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Dynamics of the Moving Ship at Complex and Sudden Impact of External Forces

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Abstract**—**The impact of the storm leads to accidents even in the case of vessels that meet the computed safety criteria for stability. That is why, in order to clarify the causes of the accident and shipwreck, it is necessary to study the dynamics of the ship under the complex sudden impact of external forces. The task is to determine the movement and landing of the ship in the complex and sudden impact of external forces, i.e. when the ship's load changes over a relatively short period of time. For the solution, a technique was used to study the ship's dynamics, which is based on the compilation of a system of differential equations of motion. A coordinate system was adopted for the equation of motion of the hull and the determination of external forces. As a numerical method of integration, the 4th order Runge-Kutta method was chosen. The results of the calculation show that dynamic deviations were lower for high-altitude vessels. The study of the movement of the hull under a difficult situation is performed: receiving of cargo, impact of a flurry of wind and subsequent displacement of the cargo. The risk of overturning and flooding was assessed.

Keywords**—**Dynamics, statics, roll, trim, dynamic load, tilt, vertical displacement.

I. Introduction

CASES of accidents and deaths of river and sea vessels that have occurred during recent years make scientific analysis of some provisions on the stability of vessels relevant. Possible causes of accidents are:

- complex character and high level of external impacts on the ship, exceeding the normative value;
- complex dynamics of ship behavior as a reaction to external impacts;
- unskilled crew actions during the operation of the vessel.

All recommendations and regulations related to ship intact stability and safety against capsizing issued by the International Maritime Organization (IMO) are consolidated nowadays in the international code on intact stability (2008 is code) adopted by res. msc.267(85) on 4th of December 2008 [1]. The safety of the vessel's navigation is established by the satisfaction of the "weather criterion". The weather criterion determines the continuity of the dynamic angle of the ship's roll resulting from the action of the standard heeling moment of a certain value (tilting angle, filling angle, regulated value). The non-overturning of a vessel from a suddenly applied heeling moment is the first of the safety criteria for navigation. Non-slashing of the hull through the holes when the vessel is tilted is the second of the ship's safety criteria. The limiting value of the dynamic roll angle is, in this case, the angle of filling, which is determined in advance using an approximate geometric construction, which is not fully justified. In the case of a strong impact of external forces or a strong vessel reaction, such a construction will not be possible due to the additional incremental angle of the trim and the vertical movement of the hull.

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II. Purpose and Methods of Research

To solve this problem, it is necessary to investigate this issue based on approaches and mathematical models of ship dynamics (rolling and controllability of the ship). Methodically, the solution of the ship's dynamics problems is based on the classification of the system of differential equations of motion; the definition of the forces acting on the hull and integration of the equations of motion and analysis of the results obtained.

In numerous solutions of the ship's dynamics problems, the end result is the hull position, defined in the parameters of the fixed coordinate system oξ, η, ζ. At the same time, the simplest form exists, the equations of motion and many categories of external forces are determined in the coordinate system g,x, y, z, which is related to the body.

Because of the complexity and cumbersomeness of the resulting equations, it is often necessary to consider individual particular types of hull movements and apply particular or combined types of computational equations of motion (Fig. 1).

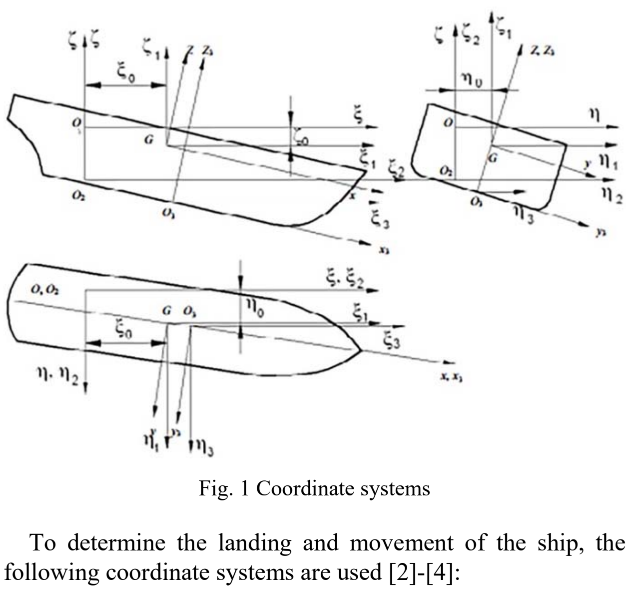


Fig. 1 Coordinate systems

To determine the landing and movement of the ship, the following coordinate systems are used [2]-[4]:

(1) O, ξ, η, ζ is a fixed coordinate system designed to read the linear displacements of the hull. The Oz axis is vertical,

and the axes Oξ and Oη are horizontal, the coordinate plane ξOη is parallel to the plane of calm water.

(2) O2ξ2, η2, ζ2 is a stationary hydro mechanical coordinate system. The origin of this coordinate system is located on the surface of calm water and, most often, on a single vertical with the origin of the fixed coordinate system, and the axes Oξ||O2ξ2, Oη||O2η2, Oζ||O2ζ2.

(3) G, x, y, z is the coordinate system associated with the hull, designed to compose the equations of motion of the hull and the determination of external forces.

(4) G, ξ1, η1, ζ1 is the first semi-coupled coordinate system whose origin coincides with the origin of the associated coordinate system, and the Gξ1||Oξ, Gη1||Oη, Gζ1||Oζ axes. This coordinate system is designed to read the angular movements of the body.

(5) O3, x3, y3, z3 is the geometric coordinate system associated with the hull, intended for describing the geometry of the hull surface, with the axes Gx||O3x3, Gy||Oy3, Gz||Oz3.

(6) O3, x3, yΘ, zΘ is the second geometrically coordinated coordinate system that is half-connected to the hull, which is obtained by rotating the axes of the associated geometric coordinate system around the axis O3, x3 by the angle of heel and designed to calculate the geometric characteristics of the submerged shell volume for an arbitrary landing.

(7) O3, ξ3, η3, and ζ3 is an auxiliary second semi-connected coordinate system designed to calculate the shoulders of stability and shoulders of gravity forces of cargo bound to the ship.

The position of the hull of the ship in a fixed coordinate system can be determined by three linear coordinates ξ0, η0, ζ0 of the center G of the associated coordinate system and by three angular coordinates Θ, Ψ, χ, which characterize the relative position of the axes of the semi- connected and bound coordinate systems. The transition from the coupled coordinate system to the fixed system is carried out according to formulas known in analytic geometry.

At spatial unlimited angles χ, ψ, Θ, the system of differential equations of motion is not divided into normal differential equations, therefore introduction of particular types of ship hull motion or restrictions on the inclination angles with subsequent simplification of the problem is a necessary step for obtaining an engineering solution.

A feature of the ship's hull movements in question is that the gravity forces of the hull and cargo are vertical and when the load changes the movement of the hull will take place in the vertical direction, along the roll and the differentia. The movement of the hull in the horizontal plane will not lead to a change in the magnitude and shape of the immersed object, since these movements will not be taken into account. It is also assumed that ξ0 = η0 = 0, that is, the origin O of the fixed coordinate system and the origin of the semi-coupled system O3 always lie on the same vertical.

We define the calculated equations of motion of the hull with a change in load. The outline of the external forces acting on the body is shown in Fig. 2.

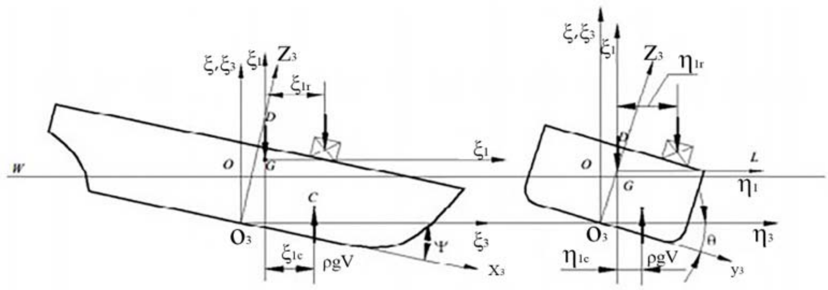


Fig. 2 The scheme of external forces

Then, the equations of motion of the hull under the constraints indicated above take the following form:

Equations

$$(m + \lambda_{33})\, dv_{\zeta}/dt = \rho_g V - D - \sum_{i=1}^{Np} Pi - b_{\xi\xi} v_{\xi};$$

where D is the gravity of the hull; ξ_g, η_g - the abscissa and the ordinate of the ship's center of gravity; $\rho_g V$ is the buoyancy force calculated for a given instantaneous landing; ξ_{1c}, η_{1c} - abscissa and ordinate of the center of magnitude; ΣP_i - the total weight of cargo received on the ship at a given time; ξ_{1Pi} , η_{1Pi} - abscissa and ordinate of the center of gravity of the accepted cargo; MKR is the heeling moment of external forces acting at a given time; MIFF is the differentiating moment of external forces acting at a given moment in time; $b_{\zeta\zeta}$, b_{44}, b_{55} - coefficients of water resistance to the movements of the hull [5], [6].

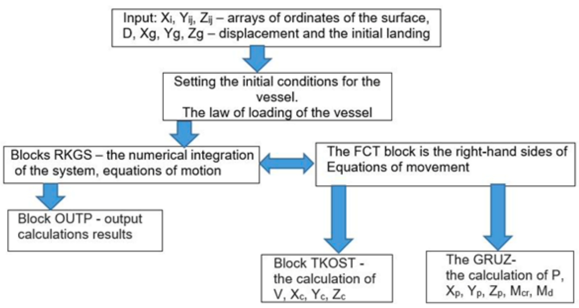


Fig. 3 Block diagram of the program landing of the ship

After reducing the system of equations to the normal form, we integrate by the numerical method. Block diagram of the algorithm Landing, oriented to the use of sufficiently powerful computers, is shown in Fig. 3.

As examples for the calculations, the hull of a small passenger vessel was drawn, the outlines of which are shown in Fig. 4.

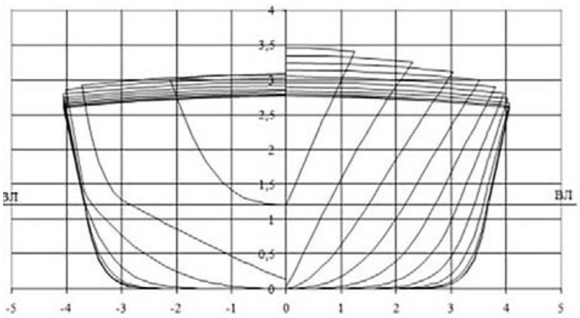


Fig. 4 Body plan

When choosing a numerical integration method, the Runge-Kutta method was used in the 4th order. In the flowchart, the algorithm TKOST is compiled according to the recommendations [7], using the method of the cross section of the hull and the rule of trapezoids with non-equidistant ordinates in the computation of certain integrals. The initial information is the arrays of coordinates of the transverse-vertical cross sections (frames) of the theoretical case.

III. Results of the Study

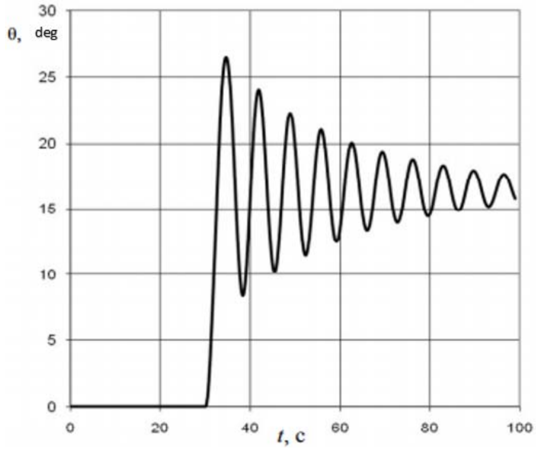
In the Static method, the inclination of the ship's hull is kinematically regarded as a rolling along the horizontal plane of the "rolling curve" F0, F1, F2, etc. The horizontal component of this movement is not taken into account, the inclination of the hull is assumed to be equal to the volume, and the rotation of the hull is carried out around the axes F0x, F1x, F2x, and so on [8].

In the Dynamics method, the movement of the hull of a ship, described by the system of differential equations (1), is represented as a set of rotations of the axes Gξ, Gη (roll and trim) and displacement in the vertical direction, therefore the results for determining the hull movement and the landing parameters may be different. The difference depends on the ratios of the main dimensions (mainly on the ratio H / T). For high-altitude vessels, there are fewer dynamic deviations, while for low-altitude vessels there are more.

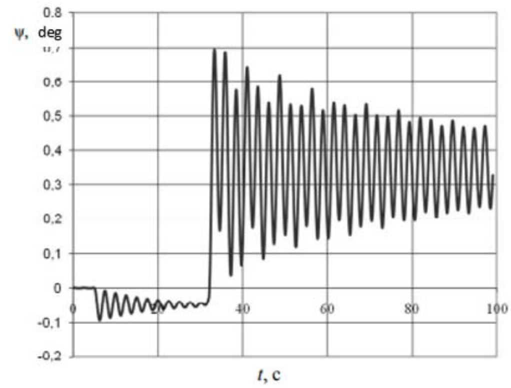
According to the developed algorithm and the program Landing, the dynamics of the ship is taken into account when receiving the cargo, in the subsequent application of the heeling moment and the displacement of the cargo [9], [10].

Calculation of the dynamic reception of cargo: the characteristics of the hull: L = 47.77 m; B = 7.33 m; T = 1.2 m; V0 = 294.6 m^3; H = 2.6 m; ZG = 3.1 m; XG = - 1.2 m; weight of cargo - 150 kN; initial coordinates of the cargo: XF = - 2.2 m; YP = 0.0 m; ZP = 3.0 m; time of the beginning of reception of cargo trp = 5 with; the heeling moment MKR = 600 kN • m; time of application of the moment: t = 30.0 c; time for the beginning of the shift of the load: t = 32.0 c; final coordinates of the cargo: XP = 15.0 m; YP = 3.0 m; ZP = 3.0 m.

Figs. 5 and 6 show graphical dependencies of ship landing parameters in time.

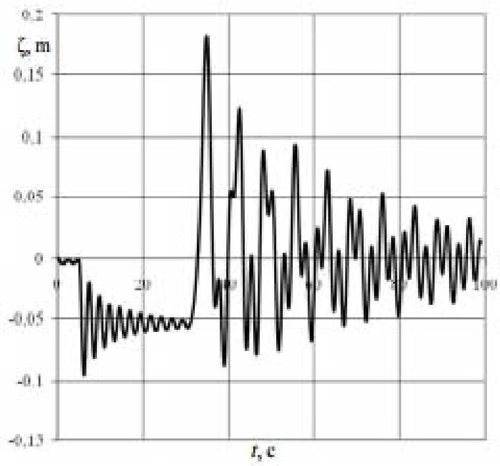


(a)

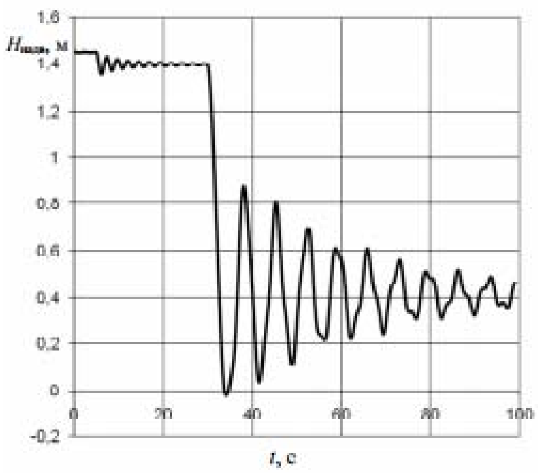


(b)

Fig. 5 (a) the angle of heel, (b) trim angle



(a)



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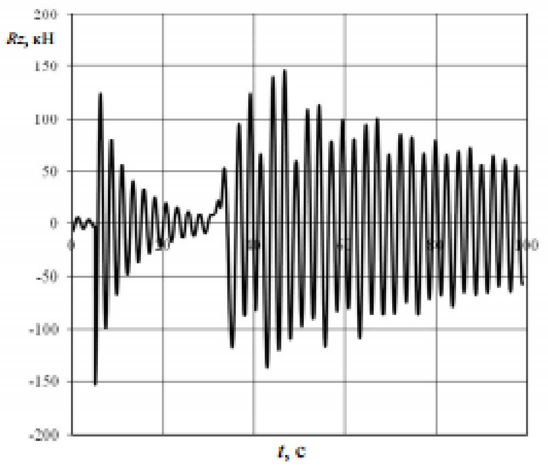

(c)

Fig. 6 (a) the vertical displacement of the center of gravity of the vessel, (b) heights of the ship's overboard ship in the area of the mid-frame, (c) excessive buoyancy force

It should be noted that the movement of the hull has a pronounced dynamic character: the dynamic roll angle (the first initial inclination) θd = 26.5 degrees; θstat = 12.0 degrees; dynamic vertical movement ζd = 0.18 m; a dynamic change in the excess buoyancy force ΔRζ = 145-152 kN; the dynamic value (the minimum value) of the height of the freeboard ζadw = -0.021 m, stat above ζ = 0.40 m; the dynamic trim angle (the first initial inclination) ψd = 0.705 deg, ψstat = 0.35 deg.

IV. Conclusions

According to the results of the study, the following conclusions can be drawn:

(1) The proposed method makes it possible to determine the dynamics of the hull under the action of time-varying external forces and to estimate the hull movements dangerous from the point of view of stability and floodability. It becomes possible to simulate such calculated situations that are not available for research using the Static method.

(2) When a heeling moment is dynamically applied, along with the roll, a vertical movement of the hull arises, which is significant in comparison with the draft and which has a dynamic character. In this case, one maximum amplitude is observed, which can be estimated as the most dangerous.

(3) The change in the excess buoyancy force with dynamic roll and vertical movements of the hull indicates the non-uniformity of its inclinations. The nature of vertical movements depends on the shape and main dimensions of the hull. Ships with a high freeboard surface float at a roll, and the low-breasted ones sink.

(4) Instead of the concept of "angle of flooding", it is advisable to consider the instantaneous height of the freeboard (instantaneous elevation of the lower edge of the open hole in the hull above the operating waterline). This parameter is complex, taking into account all changes in landing parameters.

(5) Determination of the inertial and hydrodynamic characteristics of the hull is a necessary task in the theory of rolling of ships.

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