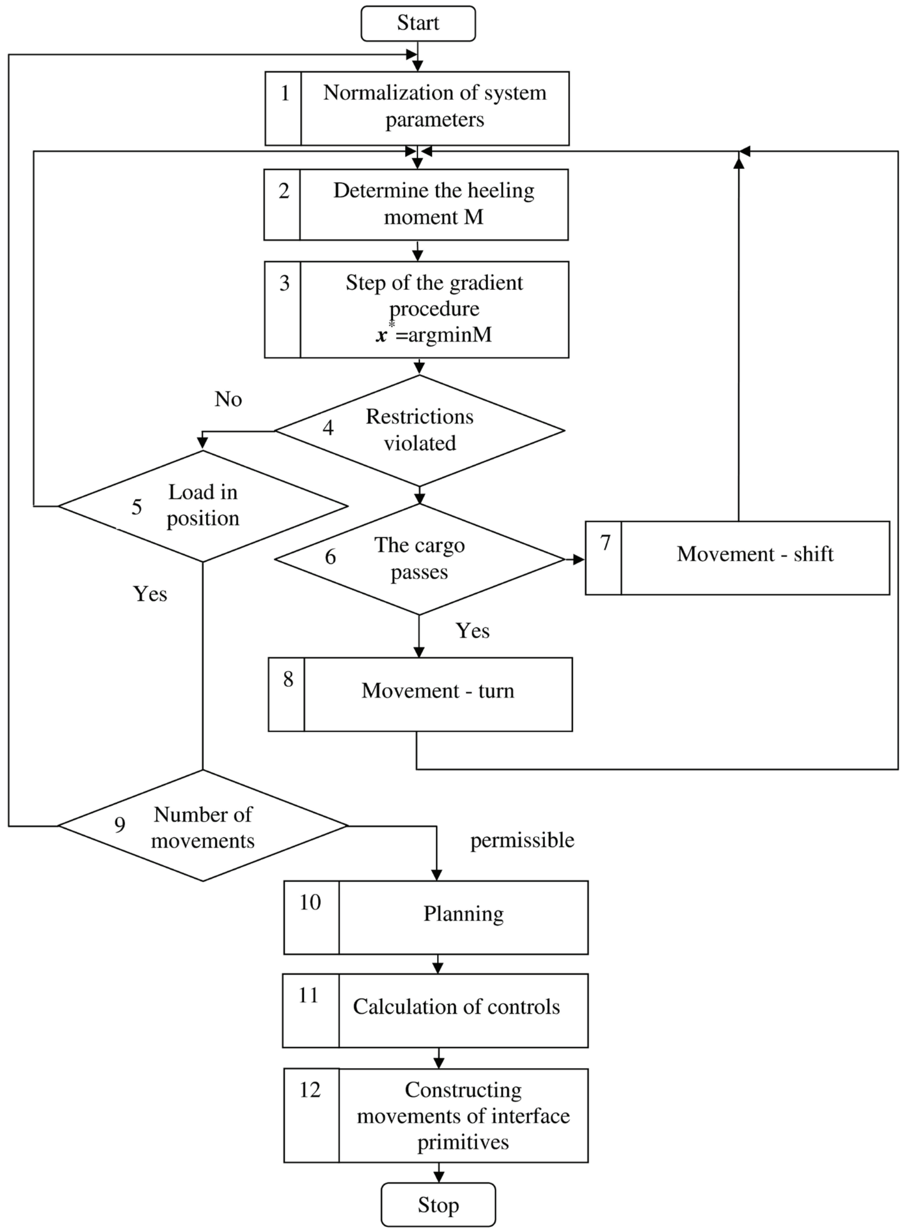

Fig. 7. Algorithm of the program for performing an operation based on the inverse algorithm

6. Discussion of research results based on loading simulation

The results of the study are explained by comparing the inverse algorithm with the existing direct method for the control optimality of cargo handling operations.

With the inverse algorithm, crane operators have a much simpler task of stabilizing the cargo, and, accordingly, the interface is reduced only to the maintenance of keeping the cargo mark in a fixed position. The inverse task complicates the work of operators who perform vessel evolution. In this case, a full algorithm is used with primitives of the vessel and cargo, trajectory drawing and a table of nodal points and characteristics of the vessel's movement (Fig. 7).

An important point is the inversion of the trajectories when passing from one algorithm to another. The movements are preserved, but the stationary coordinate system of the vessel changes with the direct algorithm as well as the absolute coordinate system with the inverse algorithm. This simplifies the formation of optimal plans for carrying out cargo handling operations.

The advantage of the inverse algorithm is the absence of the requirement to divide the trajectory into simple movements, but the simplification of control algorithms makes it preferable to preserve the principle of simple movements. In this case, a necessary component of the system is a water level control system in heeling ballast tanks and/or on pontoons – formulas (8)–(10).

An essential point that distinguishes the direct algorithm from the inverse algorithm for loading heavy lift cargo is the difference in the control that is optimal in terms of speed. On the other hand, the cargo is stationary with inverse control and there are no restrictions on the speed of change of the vessel coordinates from the cargo.

The suggested solutions allow accomplishing the task of optimal loading of the Heavy Lift vessels by synthesizing the laws of motion control in the "vessel-crane-cargo" system. A practical solution to this problem was achieved by creating a simulation model of cargo stabilization with a prediction of disturbances (Fig. 4).

The limitation of the proposed method is the necessity to use additional technical means for continuous monitoring of the vessel and cargo positioning.

Further development of the study in this direction can be aimed at creating specialized decision support systems and modeling a subsystem for stabilizing the list of a vessel when performing handling operations with heavy lift cargo.

7. Conclusions

1. The analysis of the dynamic model of the "vessel-crane-cargo" system showed that during the loading and unloading operations of heavy lift cargo, the movement control of the cargo is limited by the resulting accelerations and forces in the cargo suspension system.

2. The simulation modeling has shown that the use of PID control when moving the cargo does not eliminate overloads, and therefore does not allow speeding up the loading and unloading process.

3. The inverse loading algorithm has been developed, where the cargo is stable in sea space, and the vessel per-

forms the necessary evolutions, which makes it possible to achieve the accuracy of operations required in the study and reduce the loading time. The modeling results showed that the efficiency of the inverse algorithm increases linearly with the cargo weight. The technical feasibility of achieving invariance in the cargo stabilization system with the inverse loading algorithm on the Heavy Lift vessels has been determined. This is confirmed by the results of modeling the cargo stabilization system with a prediction of disturbance.

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