Automatic Reset of Kinetic Energy in Case of Inevitable Collision of Ships

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***Abstract*— Considered issues of automatic reset of kinetic energy along the gradient in case of inevitable collision of ships. The target function of the fastest reset of kinetic energy is formed in the form of a scalar product of the gradient vector at the location of the vessel and the vector of the right parts of the mathematical model of the longitudinal and angular movement channels containing control. To form optimal controls, a nonlinear optimization procedure was used, taking into account control restrictions. The own ship's movement parameters (speed and course) used in the optimization procedure are measured by speed and course sensors, and the target's movement parameters are estimated from the measured values of the own ship's speed and course and the measured relative movement parameters using radar. The workability method was verified by mathematical modeling in a closed circuit with a control object. The results of the simulation showed that the automatic module provides a 9-fold reduction in the kinetic energy of the collision. The use of the automatic kinetic energy reset module in the event of an imminent collision will reduce the influence of the negative impact of decisions when handling a vessel under the influence of stress, reduce crew fatigue, prevent damage or even loss of the vessel and cargo, and save human lives.**

Keywords*— *inevitable collision, reset of kinetic energy, human factor, mathematical model, automatic module.

I. Introduction

According to statistics, about 90% of accidents and disasters at sea are related to wrong decisions made by the shipmaster. Human intervention in control processes is the least perfect link in the control circuit of the ship's movement [1]. In stressful situations (inevitable collision, storm, etc.), a person does not always make the right decisions, which can lead to significant damage to the hull, or the loss of the vessel, cargo, and even human lives. A striking example of incorrect actions in a stressful situation is the collision of the passenger ship "Admiral Nakhimov" with the dry cargo ship "Petro Vasyov" in Tsemeska Bay. Today, almost all ships use modular distributed automated movement control systems that help the shipmaster to process input information and provide it in a convenient form. However, all decisions regarding ship control in such systems are always made by the shipmaster [2,3]. According to the authors of this study, the most radical way to minimization of human influence in vessel handling can be achieved by using automatic control modules. The authors' works [4-7] are devoted to the study of the application of automatic control modules to solve various functional problems. In this case, the shipmaster only decides to activate the module and observes its performance. An example is the auto-steering system, which was introduced by the German company "Antschulz" at the beginning of the last century. Since then, computer technology has appeared, its power has increased significantly, and the possibility of its application as an on-board computer for solving more complex real-time control problems has appeared. Many authors were involved in the development of control methods using an on-board computer.

For example, the article [8] investigated the issues of safe control of ship traffic in busy ports and waterways based on real-time collision risk assessment. A risk model was created based on accident data.

In the article [9], a generalized decision-making model was developed to prevent ship collisions using the reinforcement learning method. The developed model can be used for autonomous separation with several vessels.

The article [10] developed an authentication mechanism based on identification for secure information exchange in the maritime transport system. Since shared data contains sensitive vessel information, there is a need for secure data sharing methods that allow only authenticated individuals to access data received from marine Internet devices.

Article [11] examines the issues of using artificial intelligence methods for safe ship management. On the basis of remote sensing of the marine environment, a technique for assessing the dangerous event "loss of navigational control" has been created. The probability of loss of navigational control is calculated taking into account the states of the risk indicators.

The article [12] developed a time-optimal method of avoiding collisions with obstacles of an autonomous vessel, based on a nonlinear model of predictive control.

In work [13], the issue of predicting ship behavior in scenarios with several ships is considered. It is shown how nested finite state machines can separate situation assessment from decision making and provide a proven and repeatable algorithm. A method is proposed that allows predicting mutual maneuvering in a multi-ship scenario.

In the study [14] the issue of prevention of collision of vessels is considered. A collision avoidance algorithm is proposed, which includes collision risk calculation and optimal route search. Changes in collision risk, speed, course and steering deviation were analyzed.

The study [15] developed indicators of the risk of loss of navigational control of autonomous vessels. The developed risk indicators cover technical equipment, remote control power and environmental conditions. The probability of loss of navigational control is calculated taking into account the states of the risk indicators.

In work [16], the issue of building a refined model for calculating the risk of ship collisions is considered. Traditional calculation methods are based on finding the closest point approach (CPA) and the time to closest point approach (TCPA), which are insufficient. It is proposed to use an elliptical domain around the vessel for risk assessment, the size of which depends on the parameters of the vessel's movement, the vessel's maneuverability and the subjective factors of the vessel operator. Based on the constructed domain model, the coefficient of proximity of the target to the domain area and the risk function are calculated, which are used to improve calculations using traditional methods. The results of the simulation showed that the proposed method has a higher level of collision risk identification, more compatible with the requirements of navigation decision-making.

The study of the strength of ship hulls, the identification of the weakest places in the hull, the creation of materials resistant to corrosion and those that can withstand large loads, the prediction of the type and size of damage, the study of extreme directions of application of external forces and moments that lead to various degrees of destruction of the hull structure are devoted works [17-19]. The obtained results can be useful in the development of control algorithms for the inevitable collision of ships to prevent significant damage.

II. PROBLEM STATEMENT AND DECISION-MAKING SCHEME

Fig. 1 shows a diagram of a dangerous convergence of one's own ship and the target.

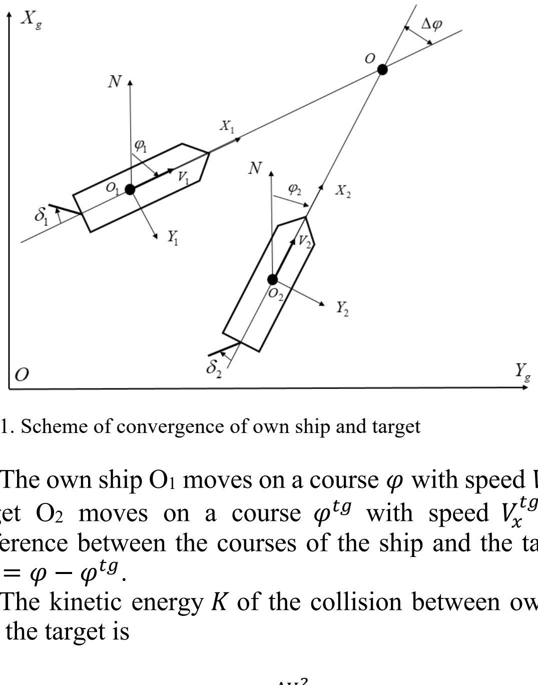

Fig. 1. Scheme of convergence of own ship and target

The own ship O_1 moves on a course φ with speed V_x. The target O_2 moves on a course φ^{tg} with speed V_x^{tg}. The difference between the courses of the ship and the target is $\Delta\varphi = \varphi - \varphi^{tg}$.

The kinetic energy K of the collision between own ship and the target is

$$K = m\frac{\Delta V^2}{2}, \quad (1)$$

where m is the mass of the vessel with the attached water masses, ΔV is the relative speed of convergence of own ship and target.

You need to find such telegraph controls Θ^* and sternum δ^*, to ensure the fastest reset of the kinetic energy of the convergence of own ship and target

III. RESEARCH RESULTS

Projections of the relative speed of movement of the vessel and the target on the axis $OX_1Y_1Z_1$ linked coordinate system (LCS) of the combined coordinate system of the own ship have the form

$$\begin{cases} \Delta V_x = V_x - V_x^{tg} cos\Delta\varphi \\ \quad -V_x^{tg} sin\Delta\varphi \end{cases}$$

The square of the relative speed of convergence used in formula (1) is equal to

$$\Delta V^2 = (V_x - V_x^{tg} cos\Delta\varphi + (-V_x^{tg} sin\Delta\varphi)^2 = \\ = V_x^2 - 2V_xV_x^{tg} cos\Delta\varphi + (V_x^{tg})^2 \quad (2)$$

Kinetic energy of convergence, taking into account (2), will have the form

$$\mathrm{K} = m\frac{\Delta V^2}{2} = \frac{m}{2}\left[V_x^2 - 2V_xV_x^{tg}\cos\left(\varphi - \varphi^{tg}\right) + \left(V_x^{tg}\right)^2\right] \quad (3)$$

Let's find the derivative of kinetic energy (3) in time

$$\frac{dK}{dt} = \frac{\partial K}{\partial V_x}\frac{\partial V_x}{\partial t} + \frac{\partial K}{\partial \varphi}\frac{\partial \varphi}{\partial t} = < \mathbf{grad}\mathrm{K}, \frac{d\boldsymbol{P}}{dt} > \quad (4)$$

where

$$\begin{cases} \mathbf{grad}\mathrm{K} = \left(\frac{\partial K}{\partial V_x}, \frac{\partial K}{\partial \varphi}\right) = \\ m\left[V_x - V_x^{tg}\cos(\varphi - \varphi^{tg}), V_x, V_x^{tg}\sin(\varphi - \varphi^{tg})\right] \\ \frac{d\boldsymbol{P}}{dt} = \left(\frac{\partial V_x}{\partial t}, \frac{\partial \varphi}{\partial t}\right) \end{cases} \quad (5)$$

Vector $\mathbf{grad}\mathrm{K} = \left(\frac{\partial K}{\partial V_x}, \frac{\partial K}{\partial \varphi}\right)$ is the gradient of kinetic energy (3) according to motion parameters V_x, φ own ship, determined by the measured parameters of the own ship's movement V_x, φ and estimated target movement parameters V_x^{tg}, φ^{tg}.

Vector $\frac{d\boldsymbol{P}}{dt} = \left(\frac{\partial V_x}{\partial t}, \frac{\partial \varphi}{\partial t}\right)$ is the vector whose components are linear acceleration $\frac{\partial V_x}{\partial t}$ and angular velocity $\frac{\partial \varphi}{\partial t}$ the yawning of own vessel.

Constituents $\frac{\partial V_x}{\partial t}, \frac{\partial \varphi}{\partial t}$ are determined by the mathematical model of own vessel

$$\begin{cases} \frac{\partial V_x}{\partial t} = \frac{1}{m}\left[P_x(\Theta) - R_x(V_x, \omega_z) - R_x(\delta)\right] = \\ \quad = f_1(V_x, \omega_z, \Theta, \delta) \\ \frac{\partial \omega_z}{\partial t} = \frac{1}{I_z}\left[M_z(\Theta) - M_z(V_x, \omega_z) - M_z(\delta)\right] = \\ \quad = f_3(V_x, \omega_z, \Theta, \delta) \\ \frac{\partial \varphi}{\partial t} = \omega_z \end{cases} \quad (6)$$

Where $P_x(\Theta)$, $M_z(\Theta)$ is the force and yawing moment from the screw, $R_x(\delta)$, $M_z(\delta)$ are the rudder resistance and yaw moment from rudder deflection.

The problem of the fastest reset of kinetic energy can be written in the form

$$\frac{dK}{dt} = \frac{\partial K}{\partial V_x}\frac{\partial V_x}{\partial t} + \frac{\partial K}{\partial \varphi}\frac{\partial \varphi}{\partial t} = < \mathbf{grad}\mathrm{K}, \frac{d\boldsymbol{P}}{dt} > \rightarrow \min, \quad (7)$$

or, taking into account (5), (6),

$$V_x - V_x^{tg}\cos(\varphi - \varphi^{tg})\, f_1(V_x, \omega_z, \Theta, \delta) + +V_x, V_x^{tg}\sin(\varphi - \varphi^{tg}) f_3(V_x, \omega_z, \Theta, \delta) \rightarrow \min \quad (8)$$

In condition (8), we leave only those components of the right-hand sides of the equations of system (6) that depend on the controls

$$[V_x - V_x^{tg}\cos(\varphi - \varphi^{tg})][P_x(\Theta) - R_x(V_x, \omega_z) - R_x(\delta)] + +V_x, V_x^{tg}\sin(\varphi - \varphi^{tg})\frac{m}{I_z}[M_z(\Theta) - M_z(V_x, \omega_z) - M_z(\delta)] \rightarrow \min \quad (9)$$

Condition (9) defines the nonlinear objective function to be optimized. Control constraints must also be taken into account when optimizing

$$|\Theta| \leq \frac{\pi}{2}, |\delta| \leq 35\frac{\pi}{180} \quad (10)$$

The optimization of the objective function (9) with linear control constraints (10) can be performed using an optimization procedure of the type fmincon(*) MATLA

$$\mathbf{U} = \mathrm{fmincon}(@\mathrm{fun}, \mathbf{U}(0), \mathbf{A}, \mathbf{b}, \mathbf{Aeq}, \mathbf{beq}, \mathbf{lb}, \mathbf{ub}, @\mathrm{nlcon}) \quad (11)$$

where (@fun is the reference to the aim function (9), $\mathbf{U}(0) = (\Theta(0), \delta(0)$is the starting value for finding optimal control, $\mathbf{A}, \mathbf{b}$ are the matrix and vector of the linear constraints system of the equalities type, in our case are absent, $\mathbf{Aeq}, \mathbf{beq}$ are the matrix and vector of the linear constraints system of the non-equalities type, in our case are absent, $\mathbf{lb}, \mathbf{ub}$ are the vectors of lower and upper control constraints (10), @nlcon is the reference to the system of nonlinear constraints.

The optimization procedure (11), with the objective function (9) and constraints (10), is performed at each step of the on-board computer. Longitudinal speed of own vessel V_x and course φ, used in aim function (9), are measured by linear speed measurement sensor and Gyrocompass, longitudinal speed V_x^{tg} and course φ^{tg} of the target are estimated by linear speed measurement sensor, Gyrocompass and RADAR measurements. The optimal controls $\mathbf{U}^* = (\Theta^*, \delta^*)$, which are formed by procedure (11), are submitted to the automation units of the power plant and the tiller.

A. Mathematical modeling of kinetic energy release processes during an inevitable collision of ships.

The workability and efficiency of the method, algorithm, and software are verified by mathematical modeling in the MATLAB environment for various convergence situations. In fig. 2, 3 show the graphs of changes in time of the vessel and target parameters for two approaches, where $V_x[m/s]$ is the measured longitudinal speed of the vessel in the linked coordinate system (LCS), Course [dg] is the measured course φ of the vessel, $dis[m]$ is the measured distance between the vessel and the target, $KinEng[Nm]$ is the kinetic energy of the collision.

Fig. 2 shows the graphs of changes in movement parameters for the first approach situation: own vessel initial position is $X_g(0) = 0m$, $Y_g(0) = 1000m$, own vessel initial speed is $V_x(0) = 10m/s$, own vessel initial course is $\varphi(0) = 0dg$; initial target position is $X^{tg}(0) = 1000m$, $Y^{tg}(0) = 0m$, initial target course is $\varphi^{tg}(0) = 90dg$, initial target speed is $V_x^{tg}(0) = 10m/s$.

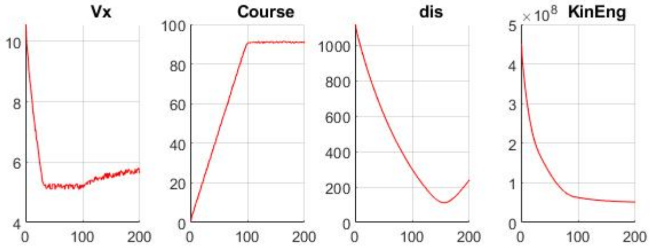

Fig. 2. Graphs of changes in movement parameters for the first approach situation

Fig. 3 shows the graphs of changes in movement parameters for the second approach situation: own vessel initial position is $X_g(0) = 0m$, $Y_g(0) = 2000m$, own vessel initial speed is $V_x(0) = 10m/s$, own vessel initial course is $\varphi(0) = -45dg$, initial target position is $X^{tg}(0) = 1000m$, $Y^{tg}(0) = 0m$, initial target course is $\varphi^{tg}(0) = 90dg$, initial target speed is $V_x^{tg}(0) = 10m/s$.

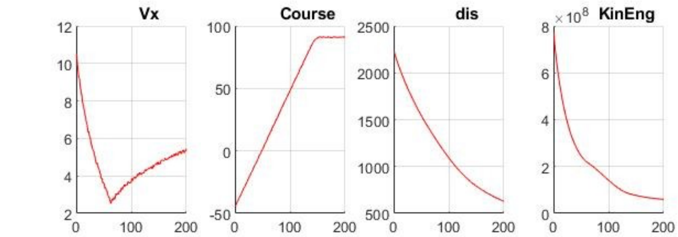

Fig. 3. Graphs of changes in movement parameters for the second approach situation

In the first approach situation, the own vessel moves perpendicular to the target's trajectory, the initial positions and speeds of the vessel and target lead to an inevitable collision. After the activation of the kinetic energy reset module, emergency braking begins (the measured speed V_x decreases from $10m/s$ to $5m/s$ and the vessel's course changes in the direction of the target's course. Starting from $t = 30s$ and up to $t = 100s$, the vessel's speed is maintained at $V_x(0) = 5m/s$, the vessel's course continues to change in the direction of the target's course. Starting from $t = 100s$, the course of the vessel coincides with the target's course and the speed of the vessel begins to increase. The distance between the vessel and target first decreases to $dis = 100m$, then begins to increase. The kinetic energy of the collision decreased from $KinEng = 4.5e^8Nm$ to $KinEng = 0.5e^8Nm$, i.e. 9 times.

In the second approach situation, the own vessel moves towards the target at an angle of $45dg$ to its course. After the activation of the kinetic energy reset module, the vessel begins to brake and simultaneously change its course in the direction of the target course. During braking from $t = 0s$ to $t = 60s$, the vessel's speed decreased from the initial value $V_x(0) = 10m/s$ to $V_x = 2.5m/s$, then began to increase again. The increase in speed is explained by the fact that at that moment the own vessel was already moving in the direction of the target at an angle of $25dg$ to its trajectory and the increase in the speed of the vessel led to a decrease in the relative speed of the vessel and target and to a decrease kinetic energy. During the maneuver, the vessel's course changed from the initial course $\varphi(0) = -45dg$ to the target course $\varphi^{tg}(0) = 90dg$. The distance between the vessel and target is constantly decreasing to $dis = 600m$. The kinetic energy of the collision during the maneuver decreased from $KinEng = 8.0e^8 Nm$ to $KinEng = 0.7e^8 Nm$, i.e. 11 times.

IV. DISCUSSION OF STUDY RESULTS

Summing up, it should be noted that the developed method and software based on it allow to automatically and optimally reset the kinetic energy in case of an inevitable collision of ships. The obtained result is explained by the use of on-board controller and optimization procedure for finding optimal controls. At each step of the on-board controller $(\mathbf{0.5-1.0})\boldsymbol{s}$ the parameters of the ship's movement are measured and the parameters of the target's movement are estimated, which are used to find the kinetic energy gradient of the collision. The kinetic energy gradient and the mathematical model of the longitudinal and angular motion channels are used in the optimization procedure to find the optimal controls, for the fastest reset of the kinetic energy, taking into account the control constraints. Finding optimal controls at each step of the calculation allows take into account changes in the relative position of own ship and the target. The determined optimal controls are applied to the automation of the power plant and the steering wheel. Unlike the existing methods of manual maneuvering before an imminent collision, the proposed method allows you to automatically and optimally reset the kinetic energy in the event of an imminent collision, reduce the impact of the human factor, increase the safety of navigation, reduce damage to ships, loss of cargo, and save human lives. The method can be applied on ships by introducing it into the on-board controller, which will make it possible to optimally reduce the kinetic energy in case of an inevitable collision.

The theoretical significance of the obtained result lies in the development of a method of automatic optimal resetting of the kinetic energy of a collision. The practical significance of the obtained result lies in the possibility of using the developed method in the modules of automatic reset of kinetic energy of collision, automation and optimization of control processes and, due to this, reducing the influence of the human factor on control processes, reducing crew fatigue and increasing reliability.

The limitations of the method include the impossibility of using it with manual control.

In further work, it is planned to investigate the possibilities of the method for vessels with other control schemes.

V. CONCLUSIONS

The issues of automatic resetting of the kinetic energy of the collision along the gradient are considered. Literary sources dedicated to this topic are analyzed. The results of the analysis showed that the issue of automatic reset of kinetic energy in the event of an imminent collision had not been considered before, and the control of the vessel was carried out manually based on the acquired experience. The article develops a method for automatically resetting the collision kinetic energy along a gradient, which uses a nonlinear optimization procedure with linear control constraints. Based on the method, the algorithmic and software of the module for automatic reset of kinetic energy was developed, the operation of which was verified by mathematical modeling in the MATLAB environment, in the closed loop "Control Object - Control System". The simulation results confirmed the efficiency and effectiveness of the developed method, algorithm and software. The developed method can be used to build automatic modules for resetting kinetic energy in case of inevitable collision of vessels, which allows to reduce kinetic energy during maneuvering by 10 times, to automate maneuvering processes, to reduce the influence of the human factor on control processes, to reduce negative consequences of collision (damage to ships, cargo loss) and save human lives.

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