Vessel dynamics modelling for a decision support system in the threat of rapid flooding

A. V. Valyaev¹, E. A. Lukina², Yu. S. Fedosenko³

¹ Postgraduate of the Department of Computer Science, Control Systems and Telecommunications, Volga State University of Water Transport, Nizhny Novgorod, Russia
² Candidate of Technical Sciences, Associate Professor of the Department of Hydrodynamics, Ship Theory and Environmental Safety of Shipping, Volga State University of Water Transport, Nizhny Novgorod, Russia
³ Doctor of Technical Sciences, Professor, Professor of Department of Computer Science, Control Systems and Telecommunications, Volga State University of Water Transport, Nizhny Novgorod, Russia

E-mail: wav-dk@mail.ru

Abstract. A concept is suggested for modeling the dynamics of the fit of a displacement river vessel trimmi for making decisions about the readiness to use technical means of evacuation and rescue of passengers and crew in the event of a rapid flooding threat. The concept is based on the imitation of loading a large cargo, prone to displacement. The concept is implemented through continuous monitoring of the vessel fitting dynamics in a beyond design basis emergency, real-time forecasting of its development, and the captain taking proactive measures to evacuate passengers and crew.

Introduction

At the stage of a displacement vessel design, an analysis of its buoyancy and stability in specific emergencies is carried out, following the approved methods and rules of both the maritime and river registers.

At the same time, in the event of force majeure circumstances during operation and possible changes in the characteristics of the vessel for these reasons, a beyond design basis accident may occur [1] with irreversible consequences for the vessel and fatal consequences for passengers and crew. First of all, such beyond design basis accidents include vessel capsizing due to flooding of compartments, accumulation of passengers on one side; reception and displacement of large unsecured and displacement-prone cargoes (vessels of technical, fishing and cargo fleets, ferries), taking onboard suspended heavyweights (crane vessels), aerodynamic effects of wind (on vessels with a significant superstructure). Some examples of such beyond design basis accidents, are described in [2-5].

When a vessel is sinking, the parameters of its fit and volumetric displacement continuously change. Accordingly, the captain of the vessel should be able to track the dynamics of the values of indicators characterizing the buoyancy and stability of the vessel in a specific emergency, especially in conditions of complex external influence.
A promising option for obtaining such information is to supplement the deckhouse equipment with a digital decision support system on the use of rescue equipment in the event of the threat of flooding a displacement vessel (hereinafter REFDV).

Functioning of the REFDV involves not only continuous monitoring of the dynamics of the fit of the vessel, but also the identification of trends and prediction of the development of a dangerous situation, and taking proactive measures to evacuate passengers and crew.

Operation of the system is based on the information taken from sensors which monitor in a continuous mode the current values of the vessel parameters and processing of this information using the digital model of the vessel dynamics embedded in the REFDV.

1. Research of vessel dynamics

1.1. Analysis of computational models for valuing the fit of a displacement vessel.
To assess the state of the damaged vessel’s hull docking [6], it is possible to use two different computational models.

In the first model, it is considered that the seawater entering the compartments when the hull is damaged is a liquid cargo, the weight of which is equal to the weight of the inflowed water. In this case, the weight displacement of the damaged vessel will exceed the displacement of the undamaged vessel by the weight of the inflowed water and its center of gravity will change its position.

In the second model, it is assumed that if the hull is damaged, the weight of the vessel remains unchanged, but only the shape of its underwater volume changes, and, accordingly, in this case, water in the damaged compartments is excluded from the underwater volume of the vessel. The weight displacement and the position of the center of gravity of the vessel remain unchanged.

Both computational models are based on physical assumptions, and their use leads to the same results of calculating the characteristics of the vessel's condition, which can be measured or calculated from them the values of the draft, roll and trim angles, stability coefficient, and restoring moment.

At the same time, when using the first computational model, one can take into account the incomplete flooding of the compartment with seawater, which is important when tracking this process in dynamics.

In the general case, a beyond design basis emergency associated with the vessel sinking can conceptually be defined as the acceptance on board of a large mass of cargo (more than 10% of the displacement of the vessel [7]), which is prone to displacement when the hull is tilted. Complicating factors are external healing and trimming moments. To determine the characteristics of the vessel, in addition to the classical models and computational methods of the theory of vessel statics, it is necessary to involve models and computational methods for assessing the dynamic characteristics of vessels.

1.2. Mathematical model of vessel hull dynamics
The physical analysis of the forces and moments acting on the vessel's hull allows using a system of differential equations of the form [8] to describe the dynamics of the vessel's hull:
where \( m, \xi, \theta, \psi, V, D \) are respectively, the mass, vertical displacement, roll and trim angles, volumetric displacement, weight displacement of the vessel; \( \lambda_{33}, \lambda_{44}, \lambda_{55} \) are added mass and moments of inertia of water; \( \lambda_{33}^\prime, \lambda_{44}^\prime, \lambda_{55}^\prime \) are added mass and moments of inertia of water to movements of the body; \( M_{2x}, M_{2\theta}, M_{2\eta} \) are disturbing vertical force and moments in roll and pitch from the action of waves; \( I_{xx}, I_{yy}, R \) are central moments of inertia of the vessel's mass relative to the longitudinal and transverse axes; \( \omega_x, \omega_\psi \) are angular speeds during roll and trim; \( \xi_g, \eta_g \) are abscissa and ordinate of the center of gravity; \( \xi_1c, \eta_1c \) are abscissa and ordinate of the center of magnitude; \( \xi_{1p}, \eta_{1p} \) are abscissa and ordinate of the center of gravity of the received load; \( M_\Theta \) is the healing moment of external forces; \( M_\Phi \) is the trimming moment of external forces.

The mathematical model (1) makes it possible to calculate the fit parameters and simulate the dynamics of the vessel to study the changes and patterns that precede its death.

1.3. Research on the dynamics of vessel flooding

According to the rate of an emergency development, it is possible to classify accidents by duration \( t \) (from the moment of its beginning to the end) according to the following types [9]:

1) "transient" - the value of \( t \) is less than the duration of the rescue operation (conventionally, the duration of such accidents is estimated at one minute [9]);
2) "final duration" - the value of \( t \) is commensurate with the duration of the rescue operation;
3) "long-term" - the development of an emergency occurs during the time interval \( t \), obviously longer than the duration of the rescue operation.

Using the DYNAMIKA complex [10] for a vessel with the parameters of a river displacement passenger motor vessel of the mass project 26-37 under various external conditions in calm water, computational experiments were carried out, during which the changes in the vessel's fit were calculated during the flooding of the compartment, and the moment of its overturning was determined.

In Fig. 1, as an example, the results of calculations for the case of congestion of passengers on the starboard side are presented: heeling moment \( M_\theta = 1500 \) kN\( \cdot \)m, trimming moment \( M_\psi = -9000 \) kN\( \cdot \)m. As can be seen from the dependence shown in the graph, as a result of the instant application of moments, within 90 seconds the vessel switches to sailing in the equilibrium position with a roll \( \theta = 2.8^\circ \) to starboard and a trim \( \psi = 0.1^\circ \) to the stern. Then, simulating the appearance of a hole, this load is added to the gradual flooding of two aft compartments with a water inflow rate of 0.85 m\(^3\)\( \cdot \)min\(^{-1}\). In this case, the level of flooding of the compartments is controlled, \( T_\beta, \) m.
The inflowed water for each moment is taken into account as the receipt of a large cargo on the vessel, which is prone to displacement when the hull is inclined. The change in the displacement of the vessel is shown in Fig. 2.

Fig. 1. The changes in the vessel's fit.

As the volume of the inflowed water increased over time, the roll and trim of the vessel increased (Fig. 1). In this case, the position of the center of gravity of the cargo (Fig. 3) and the center of the vessel's size (Fig. 4) are monitored.

Fig. 2. Change in the displacement of the vessel.

Fig. 3. The position of the center of gravity of the cargo.
As can be seen from the given graphs, the duration of flooding of the vessel's hull floor under the considered variant of the influence of external forces is more than 15 minutes. Then there is a sharp inclination and overturning of the vessel.

According to [10], the duration of rescue operation for a vessel with the above-mentioned hull parameters is 3 minutes 50 seconds, and, accordingly, under given force majeure circumstances, the time before capsizing is sufficient for the captain to decide on the measures to rescue passengers and crew members. This result confirms the need to monitor the fit and stability until the moment of inevitable death of the vessel.

The system of equations (1) can also take into account the effect of excitement as an additional effect, which will aggravate the emergency in the process of its development.

Table 1 shows the results of six numerical experiments with various combinations of initial heeling and trimming moments. The variant discussed above is presented in the third line. The calculations were performed on a computer with characteristics similar to the characteristics of vessel computers currently installed on it [11, 12]; table 1 shows the simulation time $t_{sim}$.

| №  | Death of the vessel | $M_\theta$ kN·m | $M_\phi$ kN·m | $t_\ell$ s | $T_{fl}$ m | $t_{sim}$ s |
|----|---------------------|-----------------|----------------|------------|-------------|--------------|
| 1  | no                  | 0               | 0              | 1489       | 4.134       | 989          |
| 2  | no                  | 1000            | -7000          | 1489       | 4.134       | 1012         |
| 3  | yes                 | 1500            | -9000          | 1321       | 3.9         | 882          |
| 4  | yes                 | 2000            | -14000         | 1057       | 3.442       | 675          |
| 5  | yes                 | 4000            | 0              | 722        | 2.644       | 495          |
| 6  | yes                 | 4000            | -28000         | 651        | 2.433       | 413          |

When comparing the time spent for the process of modeling an emergency with the time of its duration, we conclude that it is impossible to use the method of modeling the dynamics of the vessel for forecasting to support decision-making on the use of rescue equipment in the event of a threat of a displacement vessel flooding, since after the end of the modeling process there is no time for the operation to rescue passengers and crew. Accordingly, it would be necessary to search for a criterion, thanks to which in cases of emergencies it is possible to assess its danger, analyze the characteristics of buoyancy and stability, and effectively organize the rescue operation. As such a criterion, it is proposed to use the curves of the intensity of changes in the stability characteristics of the vessel.

2. Analysis of vessel stability states

2.1. Qualitative determination of the possible states of the vessel's stability
The work [13] defines the regularities of the loss of stability of the vessel, which allow timely detection of the danger of the loss and safely leave it before capsizing. Based on this qualitative definition of the possible states of the vessel’s stability, depending on the numerical values of the roll angles, the analysis of the diagrams of static stability (DSS) was carried out and the criteria for tracking the trend of changes in the stability characteristics were determined [14].

For a typical DSS of a river displacement passenger vessel (DSS with a rectilinear initial section), the boundary of the zone approaching the unstable equilibrium of the vessel, i.e. to the possibility of its overturning, can be at the point of deviation of the graph from the tangent to the initial section - the point "A" (see Fig. 5). Since we are talking about a change in the intensity of the increase (rate of change) of the static stability arm depending on the angle of the vessel inclination, it is advisable to plot the dependence of this speed on the roll angles - the graph of the first derivative of the DSS.

The point "B", as the largest ordinate of the DSS, corresponds to the limiting heeling moment, the static application of which does not yet cause the vessel to overturn. But after passing this point, the descending branch of the DSS begins, corresponding to the zone of unstable equilibrium of the vessel, i.e. the actual loss of stability due to the static application of the healing moment.

Also, the rectilinear section of the DSS, starting at the point "C", can be distinguished on the descending branch of the DSS. In this case, the transition to the straight section corresponds to the increasing intensity of the reduction of the static stability arm, and, therefore, to the inevitable capsizing of the vessel.

By analyzing the DSS with a straight-line initial section and the graph of its first-order derivative, it is possible to determine the points "A", "B", "C" and various stages of the emergency development (Fig. 5):

I - capsizing of the vessel is impossible, measures should be taken to straighten it;
II - capsizing of the vessel is impossible, the means of rescue should be brought into readiness;
III - capsizing of the vessel is possible;
IV - capsizing of the vessel is guaranteed.

2.2. Study of curves of the intensity of changes in stability characteristics of a vessel
Continuing the study of the stability of the vessel in the situations modeled in Section 2.3, using the TKOST complex [15], the hydrostatic characteristics were calculated and the DSS ensemble was constructed for the sequential states of the vessel corresponding to the beginning of the water flow into the compartments and an increase in its level in the flooded compartments with a step of 0.5 m. Also, for a more detailed study of the moment of the sinking of the vessel, a DSS was built when the compartment was filled to 95% of the flooded volume at the time of sinking.

To search for the point "A", the constructed DSS should be differentiated. It was found that, to obtain a satisfactory accuracy of plotting the graphs of derivatives, it is necessary to construct a DSS with a step of at least 1 [16]. Numerical differentiation was performed using the two-sided difference method.

Theoretically, the point "A" defines the end of the straight-line section of the ascending branch of the DSS and can be determined from the graph of the first derivative of the DSS, as the end of the first horizontal section of the graph of the first derivative. However, as the studies of the dynamics and analysis of the buoyancy and stability of a vessel in service show, the ascending branch of river displacement vessels is not always linear, although it is approximated by a straight line. In this regard, the point "A" is proposed to be determined by studying the first derivative of the DSS as follows: the DSS should be differentiated with a step of at least 1°, then it is necessary to find the relative changes of subsequent values relative to the previous ones at each step; deviation of the relative values by more than 5% indicates the passage of the point "A" at the previous step.

This method was used to obtain and study the ensembles of DSS and their first derivatives for all considered variants of vessel emergencies.

The point "A" is marked on the ensembles of DSS and their first derivatives on each graph. The points "A" are connected and form: on the DSS ensemble, the curve of the first threshold value of the change in stability characteristics, further denoted by $\alpha$; on the graphs of the first derivative of the DSS, the curves of the intensity of changes in the characteristics of stability of the vessel, hereinafter $\alpha'$.

Let us give an example of plotting the curves $\alpha$ (Fig. 6), $\alpha'$ (Fig. 7) for the case Variant 3. Initial data the TKOST complex for case Variant 3 are presented in Table 2.

| Parameter                          | Unit of measurement | Value  |
|------------------------------------|---------------------|--------|
| Displacement, $D$                  | tons                | 1461   |
| Draft, $T$                         | meters              | 2.38   |
| Abscissa of the center of gravity, $x_g$ | meters              | 1.112  |
| Ordinate of the center of gravity, $y_g$ |                   | 0.105  |
| Applikat of the center of gravity, $z_g$ |                   | 4.55   |

By comparing the data from the study of the dynamics of vessel wreckage (paragraph 1.3) with the results of plotting the curves of the intensity of changes in stability characteristics, it was found that after the actual bank angle (Fig. 1) reaches the value corresponding to the point "A", a sharp increase in the vessel's roll angle is observed. Reaching the point "A" is a prerequisite for approaching the beginning of a transient accident or the end of a long-term accident. Table 3 shows the results of comparing the values of the actual bank angle and the point "A".
Fig. 6. Example of plotting the curves $\alpha$.

Fig. 7. Example of plotting the curves $\alpha'$.
Table 3. Results of comparing the values of the actual bank angle and the point "A" for case Variant 3

| The level of flooding of the compartments, m | Position point "A" in DSS, deg | Actual roll angle, deg | Time, s |
|-------------------------------------------|-------------------------------|-----------------------|--------|
| 0                                        | 18                            | 2.8                   | 90     |
| 0.5                                      | 18                            | 3.1                   | 166    |
| 1                                        | 17                            | 3.7                   | 270    |
| 1.5                                      | 15                            | 4.5                   | 385    |
| 2                                        | 13                            | 5.0                   | 519    |
| 2.5                                      | 9                             | 5.0                   | 673    |
| 3                                        | 5                             | 4.8                   | 858    |
| 3.5                                      | -                             | 7.9                   | 1086   |
| 3.7                                      | -                             | 11.7                  | 1197   |
| 3.9                                      | 7                             | -                     | 1320   |

This correspondence was established for five more design cases: Variants 1, 2, 4-6.

3. Conclusion

In the course of modeling the dynamics of the vessel to create a decision support system for the threat of rapid flooding, the following results were obtained:

1. The analysis of computational models for assessing the fit of a displacement vessel has been carried out. The problem of calculating the characteristics of buoyancy and stability for an emergency related to the hull flooding must be considered within the framework of the model for receiving cargo, which is prone to displacement when the vessel's hull is inclined.

2. A mathematical model of the vessel's hull motion (1) has been determined, which allows calculating the fit parameters and simulating the vessel's dynamics during flooding.

3. The expediency of using the characteristics of DSS for predicting accidents associated with loss of stability has been established. This will allow you to quickly monitor the stability of the vessel during operation, including in the event of occurrence and development of emergencies in dynamics.

4. The characteristic points of the DSS were established, corresponding to various stages of the accident development. Comparison of the current values of the roll angles obtained from the sensors with the threshold (critical) numerical values of the characteristic points of the DSS for each vessel will allow establishing the degree of danger of death from loss of stability in real-time.

5. A technique has been developed to study the curves of the intensity of changes in the characteristics of stability of the vessel, which will make it possible to predict the development of an accident on board the vessel in real-time.

Acknowledgements

The project was supported by a grant from the the Foundation for Assistance to Small Innovative Enterprises in Science and Technology (Application No. C1-86278).

References

[1] Beyond the design basis [Electronic resource]. - URL: https://www.mchs.gov.ru/ministerstvo/o-ministerstve/terminy-mchs-rossii/term/292 (date of access: 11/21/2020).
[2] Maľcev N.Ya., Dorogostajskij D.V., Prytkov Yu.K. Teoriya nepotoplyaemosti sudna (Theory unsinkable ship), Sudostroenie, Leningrad, 1983.
[3] The col lapse of the South Korean ferry [Electronic resource]. URL: https://www.vesti.ru/doc.html?id=1485039 (date of access: 11/08/2020).
[4] Completed the investigation of the criminal case on the wreck of the trawler "Far East" in 2015 [Electronic resource]. - URL: https://sledcom.ru/news/item/1082970 (date accessed: 08/11/2020).
[5] The probable cause of the tragedy with the barge at the Rybinsk reservoir was the displacement of the cargo [Electronic resource]. - URL: https://portnews.ru/news/300971/ (date accessed: 31/08/2020).

[6] Alfer'ev M.Ya. Teoriya korablya (Ship theory). Transport, Moskow, 1972.

[7] Milova I.I. Teoriya korablya. Chast I. Statika sudov vnutrennego i smeshannogo plavaniya (Ship theory. Part I. Statics of inland and mixed navigation vessels), VGAVT, Nizhnij Novgorod, 2008.

[8] Vaganov A.B., Krasnokutskij I.D., Nguen N.T. Application of a numerical method for calculating the restoring forces and moments of a displacement vessel in the study of its dynamics under the influence of external forces in conditions of wind and sea waves // Scientific journal "Transport Systems" NNSTU No. 2, 2016 - pp. 8-16.

[9] Aleksandrov M.N. Bezopasnost 'cheloveka na more (Human safety at sea) Sudostroenie, Leningrad, 1983.

[10] Vaganov A.B., Krasnokutskiy I.D. Certificate of State Registration of the computer program, No. 2014612348 "Calculation of the pitching of ships and floating structures on sea waves".

[11] Ship computer MIRAN® IS-11-04 [Electronic resource]. URL: https://seacomm.ru/catalog/352/12262/ (date of access: 11/21/2020).

[12] System blocks of the MOS-B series [Electronic resource]. - URL: https://valcom.ru/catalog/35/ (date of access: 11/21/2020).

[13] Ershov A.A. The ways of survival of people in sea and river accidents // Bulletin of the state university of marine and river fleet Admiral S.O. Makarov, 2016. No. 4 (38) - pp. 15-22.

[14] Valyaev A.V., Lukina E.A., Lyubimov V.I., Fedosenko Yu.S. Monitoring of stability in digital intelligent support system at risk of fleeting accident of a displacement vessel // Marine Intelligent Technology. 2018.Vol. 2.No.4 (42). - pp. 18-24.

[15] Vaganov A.B., Krasnokutskiy I.D. Certificate of State Registration of a computer program, No. 2014612390 "Calculation of hydrostatic characteristics and stability diagrams of ship hulls of complex geometrical shape at random landing".

[16] Valyaev A.V., Lukina E.A. Proactive monitoring of an emergency situation of a river displacement vessel // XXV International Scientific and Technical Conference "Information Systems and Technologies" IST-2019, Conference proceedings. - Nizhny Novgorod: NSTU, 2019 - CD disc.