Automatic Prevention of the Vessel's Parametric Rolling on the Wave

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Abstract

Parametric resonance is one of the most dangerous phenomena that occurs during a storm. In the event of a parametric resonance, an undamaged and properly loaded vessel can capsize within seconds. The essence of parametric resonance is to change the parameters of the vessel as an oscillating system. In this case, the coefficients of the differential equations of the vessel model become functions of time. Parametric oscillations are observed at a certain ratio between the frequency of the external influence and the frequency of the system's own oscillations. Parametric resonance in the roll channel is especially dangerous, which leads to a sharp increase in the amplitude of the vessel's rolling, water entering the deck and inside the vessel's hull, loss of stability and possible capsizing. The existing methods of storming are not effective enough, which is due to the use of visual methods for estimating the parameters of turbulence and manual graphic constructions, significant time delays between obtaining data for calculation and determining safe parameters of motion, the lack of constant measurement of turbulence parameters and refinement of safe motion parameters, the difficulty of selecting the dominant factor from the system dangerous factors, intuitive assessment of the level of danger. The authors have developed a method of automatic avoidance of parametric resonance, which differs from existing methods in that it automates the processes of measurement and information processing, reduces delays in decision-making, reduces the influence of the human factor on control processes, reduces crew fatigue, reduces the risks of losing the vessel and cargo, and in general increases the navigation safety. The developed method can be used for both manual and automatic control. In the manual control mode, the shipmaster has the opportunity to use automatically measured information and the results of its processing - visualization of parametric resonance areas and the position of the phase point for making management decisions. In the automatic control mode, the system itself calculates and implements safe movement parameters, and the shipmaster only observes its operation. The obtained results are reproducible and can be used to develop the functionality of automated systems and/or automatic parametric resonance avoidance modules.

Keywords

Intelligent systems, human factor, navigation safety, automated systems, parametric rolling

1. Introduction

Analysis of global and domestic accident statistics shows that the main cause of ship death is the loss of seaworthiness of the vessel in storm conditions [1]. Stormy sailing conditions are one of the most difficult sailing conditions on the route. The pitching, the need for constant concentration of attention greatly exhausts the crew and leads to wrong decisions. The situation worsens also due to the fact that during a storm, such dangerous phenomena as harmonic and parametric resonances occur much more often, deforming forces and moments increase, which can reach the maximum allowable values and lead to the destruction of the hull, the lateral

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stability of the ship in following seas decreases, etc. Works [2-4] are devoted to the study of the strength of vessel hulls, materials for the manufacture of hulls. Guidelines and Recommendations for safe sailing in difficult weather conditions are given in IMO documents [5,6].

Parametric resonance is one of the most dangerous phenomena that occurs when a vessel rocks in a storm. If parametric resonance occurs, an intact and properly loaded vessel can capsize within seconds. The essence of parametric resonance is the change, under the influence of external forces during movement, of the parameters of the vessel as an oscillating system. In this case, the coefficients of differential equations, depending on the parameters of the system, become functions of time. Such oscillations are called parametric. They can be fading or increasing over time. Parametric oscillations are observed at a certain ratio between the frequency of external influence and the frequency of natural oscillations of the system. For this reason, the dangerous relationships that arise between the frequency of forced and natural vibrations of a vessel are called parametric resonance. Parametric resonance due to roll can lead to a sharp increase in the amplitude of the vessel's rolling, to sea water entering the deck as the roll angles increase during the rolling, to water getting inside the vessel's hull, to loss of stability and, as a consequence, to a possible capsizing of the vessel. The existing methods of storming are not very effective, as they have low accuracy, due to the use of visual methods of estimating the parameters of turbulence and manual graphic constructions, significant time delays between obtaining data for calculation and determining safe parameters of movement, lack of constant measurement of parameters of turbulence and refinement of safe parameters of movement, the difficulty of identifying the dominant factor from the system of dangerous factors, intuitive assessment of the level of danger.

The authors of the article believe that the most effective direction in the development of ship traffic control systems is the use of automatic control modules in automated systems, which will significantly reduce the influence of the human factor on the processes of ship traffic control and increase the safety of shipping.

2. Related works

The question of safe sailing in a storm has been previously considered by many authors. The books [7,8] should be included among the fundamental works of this direction.

In the work [9] the author cites dangerous phenomena that can occur during storm sailing, in particular: surf-riding and broaching, which occur when the vessel is on the steep front edge of a high wave in following seas. In this case, the vessel can be accelerated by going down the wave, but there is a danger of capsizing with a sudden change of course; reduction of intact stability when riding a wave crest amidships, occurs when the vessel moves on the crest of a wave. The danger of the situation is a significant decrease in stability, especially when the wavelength is (0.6 - 2.3) the length of the vessel; synchronous rolling motion, also known as synchronous resonance, occurs when the period of the vessel's own oscillations coincides with the period of oncoming waves; parametric roll motions, also known as parametric resonance, leads to a sharp increase in roll amplitude due to a periodic change in stability at the crests and troughs of waves. The author describes the possible situations of occurrence of parametric resonance: the period of natural oscillations of the vessel coincides with the period of waves, the stability of the vessel decreases to a minimum once per oscillation period, the situation is characterized by asymmetric oscillations, when the roll amplitudes in different directions differ from each other, the transition of this type of parametric resonance is possible in synchronous; when the period of the vessel's own oscillations is twice as long as the wave period, the stability of the vessel decreases to a minimum of two times during the oscillation period, the situation is characterized by symmetrical oscillations; when there is a consistent and periodic submersion and surfacing of the stern and bow part of the vessel, which can lead to serious rolling movements, even if the vessel is stable. The work also includes mathematical formulas that describe the conditions for the occurrence of dangerous phenomena.

In the article [10] listed the main precautions to be taken when sailing in storms, namely: switch to manual steering to avoid sudden waves hitting the rudder; check all oil levels, connections and other important steering control elements; create conditions for obtaining the maximum torque on the rudder shaft; ensure a sufficient man power including senior officers to be present in the bridge; ensure a sufficient number of engineers in the engine room; monitoring all the parameters of the main propulsion plant and auxiliary power plant machineries; after getting rough weather warning, all the spares in the engine room are to be stowed and lashed properly; in bad weather, propeller will come in and out of water and will fluctuate the main engine load. Hence rpm is to be reduced or main engine control setting is to be put on rough weather mode; always make sure for correct sump level of all the machineries as during rough sea ship will roll, resulting in false level alarm which can even trip the running machine and lead to dangerous situation in bad weather; level of all the important tanks is to be maintained so that pump inlet should not loose suction at any time; stand by generator is to be kept on load until the bad weather situation stops; water tight doors in the machinery spaces to be closed; sky light and other opening to be closed; all trays are to be avoided from spilling in event of rough weather; all deck items (mooring cables, lashing equipment, drums, etc.) should be properly secured; all openings on the cargo deck and other spaces must be closed; keep all openings leading to the dwelling closed; everyone must know their duties according to their rank; turn off the elevators to avoid injury; wear personal protective equipment, hold on to handrails to avoid tripping and falling; be alert and work in a team.

In the article [11] considered issues of increasing speed and reducing energy consumption during cargo and ballast transits of a tanker. Based on the results of experiments and observations carried out on the tanker itself, a method of increasing speed and reducing fuel consumption in stormy conditions is proposed. It is shown that an increase in speed and fuel economy can be achieved with the same wind and wave angles. This rule must be taken into account both at the stage of planning the transition and in conditions of stormy sailing. The obtained results can be extended to other types of vessels.

In the candidate's thesis [12] the author established a relationship between: steady motion of the vessel, its seaworthiness characteristics and wave parameters, presented in the form of a non-linear mathematical model; the shape of the submerged part of the cross-section of the hull and its local draft, presented in the form of a two-layer artificial neural network; parameters of the vessel's movement, the work spent on the transition and the additional work spent on compensating the disturbing forces and reducing the risk associated with them in the form of integral dependence; volatility parameters and the level of risk, using methods of heuristic analysis and fuzzy logic. Improved: the method of calculating the seaworthiness of the vessel due to more accurate determination of the zones of dangerous side rocking, slamming, flooding and loss of speed in irregular waves; a two-level system for evaluating the effectiveness of route planning and ship management in stormy conditions using methods of fuzzy logic and risk assessment.

In the doctoral thesis [13], in the part of storm sailing, the author considered the forces and moments acting on the vessel's hull, mathematical modeling of the vessel's rocking (chapter 3) and simulation of stability in real time on waves (chapter 4). A conclusion was made regarding the expediency of using different models depending on the navigational task, namely: a linear model of vessel rocking in 6 degrees of freedom, which is advisable to use for calculating amplitude-frequency characteristics in the linear range, for estimating rocking amplitudes, optimizing the vessel's route, when designing channels and fairways, when planning vessel operations at shallow depths; a non-linear model of vessel sway in 6 degrees of freedom, which is used for modeling dynamics in studies of stability, parametric resonance, broaching, etc.

In the article [14] investigated issues of parametric roll on regular excitation. Parametric roll is a dangerous phenomenon that can lead to a sharp increase in the amplitude of oscillations at the frequency of the external influence, which coincides with the frequency of the vessel's own oscillations. The problem was investigated experimentally on a typical Norwegian fishing vessel with a blunt hull and a small ratio of length to width, as well as using numerical simulations. Tests were performed without and with longitudinal velocity, with corresponding Froude numbers $F_n = 0.09$ and $F_n = 0.18$. Nonlinearities in Froude-Krylov loads and recoverable loads were taken into account by integrating the pressure on the instantaneous wetted surface of the hull. It was found that near the instability boundary of the Mathieu 1-DOF diagram, the physical and numerical predictions were different in terms of the appearance of parametric roll. The limits of instability in the experiment also differed from the limits of instability of the 1-DOF Mathieu diagram. The instability region for the 6-DOF experiments and simulations spans a wider range of frequency ratios, and the metacentric height change amplitude threshold was found to be lower than that predicted by the 1 DOF Mathieu diagram. The results also showed that the region of instability, in the presence of speed, shifts towards smaller ratios of frequencies of natural and forced oscillations.

According to the authors of the article [15], container shipping accounts for 52% of the world's total maritime trade, and safe container shipping practices are paramount in maritime trade. Between 2008 and 2016, about 568 containers were lost annually in accidents and about 1,582 containers in disasters. This led to disruptions in major supply chains. The most common and most dangerous phenomenon that causes the loss of containers is the parametric rocking on the oncoming and traveling wave, which arises as a result of the dynamic instability of the vessel. The container ship APL China suffered the most damage due to parametric rocking (406 containers were lost and 1000 were damaged, the amount of damage was 100 million dollars). This incident led to the revision of the IMO Code on the Stability of an Intact Vessel and the Master's Guide for Avoiding Dangerous Situations in Adverse Weather Conditions. The causes of parametric roll are periodic (with a period twice the period of the oncoming wave) changes in the metacentric height during the movement of the ship across the waves. Parametric roll is also facilitated by special hull shapes (use of extended sides in the front of the hull, etc.). The authors of the article, in the MATLAB environment, investigated the influence of various parameters (wave height, wavelength, and ship speed) on the parametric resonance of a specific container ship. The enveloping stability curve for counter and accompanying excitation is determined. Damping effects are taken into account when evaluating the range of metacentric height change.

In the article [16] considered the issues of choosing the optimal route of a sea vessel, building universal storm charts that would allow avoiding the dangers of stormy navigation and ensure proper seaworthiness in difficult weather conditions. In the Excel program, a universal storm diagram was built, the zones of synchronous and parametric resonances, broaching were calculated, and the ship's speed was estimated on waves. The safest and most efficient route of the ship in stormy sailing conditions is chosen. A comparison of the behavior of the ship model, calculated according to the considered scheme, and the behavior of the real ship was made. It has been found that the danger zones shown on the chart agree well with the danger zones obtained by observation on the vessel. The simplicity and availability of the method of choosing the optimal combinations of course and speed while sailing in stormy weather conditions has been proven.

In the article [17] stated that the conditions for the occurrence of chaotic roll are most likely in the zone of the main parametric resonance, when its period is successively doubled, and subharmonic oscillations turn into chaotic ones. This circumstance necessitates a detailed study of the modes of parametric roll: issues of its occurrence, development and establishment, as well as methods of calculating its amplitudes. In the paper, the research of parametric roll was carried out on the basis of Luhovsky's formula. Additional nonlinear moments obtained using the small parameter method are taken into account. The results of parametric roll calculation for five different vessels moving at different course angles both with and without taking into account nonlinear moments are presented. The obtained results showed a significant influence of nonlinear moments on the maximum amplitudes of parametric roll, especially in the case of beam waves.

In the work [18] investigated parametric vibration and combined resonance of a turbine blade under the action of parametric and forced excitation. The blade is modeled as a rotating beam taking into account centrifugal, gyroscopic and bending-torque forces and moments. The region of instability of a linear system with parametric excitation is analyzed using the Floquet theory, the influence of blade parameters on the region of instability is discussed. Parametric oscillation in the torsion channel caused by parametric excitation in the bending channel was found. The results showed that the size and position of the resonance region depend on the aspect ratio of the blade and its installation angle. A multi-scale method is used to study the combined resonance caused by forced excitation and a gyroscopic element. The influence of blade parameters and excitation characteristics on the regions of combined resonance was studied. It was established that the change in the excitation frequency caused the phenomenon of heteroclinic bifurcation, as a result of which the harmonic components accompanying the bifurcation changed. The multi-period characteristic, in which the excitation frequency and subharmonic components predominated, shifted to the single-period characteristic, in which the subharmonic components predominated. The conducted research gives a theoretical explanation of the non-synchronous resonance of blades and subharmonic signals in the vibration of blades, allows to determine the design parameters of blades, especially for wind turbines.

The human factor plays a significant negative role in ship management, especially in stormy conditions. In order to reduce the influence of the human factor on control processes, work [19] considered the issues of automated identification of the shipmaster's condition and the formation of warning messages. At the same time, according to the authors of this article, the most effective way to reduce the influence of the human factor on management processes is the use of automatic modules in automated systems. Articles [20,21] consider the issue of using such modules to optimize control processes in bottlenecks, and article [22] considers the issue of automatic control of redundant structures of executive devices.

From the given overview of literary sources, it is possible to see a range of issues that have been solved by the authors recently. However, the authors of this article did not find methods of automatic avoidance of parametric resonance. Therefore, conducting such research is an urgent scientific and technical task.

3. Methods and materials

The IMO documents and the works of a number of authors describe the causes of parametric resonance - the coincidence of the change period in the vessel's metacentric height with the period of forced oscillations in the roll channel. The differential equation of the angular motion of the vessel in the roll channel can be written in the form

$$(I_x + \lambda_{44})\dot{\omega}_x = -M_x(\omega_x) - M_x(\theta) + M_x(t), \tag{1}$$

where I_x is the axial inertia moment in roll channel, λ_{44} is the inertia moment of the attached mass of water, $M_x(\omega_x)$ is the damping moment, $M_x(\theta)$ - is the restoring moment, $M_x(t)$ is the moment of external influences of wind, current and turbulence, ω_x is the angular rate in the roll channel, θ - is the roll angle.

The linearized equation (1) will have the form

$$(I_x + \lambda_{44})\dot{\omega}_x = -\frac{\partial M_x(\omega_x)}{\partial \omega_x}\omega_x - \frac{\partial M_x(\theta)}{\partial \theta}\theta + M_x \sin \Omega t, \tag{2}$$

where $\frac{\partial M_x(\omega_x)}{\partial \omega_x}$ is the coefficient of the damping moment in the roll channel, $\frac{\partial M_x(\theta)}{\partial \theta}$ is the coefficient of restoring moment, M_x is the amplitude of external influence, Ω is the frequency of external influence.

Taking into account that $\omega_x = \dot{\theta}$, $\dot{\omega}_x = \ddot{\theta}$, equation (2) will be rewritten in the form

$$\ddot{\theta} + \frac{1}{(I_x+\lambda_{44})}\left(\frac{\partial M_x(\omega_x)}{\partial \omega_x}\right)\dot{\theta} + \frac{1}{(I_x+\lambda_{44})}\left(\frac{\partial M_x(\theta)}{\partial \theta}\right)\theta = \frac{M_x \sin(\Omega t}{(I_x+\lambda_{44})}. \tag{3}$$

After entering the markings

$$\frac{1}{(I_x+\lambda_{44})}\left(\frac{\partial M_x(\omega_x)}{\partial \omega_x}\right) = m_x^{\omega x} = 2\varepsilon_D,\ \frac{1}{(I_x+\lambda_{44})}\left(\frac{\partial M_x(\theta)}{\partial \theta}\right) = m_x^{\theta} = \omega_0^2,\ \frac{M_x}{(I_x+\lambda_{44})} = m_x,$$

the differential equation (3) will take the form

$$\ddot{\theta} + 2\varepsilon_D\dot{\theta} + \omega_0^2\theta = m_x \sin\Omega t. \tag{4}$$

The differential equation (4) is an oscillatory chain, where ε_D is the damping decrement and ω_0 is the frequency of the natural oscillations. The occurrence of parametric resonance is related to the harmonic change of the parameter

$$m_x^{\theta} = \omega_0^2 = \frac{1}{(I_x+\lambda_{44})}\left(\frac{\partial M_x(\theta)}{\partial \theta}\right) \tag{5}$$

due to the presence of a harmonic component in the restoring moment coefficient

$$\frac{\partial M_x(\theta)}{\partial \theta} = \overline{M}_x^{\theta} + \Delta M_x^{\theta}\sin\omega t, \tag{6}$$

where $\overline{M}_x^{\theta}$ is the average value of the restoring moment coefficient, ΔM_x^{θ} is the amplitude of the harmonic component of the restoring moment coefficient, ω is the frequency of the harmonic component of the restoring moment coefficient. Taking (5) into account, equation (6) can be written in the form

$$\begin{aligned} m_x^{\theta} &= \overline{m}_x^{\theta} + \Delta m_x^{\theta}\sin\omega t \\ \omega_0^2 &= \overline{\omega}_0^2 + \Delta m_x^{\theta}\sin\omega t \end{aligned}, \tag{7}$$

Equation (4) can be rewritten in the form

$$\ddot{\theta} + 2\varepsilon_D\dot{\theta} + \left(\overline{\omega}_0^2 + \Delta m_x^{\theta}\sin\omega t\right)\theta = m_x \sin\Omega t \tag{8}$$

The component $\Delta m_x^{\theta}\sin\omega t$ is the cause of parametric resonance. Figure 1 shows the result of modeling the differential equation (8) for $m_x = 0$.

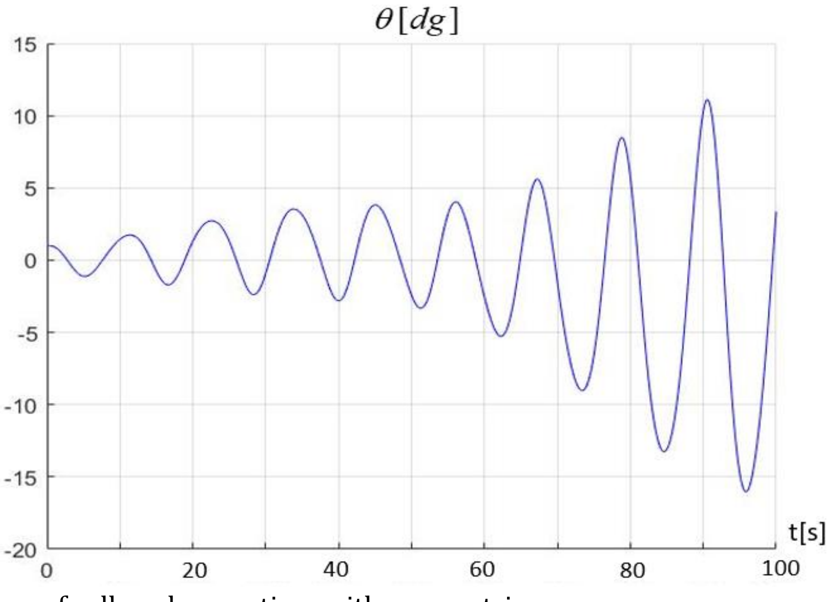

Figure 1: Change of roll angle over time with parametric resonance

As can be seen from Fig. 1, even in the absence of external influences ($m_x = 0$), a harmonic change in the component $\Delta m_x^{\theta} \sin \omega t$ of the restoring moment can lead to swaying of the roll angle (parametric resonance). The possibility of swinging depends on the value of the damping coefficient and the amplitude of the harmonic component of the restoring moment.

The condition for the occurrence of parametric resonance is the coincidence of the period of forced oscillations T_E with the period of natural oscillations T_C of the vessel in the roll channel, or the coincidence of the period of forced oscillations T_E with half the period $\frac{T_C}{2}$ of natural oscillations of the vessel

$$\begin{cases} T_E = T_C \\ T_E = \dfrac{T_C}{2} \end{cases} \tag{9}$$

The period of forced oscillations can be written in the form

$$T_E = \frac{\lambda}{C + V\cos q}, \tag{10}$$

where λ is the wavelength, $C = 1{,}25\sqrt{\lambda}$ is the speed of wave propagation, V is the vessel's speed, q is the course angle of the wave.

Taking formula (10) into account, system (9) can be rewritten in the form

$$\begin{cases} V\cos q = \left(2\dfrac{\lambda}{T_C} - 1{,}25\sqrt{\lambda}\right) \\ V\cos q = \left(\dfrac{\lambda}{T_C} - 1{,}25\sqrt{\lambda}\right) \end{cases} \tag{11}$$

Equations of system (11) determine the regions of parametric resonance of the first and second type in the "Vsinq-Vcosq" coordinate system. In fig. 2 shows the areas of parametric resonance for the period of the vessel's natural oscillations $T_C = 12.5\,s$ and the wavelength $\lambda = 90\,m$.

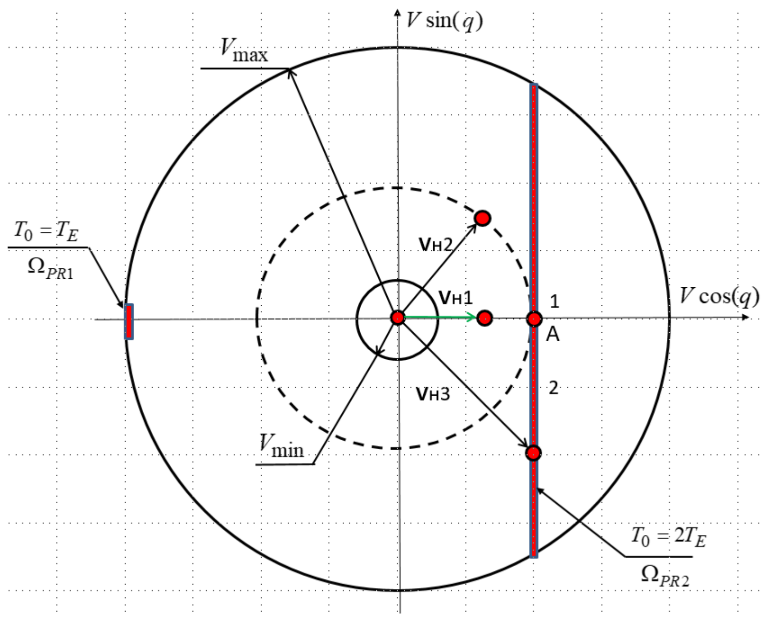

Figure 2: Areas of parametric resonance

As can be seen from the given diagram, the regions of parametric resonance are elongated along the Vsin(q) axis. The most dangerous option is to remove the phase point A from the area of parametric resonance by a combined maneuver (velocity vector Vn3), when the phase point moves along the resonance zone. When maneuvering the course (velocity vector Vn2), the phase point A will move along the circle depicted by the dashed line. In this case, the time the phase point stays in the resonance zone is significantly reduced. The optimal speed maneuver (velocity vector Vn1) is when the phase point moves along the Vcos(q) axis and is removed from the resonance zone by the shortest path.

In fig. 3 shows a fragment of the module for creating controls in the MATLAB environment.

```
25   T0=cc(5);
26   xz(1)=cc(46);          %set speed
27   xz(9)=cc(54);          %set course
28   xz(11)=cc(56);         %set lateral displacement
29   TE=xm(13)/(xm(1)*cos(q)+1.25*sqrt(xm(13))); % imaginary period
30   if (abs(TE-T0)<delT1 or abs(2*TE-T0)<delT2) % resonance condition
31   xz(1)=0.2*xz(1);
32   end
33   %projections of the ship's speed in the basic coordinate system
34   vnxg=xm(1)*cos(xm(9))-xm(2)*sin(xm(9));
35   vnyg=xm(1)*sin(xm(9))+xm(2)*cos(xm(9));
36   %PID controller settings
37   k(1)=2.0;
38   k(2)=5.0;
39   k(3)=0.001;
40   k(4)=0.0;
41   k(5)=0.0;
42   k(6)=0.0;
43   %determination of angular and lateral deviations
44   Dpsi=xm(9)-xz(9);
45   intDpsi=intDpsi+Dpsi;
46   Dy=xm(11)-xz(11);
47   intDy=intDy+Dy;
48   %determination of controls for working out angular and lateral deviations
49   sig1=k(1)*xm(6)+k(2)*Dpsi+k(3)*intDpsi;
50   sig2=k(4)*vnyg+k(5)*Dy+k(6)*intDy;
51   delta=sig1+sig2;
52   teta=(pi/2)*(xz(1)/Vmax)^2;
```

Figure 3: A fragment of the control formation module

In rows 26-28, the set motion parameters necessary for the module are transferred from the general data array: the set values of speed, course, and lateral displacement. In line 29, the imaginary period of the wave is calculated. In rows 30-32, the period of the vessel's own oscillations is compared with the calculated imaginary period of the wave and its double imaginary period. If one of the imaginary periods coincides with the period of natural oscillations, the set speed of movement is reduced by 20%. In rows 34-35, projections of the vessel's speed on the axis of the base coordinate system are calculated. In rows 37-42, the gain coefficients of the PID controller are specified. In rows 44-47, the angular and lateral deviations from the specified movement parameters and the integrals of these deviations are calculated. In rows 49-51, the deviations of the stern are calculated to work out the angular and lateral deviations of the vessel from the given values. In row 52, the angle of deviation of the telegraph is determined to ensure the movement of the vessel at a given speed.

4. Experiment

The workability and effectiveness of the method of automatic prevention of parametric resonance are verified by mathematical modeling in the MATLAB environment.

In fig. 4, 5 show the results of the experiments in the form of graphs of the change in time of the ship's movement parameters for the starting point A, Fig. 2. The first and second graphs show the change in time of longitudinal speed $V_x[m/s]$ and longitudinal displacement $X_g[m]$. The third and fourth graphs show the change in time of lateral speed $V_y[m/s]$ and lateral displacement $Y_g[m]$. The fifth and sixth graphs show the change in time of the roll angular rate $\omega_x[dg/s]$ and the roll angle $\theta[dg]$. The seventh and eighth graphs show the change in time of the trim angular rate $\omega_y[dg/s]$ and the trim angle $\psi[dg]$. The ninth and tenth graphs show the change in time of yaw angular rate $\omega_z[dg/s]$ and yaw angle $\varphi[dg]$. The eleventh and twelfth graphs show the change in time of vertical speed $V_z[m/s]$ and draft $T[m]$.

The first experiment. The initial parameters of the movement of the vessel and the wave correspond to the p. A of the parametric resonance area, fig. 2: ship course is $K(0) = 0\,dg$, ship speed is $V(0) = 2.5m/s$, wave course is $K_W = 180\,dg$, wave speed is $C = 11.9m/s$. The control system maintains the vessel's initial course and speed. The simulation results are shown in Fig. 4.

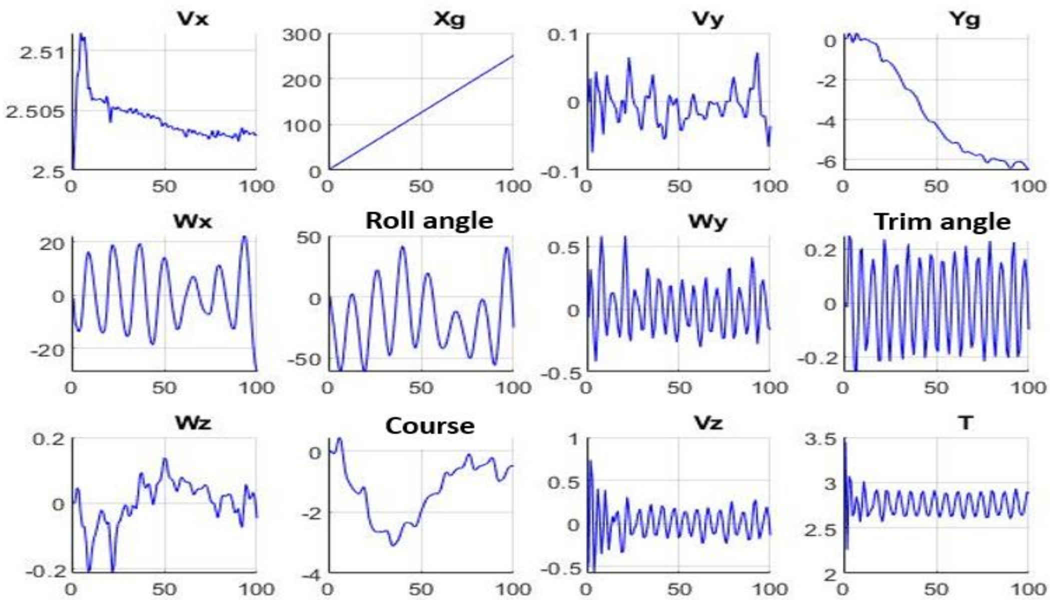

Figure 4: Results of the first experiment

As can be seen from the results of the experiment, the period of forced oscillations is ~ (6-7) s., which can be seen from the period of the vertical speed oscillations V_z, draft T, trim angular rate ω_y and trim angle ψ. The period of oscillation in the roll of the channel is $\approx 12.5s$, which coincides with the period of free oscillations of the vessel in the roll channel and is twice the period of forced oscillations. In combination with a significant amplitude of oscillations $\approx 50dg$, this indicates the presence of parametric resonance of the 2-nd type.

The second experiment. As in the first experiment, the initial parameters of the vessel's movement and the wave correspond to the p. A of the parametric resonance area, fig. 2: ship course is $K(0) = 0\,dg$, ship speed is $V(0) = 2{,}5\,m/s$, wave course is $K_W = 180\,dg$, wave speed is $C = 11{,}9\,m/s$. The control system constantly monitors the conditions for the occurrence of parametric resonance. The simulation results are shown in Fig. 5.

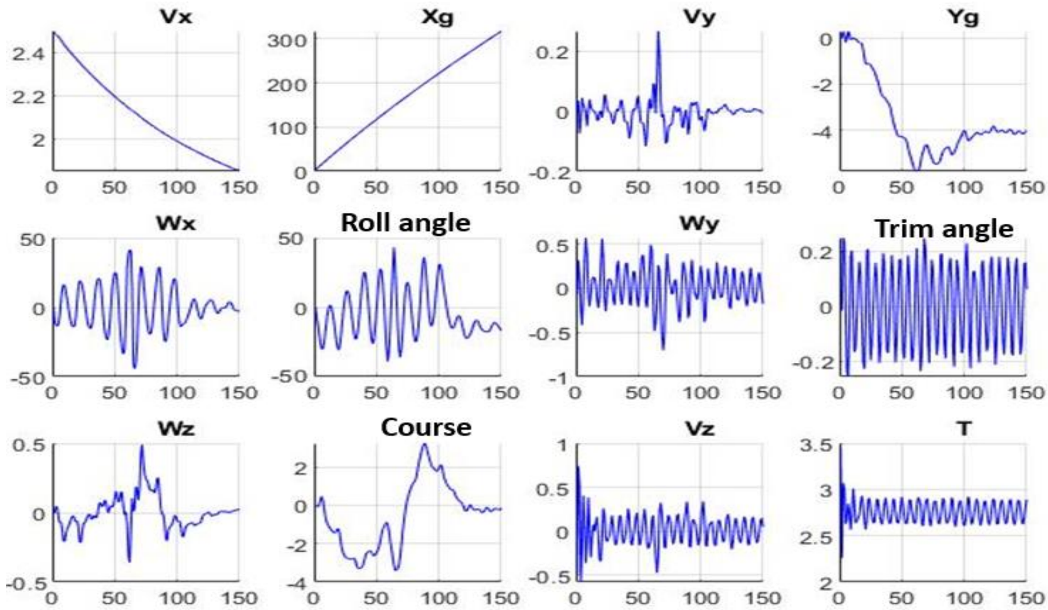

Figure 5: Results of the second experiment

As can be seen from the given results, starting from the time $t = 0\,s$ control system starts to reduce the speed of movement. This is explained by the fact that the initial position of phase point A is in the area of parametric resonance, and to avoid its development, the control system automatically calculated the safe speed and course, which are $V^* \approx 2{,}1\,m/s,\ K^* \approx 0\,dg$ and began to reduce the speed to the calculated safe value. At the same time, the control system maintains a safe course with accuracy $|\Delta K| \le 2\,dg$.

The results also show that during the decrease in speed, an increase in the amplitude of oscillations in the roll channel is observed, which reached a value of $\theta^{\max} \approx 40dg$ by $t = 60\,s$. After $t = 60\,s$, the increase in the amplitude of oscillations stops, and starting from $t \approx 100\,s$, the amplitude of oscillations in the roll channel sharply decreases to the value of forced oscillations, which indicates an exit from the parametric resonance area.

Analysis of the given results shows that the control system allows to automatically calculate the safe parameters of the vessel's movement and support them when deriving the phase point from the parametric resonance area.

5. Discussion

A method of automatic avoidance of parametric resonance has been developed, which consists in: constant, with the on-board computer, measuring the speed and course of the vessel, the length and course of the wave, the roll angle; using the measured parameters to calculate the imaginary period of the wave; construction and visualization of parametric resonance area; construction and visualization of the position of the phase point in the coordinate system of parametric resonance areas; estimation of the phase point position relative to the areas of parametric resonance; calculating the safe speed and course of the vessel when the phase point approaches the area of parametric resonance; changes in current speed and course by safe means of the automatic control system.

The developed method differs from existing manual control methods in that it automates manual control processes, reduces delays in decisions, reduces the influence of the human factor on control processes, reduces crew fatigue, reduces the risks of vessel and cargo loss, and generally improves shipping safety.

The developed method can be used for both manual and automatic control. In the manual control mode, the shipmaster has the opportunity to use automatically measured information and the results of its processing - visualization of parametric resonance areas and the position of the phase point for making management decisions. In the automatic control mode, the system itself calculates and implements safe movement parameters, and the shipmaster only observes its operation.

The obtained results are reproducible and can be used to develop functions of automated systems and automatic parametric resonance avoidance modules.

6. Conclusion

A method of automatic avoidance of parametric resonance has been developed, which allows automating vessel control processes when parametric resonance occurs, reduces the influence of the human factor on control processes, reduces decision-making time, reduces risks of vessel and cargo loss, and generally improves shipping safety.

The obtained results are explained by the use of an on-board computer, constant, with the clock of the on-board computer, measurement of the vessel's movement parameters and waves, calculation of parameters inaccessible to direct measurement, construction and visualization of parametric resonance areas and the position of the phase point in the coordinate system of the parametric resonance areas, assessment of the position of the phase point relative to the areas parametric resonance, calculation and implementation of safe vessel movement parameters.

The theoretical significance of the obtained results lies in the development of a method of automatic parametric resonance avoidance.

The practical significance of the obtained result lies in the possibility of applying the method for the development of modules for the automatic avoidance of parametric resonance, which will allow to automate control processes, reduce the influence of the human factor on control processes, reduce delays in making management decisions, reduce the risks of vessel and cargo loss, and generally increase the shipping safety.

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