Control of Functioning Regimes of On-Board Intelligence Systems of Safety Monitoring

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ABSTRACT

The questions of the control of functioning regimes of onboard intelligence system in various operating conditions are discussed. The functioning regimes are developed with use of concept of a climatic spectrum of sea waves. Identification and control of making processes of oscillatory movement of a ship for non-standard (not regular and extreme) situations are carried out on the basis of methods of fuzzy logic. The basic attention is inverted on feature of behaviour of a ship at intensive external disturbance. The examples of modelling of rolling regimes of a ship at influence of packages of irregular waves are given. The rolling regimes are allocated at forming the attractor sets in the form of unstable limit cycles.

KEYWORDS

Fuzzy logic; safety monitoring; intelligence system; attractor; limit cycle; stability; rolling

PROPOUNDING

The problem complexity, the incompleteness and the uncertainty of the source information about behaviour of a ship and "Ship – Environment" system lead us to the necessity of development of computing technology that assures real-time data handling with the use of high-performance computing facilities. The basic role in this technology belongs to the data of dynamic measurements acting from sensors of onboard measuring system.

Let's discuss the discrete stochastically disturbed system with r-dimensional input space. At the point of time t system output are column vectors $\theta_t, \Psi_t, \ldots, \zeta_t$ of oscillatory movement parameters that determine the result of interaction of the dynamic object and environment in sea conditions. The measurements fix at the discrete points of time 1,2,3,…,t and define the trajectories of parameters that form informational vector in the range T:

$$J = \{\theta_t, \psi_t, ..., \zeta_t, ..., t \in [0, T]\}. \qquad (1)$$

If behaviour of the system is observed from the point of time 1 till the point of time t then vectors can be represented as

$$\begin{aligned} &\theta_t = [\theta(t), \theta(t-1), ..., \theta(1)]^T; \\ &\psi_t = [\psi(t), \psi(t-1), ..., \psi(1)]^T; \\ &... \\ &\zeta_t = [\zeta(t), \zeta(t-1), ..., \zeta(1)]^T, \end{aligned} \qquad (2)$$

where T is transposition operator.

It is necessary to hold the analysis of the situation and to construct the forecast function in the best way displaying the tendencies in change of components of an information vector (1) on the basis of data about parameters $\theta_t, \Psi_t, \ldots, \zeta_t$. The critical ranges $\tau = \tau_{CR}$ within the limits of which safe operation of a ship is not provided can be found in the curves of ship oscillatory movement by assigning limiting values $\theta_t^*, \Psi_t^*, \ldots, \zeta_t^*$ of ship characteristics reasoning from maintenance of safety requirements:

$$\tau = \tau_{CR} \; when \, \theta(t_1) \geq \left|\theta^*\right|, \quad \psi(t_2) \geq \left|\psi^*\right|, \ldots, \zeta(t_n) \geq \left|\zeta^*\right|. \qquad (3)$$

The features of ship behaviour at a various level of external disturbance are taken into consideration at the decision of a task on the basis of scenarios of storm development in the established operating conditions. The essential factors defining adverse modes of ship rolling are as a result established and the structure of mathematical model is formed.

SCENARIOS OF STORM DEVELOPMENT

The control of functioning regimes of intelligence system is carried out on the basis of mathematical modelling of extreme situations with the use of a climatic spectrum of sea waves (Lopatoukhin et al, 2000). The classification of frequency-directed spectra is presented in Fig. 1. The approach for typification of spectra of sea waves in frequency range on genetic set of patterns is used for modelling of weather scenarios so that the spectra of each type were geometrically similar and differed just by parameters of the corresponding various wave making conditions (Lopatoukhin et al, 2000). The essence of typification is in relating the records of wave ordinate $\zeta(t)$ to chop, wind wave or hybrid wave. Hence the genetic classification of spectral density of waves comes to typification by truncated or full spectrum moments and associated with them values. In that case any spectral density $S(\omega)$, that is a stochastic function as a result of the averaging, can be represented as a non-random function $S(\omega,\Xi)$ with the set of random parameters Ξ. The described in work (Lopatoukhin et al, 2000) procedure of classification of genetically similar spectra assures the classification of frequency-directed spectra of waves on the basis of on-site data and modelling calculations. These spectra are represented as:

$$S(\omega,\beta) = m_{00} \sum_{p=1}^{N} \gamma_p S_p(\omega,\beta \,|\, \omega_{max}, \beta_{max})^{\sim} \qquad (4)$$

$$\sum_{p=1}^{N} \gamma_p = 1$$

Here m_{00} is the zero moment of a spectrum (a dispersion of choppy surface), γ_p – the weight investment of each wave system into aggregate energy, ω_{max} – the frequencies of spectrum peaks and β_{max} – the corresponding directions of each wave system.

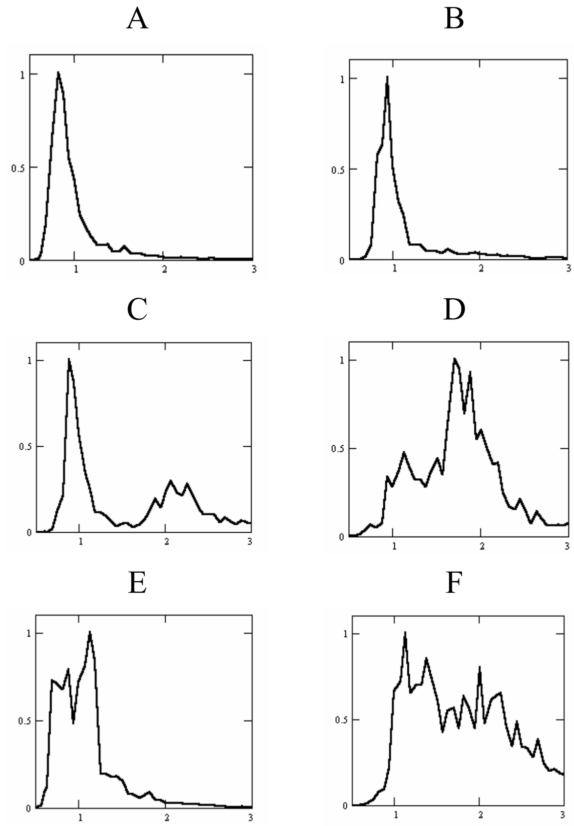


Fig. 1. Typical normalized spectra of sea waves: A – a chop; B – a wind wave; C – a hybrid wave with the split of systems and with the prevalence of a chop; D – a hybrid wave with the split of systems and with the prevalence of a wind wave; E – a hybrid wave without the split of systems and with the prevalence of a chop; F – a hybrid wave without the split of systems and with the prevalence of a wind wave. The vertical axis is the spectral density $S(\omega)/S_{max}$; the horizontal axis is the frequency ω, sec^{-1}.

This approach allows typifying each wave system using five parameters $\{\gamma_i, \omega_{maxi}, \beta_{maxi}, n, m\}$ (here n, m – parameters of spectrum shape).

The model of autoregression of moving average is used in modelling spacio-temporal field $\zeta_W(\vec{r},t)$ of choppy surface of sea waves (Fig. 3). This model is based on the representation of heaving process as a linear dynamic system of order N with the distributed parameters and stochastic input signal (Hayashi, 1968):

$$A[\vec{r},t]\cdot\zeta_W(\vec{r},t) = B[\vec{r},t]\cdot\varepsilon(\vec{r},t)$$

where

$$A[x,t] = \sum_{i=0}^{N} a_i \frac{\partial^i}{\partial t^i} + b_i \frac{\partial^i}{\partial \vec{r}^{\,i}}; \qquad (5)$$

$$B[x,t] = \sum_{j=0}^{M} c_j \frac{\partial^j}{\partial t^j} + d_i \frac{\partial^j}{\partial \vec{r}^{\,j}}$$

are linear differential operators with the autoregression coefficients *(a_i,b_i)* and the moving average *(c_j,d_j)*, and $\varepsilon(\vec{r},t)$ is the field of centralized white noise with the unit variance.

Model parameters are identified by means of Yule-Walker equations using the spacio-temporal correlation function of the ordinates of waves

$$K_\varsigma(x,y,\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_\varsigma(u,v)\cos(xu + yv - \omega(u,v)\tau)dudv \qquad (6)$$

where $E_\zeta(u,v)$ is the energy spectrum in the plane of wave numbers *(u,v)*. This spectrum is connected with the frequency-directed spectrum of waves $S_\zeta(\omega,\theta)=S_\zeta(\omega)Q(\omega,\theta)$ by means of dispersion relation $\omega = \omega(u,v)$ where ω is the frequency and θ is the corresponding direction.

CONTROL OF REGIME SYSTEM FUNCTIONING

The control of dynamics of a ship-environment interaction, danger levels of various disruptions in its behaviour and forming the corresponding criteria is carried out on the basis of methods and models that allow to formalize the range of deviation from the regime of normal operation and to estimate its safety. The information gathered in the process of intelligence system functioning takes on special significance during the solving of this task. Identification of mathematical models that describe non-standard (not regular and extreme) situations is carried out on the basis of statistical analysis of measuring data gained in the operating conditions and within the process of simulation of the ship-environment interaction. Time curves of the investigated processes are represented as (Anderson, 1971),(Kendal et al, 1976):

$$\Re(t_i) = F(t_i) + \Im(t_i) + S(t_i). \qquad (7)$$

Here $\Re(t_i)$ is interpreted as investigated processes $\zeta(t_i),\theta(t_i),\Psi(t_i)$; $F(t_i)$ is a slowly changing function of time (trend)$_i$; $\Im(t_i)$ is the periodic (cyclic) component; $S(t_i)$ is the stochastic component:

$$S(t_i) = \xi(t_i) + \varepsilon(t_i). \qquad (8)$$

where $\xi(t_i)$ is the independent random sequence (noise) with the average of distribution $M[\xi(t_i)]=0$ and the dispersion $\sigma_\varepsilon^2(t_i)$; $\varepsilon(t_i)$ is a sequence of accidental events ("peaks") which represents irregular observations at the random points of time τ_i:

$$\varepsilon(t_i) = \begin{cases} A_i, & if \quad t_i = \tau \\ 0, & if \quad t_i \neq \tau \end{cases} \qquad (9)$$

Here A_i is amplitude of irregular observation considerably exceeding the swing of initial observation series. The sequence of irregular observations forms Poisson flow of events with the parameter λ.

Building of model (7) at experimental data handling comes to identification of analytic representation of each item. It is convenient to use fuzzy methods in the basis of the representation of intelligence system knowledge base as methods of estimation of allowable variation. When formalization of uncertainties the degree of conformity to the regime of normal operation assigns in the form of corresponding fuzzy sets and membership functions (Averkin et al, 1986),(Terano et al, 1983),(Zadeh, 1976). For example, when controlling the frequency of irregular data the estimation of Poisson flow density is used in the form of average frequency of events $\lambda=n_0/T_0$, where n_0 is the number of peaks during observing time T_0 and $\sigma^2(\lambda)=\lambda$. The true value of density lies within the ambit of $\lambda \pm 1{,}96\lambda^{1/2}$ for 95% confidence interval and within the ambit of $\lambda \pm 3\lambda^{1/2}$ for 99,9% confidence interval. These statistical estimations allow to reasonably soundly formalize the representation of fuzzy set $A=\{(x,\mu_\lambda(x))\}$ with the membership function $\mu_\lambda(x)$ assigning the measure of concordance of new density to the density previously determined in the process of information gathering during the operation of intelligence system. If the necessary degree of conformity is assigned as $\alpha\in[0,1]$, then the ambit of allowable variations of irregular data density can be determined. Within the ambit an observed density corresponds to a regime of normal operation. The situation where the new estimation of the investigated parameter λ exceeds the bounds of $\lambda \pm 3\lambda^{1/2}$ may be interpreted as a complete unconformity to the previous state which leads to rebuilding of model and to establishing the reasons of meddling in the normal regime.

The degree of concordance between spectral characteristics and new observations of initial data is defined using a fuzzy set $B=\{(s,\mu(s))\}$ and a membership function $\mu(S)$ of the mean-square deviation of a noise term of new observations and a regime of normal operation with fixed deviation. The small values of membership function define the situation when virtually all peaks around the average represent the stochastic process $\xi(t)$ in (7). In that case the description of a cyclic component of the model $\Im(t_i)$ needs the inclusion of a number of harmonics into the estimating model. Another variant consisting in the increased swing of data oscillation around the average level is related with the necessity of recurring determination of $\xi(t)$ (Fig. 2). The choice of a degree of concordance $\alpha\in[0,1]$ determines the ambit of allowable variations of the investigated parameter S using the equation $\mu(S)=\alpha$. When $S \le S_\alpha$ the spectral characteristic remains changeless (Anderson, 1971),(Domrachev et al, 2006).

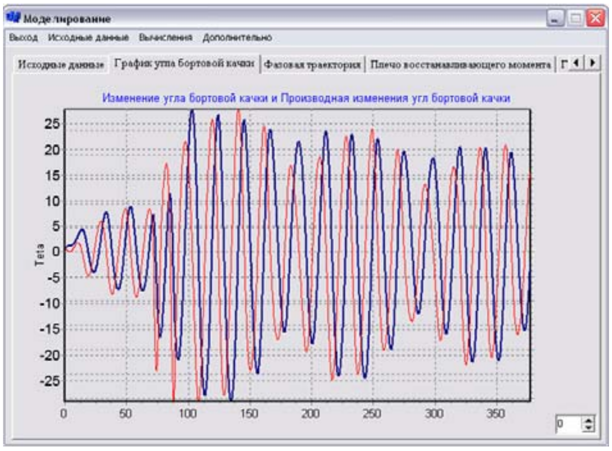


Fig.2. The origin of a considerable amplitude of oscillation as a result of an influence of the large single wave in the structure of random sea.

The reviewed situations of deviation from the regime of normal operation expect the presence of the required information to identification of the model parameters in new conditions. In the absence of new data about the components of forecasting model the work is carried out using an average value $\Re(t_i)^*$ and the mean-square deviation S in a short time after the warning about the inconsistency between the new data and the regime of normal operation. The registration data are considered as a sampling from the entire assembly with the average of distribution $\Re(t_i)^*$ and the dispersion S^2. Used estimations assume that the series of sequential observations is the entire assembly with the same parameter of dispersion S^2 but with new average of distribution. The average of distribution of new assembly is $(\Re(t_i)^* + b)$.

Two situations can be realized as a result of a sudden change with the value b. The first one characterizes by the presence of a sudden change and the situation that is not close to the limiting values ζ^*,θ^*,Ψ^*. In that case the conversion to the regime of current registration and data gathering is carried out in order to adjust the forecasting model. The second situation is close to the limiting values

ζ^*,θ^*,Ψ^* as a result of a sudden change. This situation is described below during the estimation of a danger level of system functioning. The analysis of probabilistic properties shows that the value |b| should exceed S in order to safely determine a sudden change with a confidence level of 0.99. This preliminary statistical estimation allows estimating the measure of concordance between the first situation and the "old" system state. The fuzzy set $C=\{(z,\mu_C(z))\}$ with the membership function $\mu_C(z)$ assigns the measure of unconformity between the new state z and the initial state z_0. The choice of an acceptable measure of unconformity $\alpha\in[0,1]$ allows determining the ambit of acceptable changes of the average level z from an equation $\mu_C(z)=\alpha$. Within the ambit the average value is supposed to be the same; there is no need to recalculate the forecasting model. The situation where the new estimation $z=z_0$ exceeds the bounds of $\Re(t_i)^*\pm 3S$ may be interpreted as a complete unconformity to the previous state which leads to rebuilding of model.

An expansion for the multidimensional case allows turning to the fuzzy estimation of concordance of the situation as a whole (Domrachev et al, 2006). The introduced fuzzy set $D=\{(x,s,z),\mu_D(x,s,z))\},x>0,s>0,z>0$ is specified in the Cartesian product $X\times R\times Y$ with the membership function $\mu_D(x,s,z)$ of a point $(x,s,z)\in X\times R\times Y$. The resulting membership function is the composition of functions of individual fuzzy sets:

$$\begin{aligned}&\mu_D(x,s,z)=\mu_\lambda(x)\wedge\mu(s)\wedge\mu_C(z)=\\&\min_{x,s,z}\{\mu_\lambda(x),\mu(s),\mu_C(z)\}, \qquad (10)\\&\{x\in X, s\in R, z\in Y\}\end{aligned}$$

The choice of measure of concordance $\alpha\in[0,1]$ allows controlling the preservation of normal regime of current data registration during the monitoring of alighting system using the equation (7). If $\mu_D(x,s,z)<\alpha$ then the return to the stage of learning with data analysis in corpore and of building of new forecasting model happens. Dangerous deviations from a stable system functioning are determined on the basis of field experience and analysis of influence on the quality of work of the system. Thus the monitoring is carried out by means of identification of mathematical model with the following control of normal regime parameters, lurking for moments of regime changing, correction and recalculation of the model and its parameters, monitoring the dangerous approach of the regimes to the conditions of loss of information.

SPECIALITY OF ROLLING REGIME

It is significant that the easiest way of solving the safety problems may be achieved during the design process through guaranteeing the rolling amplitudes not exceeding allowable values. At first glance, this approach seems tempting. Really, after achieving the conditions $\theta\leq\theta^*,\Psi\leq\Psi^*,\ldots,\zeta\leq\zeta^*$ there is no need in building complex models and control system dynamics. But in practice, the situations with significant rolling amplitudes that cause disastrous effects may appear. One can't help but remember the tragedy with large container carrier (Nechaev, Dorogov, 2006), which was about 320 meters long. The phenomenon of parametric resonance under the influence of extreme wave packets was discovered as a result of this accident. This phenomenon became the topic of discussion at international conferences on safety for some years. Time curves and phase-plane portraits of oscillatory movement of the ship in an irregular head sea in parametric resonance regime under the influence of a large with a chop-like structure wave packet are shown in Fig. 3. As may be seen at the figure, the amplitude of parametric rolling in this situation increases fast and becomes stabilize around 30^o as a result of an influence of nonlinear effects.

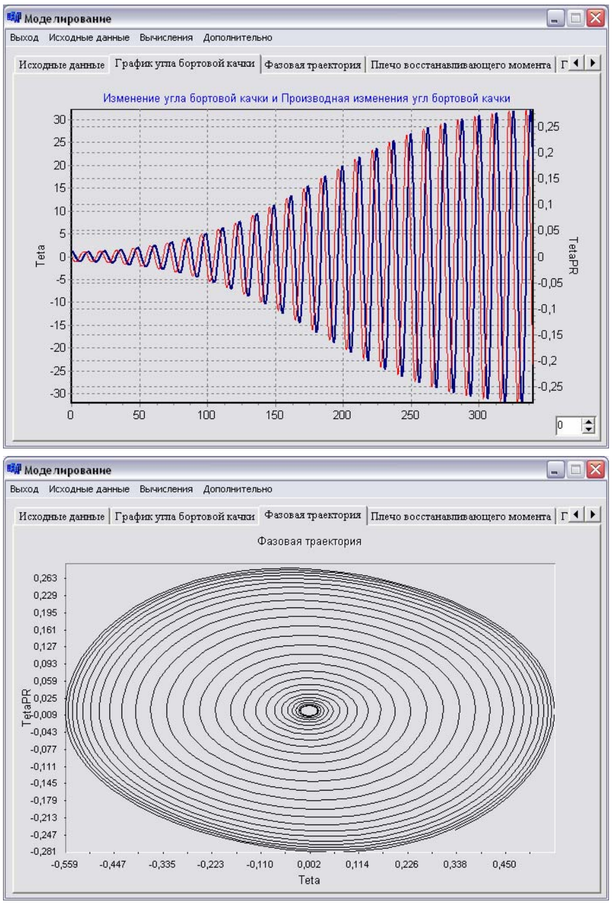


Fig.3. Time curves and phase-plane portrait of the parametric resonance regime during the rolling oscillation of dynamic object.

It is interesting to mention that pitching happens in a regime that is close to the principal resonance. Therefore pitching amplitude can achieve significant values as a result of intensive external disturbance. These values may exceed allowable angles of trim determined by the requirements of navigability. Modelling results of oscillatory movement in the pitching resonance regime are presented in Fig. 4.

The research results of ship oscillation features in the conditions of different structure of wave packets with the small amplitude of disturbance are represented in Fig. 5 (Nechaev, Petrov, 2006).

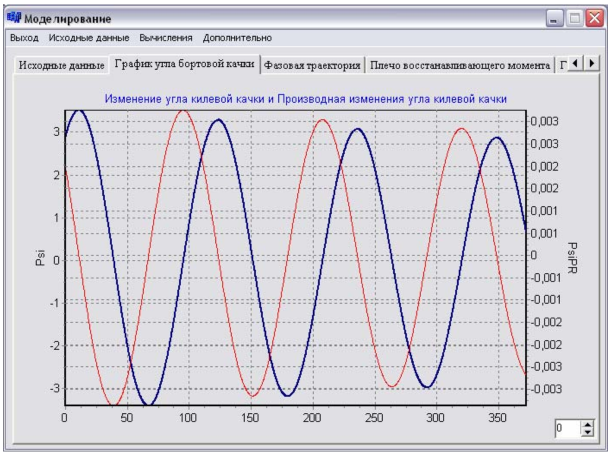
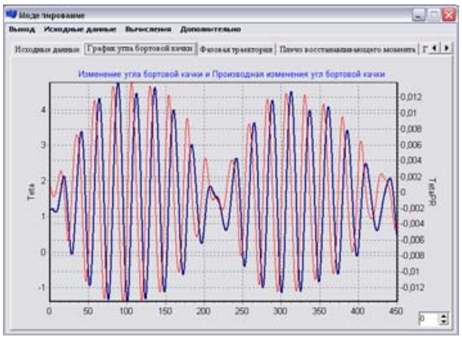


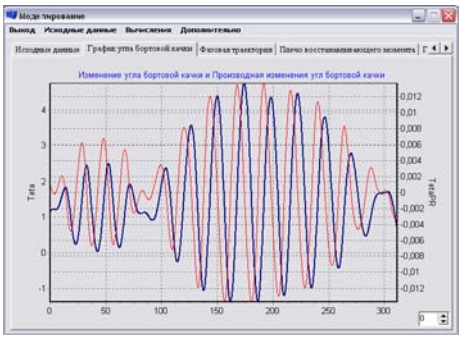
Fig.4. Time curves of the principal resonance regime ship during the pitching oscillation of ship.

Here the upper figures represent time curves of typical cases of oscillatory movement, the lower figures are the corresponding phase-plane portraits. Findings show the building of complex structures of rolling oscillatory regimes during the passing of wave packets. The feature of these structures consists in forming the attractor sets in the form of unstable limit cycles.

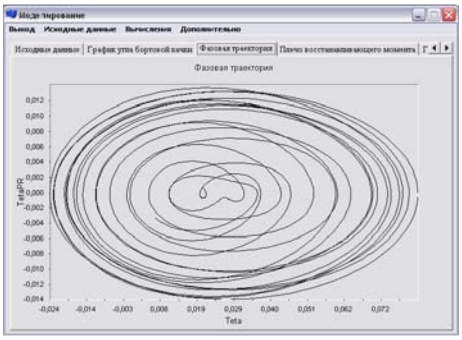
A



B



C



D

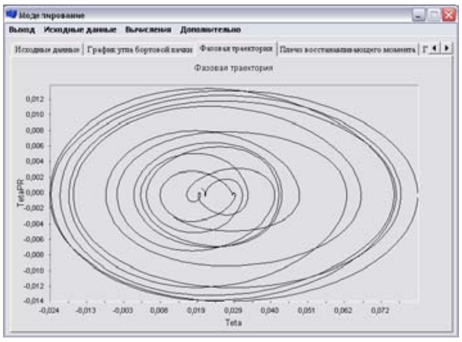


Fig.5. Forming the attractor sets under the influence of wave packets: A, C – time curves and phase-plane portraits under the influence of chop packets; B, D – time curves and phase-plane portraits of sequential influence of wave packets of various densities.

Buckling failure of cycle-attractor in the discussed one-parametric system happens by various scenarios. The interpretation of these scenarios is given in Fig. 6, 7. The easiest scenario is connected with the features of chop packet that forms the limit cycle characterized by amplitude stabilization as a result of nonlinear influence (Fig. 6A). This cycle appears in the area where the wave sequence in a packet exceeds the value $(h_w)_{CR}$ that forms the oscillatory regime with virtually constant amplitude θ_{max}. But the following height decreasing leads to breaking of stability conditions and the cycle disappears (Fig. 6B).

A more complex scenario is the collision with the unstable cycle (Fig. 7). In practice this situation happens much rarely and is characterized by the sequential wave packets consisting of waves with various densities. For instance the first packet with small height of resonance waves leads to forming the limit cycle of small amplitude, and the second one – of big amplitude. An initiation and a buckling failure of oscillatory regime ("the birth and the death of a cycle" by nomenclature of Andronov A.A. (1981)) are the result of the limitation of rolling resonance area in the relatively small range of intense oscillation during wave packets passing.

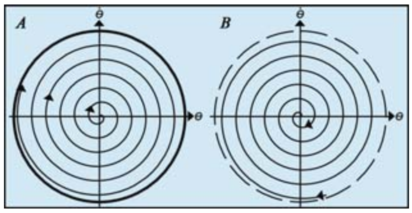


Fig.6. Forming (A is a birth and B is a death) of a limit cycle under the influence of wave sequence.

The indicated features of oscillatory movement should be taken into account during the control and forecast of ship behaviour in extreme situations connected with the execution of marine operations.

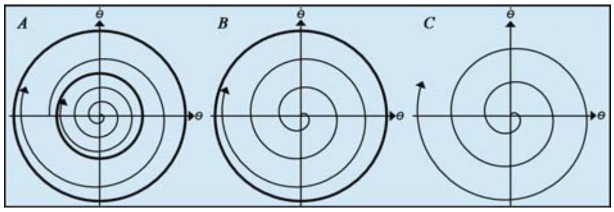


Fig.7. An initiation (A) and a buckling failure (B), (C) of the cycle.

It is interesting to mention that an evolution of parametric oscillations during the limit cycle forming appears more often in wave systems consisting of groups of almost regular waves. In that case initial conditions form by the large modulation depth of the parameter that plays a role of the multiplier of periodic function of the Mathieu equation (Hayashi, 1968). These conditions assure an overcoming of the "excitation threshold" of parametric resonance. As a result the initiation and evolution of parametric oscillations are registered even on the waves of relatively smaller steepness.

The comparison of the topology of phase space for nonlinear mathematical model and the topology of phase space for linearized mathematical model was made during the process of calculating experiment. Findings show the practically impossibility of saving the phase streams which generate strange attractors and determinate chaos in the linearized systems.

CONCLUSION

The research allowed building the mathematical control model of the features of intelligence system functioning under the influence of various external disturbances determined by the scenarios of storm development. The modelling strategy is based on the notion of climatic spectrum of sea waves. An analysis of dynamics of a ship-environment interaction, danger levels of various disruptions in its behaviour and forming the corresponding criteria are carried out with the use of methods of uncertainty formalization on the basis of fuzzy logic.

Thus, a new paradigm of information processing in dynamic environment consists in the rational organisation of calculating technology. An inclusion of fuzzy models into the informational basis allowed widening the functional capabilities of calculating system and increasing the validity of taken decisions in extreme situations. The various scenarios of attractor sets initiation connected with the complex nonlinear interaction between the ship and an environment in the conditions of irregular waves were determined as a result of the analysis. The most typical scenario is forming the unstable limit cycle. The laws of phase path behaviour in the conditions of instability are assumed as a basis of the development of a dynamic knowledge base realizing the forecast and the interpretation of extreme situations in onboard real-time intelligence systems. The developed methods and algorithms of their realization can adapt to the varying external conditions and recognize the "templates" (cause-and-effect relations) of each process under control. This continuous self-instruction process allows the intelligence system to accumulate information on the interaction dynamics and to forecast the deviation of parameters from the regime (allowable) values.

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