EVOLUTION OF ANALYSIS AND STANDARDIZATION OF SHIP STABILITY: PROBLEMS AND PERSPECTIVES

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ABSTRACT

This paper describes the research and development in the field of ship stability in waves, including works from more than 50 years of the author's experience. The first works of the author on stability were submitted to IMO in 1965, regarding development of stability regulations for fishing vessels.

1. INTRODUCTION

Analysis of the behavior of a ship under action of external forces in various operational conditions is one of the most complex problems of dynamics of nonlinear systems. Extreme situations present an especially difficult challenge. All of the mathematical models describing the behavior of a ship in waves have a similar structure; all of them are nonlinear. Weak nonlinearity is a relatively well-studied area of a ship dynamics. General methods for obtaining solutions and effective algorithms for practical applications exist. The methods for the analysis of ship stability in waves are based on more complex mathematical models and advanced computational methods, due to the nonlinearity of these problems.

The analysis of nonlinearity allows insight into the problem and the ability to construct a general theory describing ship behavior as a nonlinear dynamical system for the control and forecasting of stability changes in various conditions of operation. The in-depth research of ship dynamics in waves requires understanding of physical laws, effects, and phenomena. New methods and concepts are developed, along with experimental research using radio-controlled models of ships in natural waves.

2. PHASES OF STABILITY RESEARCH

The research of ship stability in waves is complemented by the development of intelligent decision support systems [1]-[61]. More frequently these applications use artificial intelligence [31]-[47]. These technologies are focused on the process chain: modeling-forecasting-decision-making using complex integrated intelligent systems (IS). The analysis of "informational snapshots" of the investigated situations allows one to formulate the basic principles determining "latent" information processes. Currently new approaches for intelligent technologies, including non-algorithmic control which is naturally parallel and non-deterministic, are under development [51].

The period of development of the studies about ship stability is marked by a change of paradigms as shown in Fig. 1.

Theoretical-experimental paradigm marks the beginning of research on ships stability in waves. At this stage, the basis of experimental and theoretical methods occur within the framework A. N. Krylov's hypothesis- the ship does not affect the wave [17]. The main attention here is given to the development of theoretical models for the description of the righting moment and estimation of dynamic roll of a ship in waves [9], [10]. Physical pictures of roll and capsizing ships from experimental research with radio-controlled models of ships with natural waves were also used [23], [24]. The basic scientific result of the research was the determination of critical situations for a ships in waves (complete loss of stability, low-frequency resonance, broaching) and justification of the necessity for theoretical models of dynamics to account for nonlinear wave interference components — for ships with small L/B ratios having high Froude numbers. The generalization of the results using physical models allowed the author to develop linear regression formula (submitted in IMO in 1965 [22]), describing the function of the righting moment for a preliminary estimation of stability in waves. The main works of Russian researchers this paradigm, were performed within 1960-1970. The theoretical-experimental paradigm was implemented on the basis of digital and analog computers with serial processing.

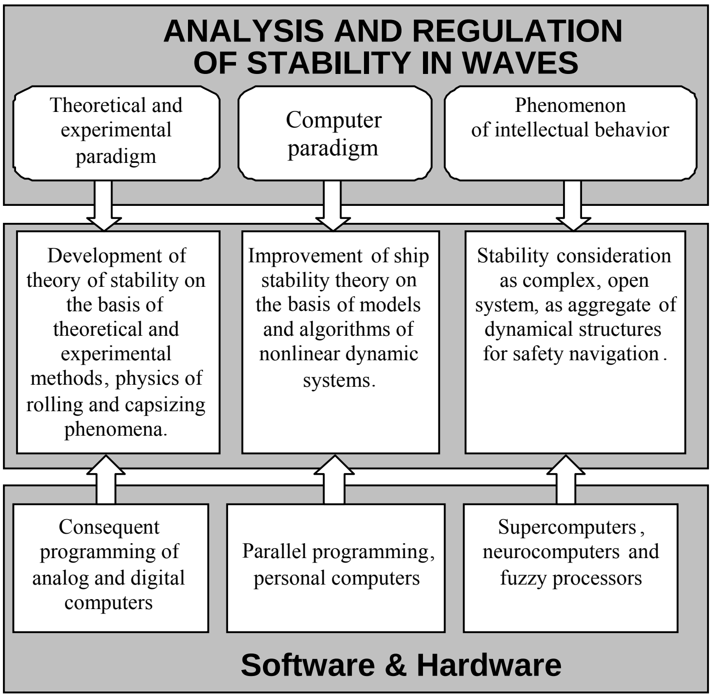

Figure 1. The approaches to paradigms for information processes for research of ship stability in waves.

Computer paradigm, where the majority of works on ship dynamics in waves is currently carried out in Russia, is connected to the further development of stability theory using methods and models of research of nonlinear dynamical systems (ex. Fokker-Plank-Kolmogorov equation, method of Monte-Carlo, method of moments, phase plane, catastrophe theory), and also using modern methods of data processing of physical experimental data with fast algorithms.

Most of the principle advancements in ship dynamics in waves were achieved within the frames of this paradigm (works performed during 1971-1995). Development of software and analysis procedures for ship stability in waves was the most important part of these works; with the particular emphasis on probabilistic models and criteria. [11], [23], [24], [50]. Availability of high-performance computers allowed the author to carry out robust analysis of experimental results and develop a nonlinear regression model describing the spatial function of the righting moment on waves [23], [24]. Different types of bifurcations, including strange attractors and the phenomenon of deterministic chaos were also studied within the framework of the computer paradigm; leading to a better understanding of the behavior of nonlinear dynamical systems describing large-amplitude motions of a ship in waves [25], [49]. Implementation of the computer paradigm is related with processing of information using parallel and network computing.

The phenomenon of artificial intelligence; its application in ship dynamics marked a new paradigm. *Artificial intelligence* is a principle component of on-board intelligent systems (IS) with intended applications for prediction and control of ship motions in waves as well as monitoring of safe navigation [31]-[47]. Development of these systems involves significant difficulties related to formalization of knowledge and very complex computation algorithms. This concept considers stability in waves as a complex, open set of coordinated dynamical procedures that are carried out for analysis of extreme situations with an objective of safe navigation. Implementation of new technology for ship control and the prediction of stability on waves requires extensive use of mathematical modeling and supercomputers [40], [41].

The development of new generation IS with a dynamic knowledge base and a system of adaptation requires reconsideration of general principles of organization and formalization of knowledge of interaction between a ship and its environment, as well as with hardware and software [46]. The requirements of self-training and self-organizing in a continuously changing and fuzzy environment lead to re-examination of the contents of adaptive components of the knowledge base. These requirements also have increased a role of mathematical modeling for prediction of ship behavior in waves as a complex dynamic object (DO). Most of the information here comes from sensors of a measuring system; analysis, prediction and interpretation of extreme situations is carried out on the basis of this information. As a result, problems of integration of information and an analysis of alternatives were revealed. Complimenting the knowledge base with solvers for numerical, logical, and combinatorics problems, enabled the author to achieve significant progress in one of the most complex areas of knowledge engineering – development of methods for processing of information in dynamic environment [16, 51].

The development of new methods of control of information processing gave birth to new generation onboard IS for motion and stability control. The associative approach of this technology allows organizing the process of making decisions for control of a dynamical object by integration of information and algorithms, taking into account restrictions and under-determinate of models. This new paradigm of the control and prediction of ship stability in waves with on-board IS is focused on extreme situations while using a wide variety of mathematical models [37], [46]. The model of an extreme situation is based on direct interaction with the environment; in this context the application of parallel computing is both necessary and natural. This new type of control is based on the measurements from sensors and results of simulation; such an approach considerably changes organization of data processing by the onboard IS, making it distributed and independent of number of processors. A new conceptual approach is underway to substitute non-random and consecutive computational processes; this process is based on models of the current situation and associative self-organizing in parallel computational processes [46].

Thus, the research and development in the area of ship stability in waves allows consideration of a model of ship/environment interaction as a complex holistic open system. One of the main focuses of the analysis is the development of integrated on-board IS, using models based on fuzzy logic and neural networks. It allows development of more flexible systems and adequate description of a phenomenon of ship behavior as complex dynamic object in conditions of uncertainty and incompleteness of the initial information.

3. ANALYSIS AND CRITERIA OF STABILITY OF SHIP IN WAVES. BACKGROUND THEORY AND VALIDATION

Dynamics of the interaction of a ship with environment as a problem of stability in waves generally can be described as follows:

$$\begin{aligned} &\frac{dx}{dt} = f(X, Y, t), \quad x(t_0) = X_0, \\ &F(X, t) \le 0, \quad t \in [t_0, T] \end{aligned} \tag{1}$$

where X is a n-dimensional vector of phase coordinates; Y is a m-dimensional vector stochastic excitations; $F(X, t)$ is the area of phase coordinates corresponding to a safe operation; $f(X,Y,t)$ is a vector-valued function describing the dynamical system and $x(t_0) = X_0$ are initial conditions.

The solution of a problem (1) results in allowable values of output, used for formulation of stability criteria:

$$\begin{aligned} &R_1 \in Q_j, \quad j = 1, \ldots, J; \\ &Q_1 \in \Omega_1 \mid z_1^* < FG_1 < z_j^{**}, \\ &\ldots \\ &Q_1 \in \Omega_J \mid z_1^* < FG_1 < z_j^{**}, \\ &KG_{CR} = KG_{\min}. \end{aligned} \tag{2}$$

Here $\Omega_1, \ldots, \Omega_J$ are the area of possible values of criteria, taking into account uncertainty and incompleteness of the initial information; KG_{CR} — is the critical elevation of a centre gravity of a ship.

Using a concept of KG_{CR}, it is possible to associate probability of capsizing with a probability of a parameter exceeding some allowable value

$$P(Z_G > Z_{CR}) = \int_{\Omega} P(C_1, \ldots, C_k) dC_1, \ldots, dC_k \tag{3}$$

where Ω is the area where variables $C_1, \ldots, C_k$ satisfy the following inequality

$$Z_G(C_1, \ldots, C_k) > Z_{CR}. \tag{4}$$

An alternative formulation of a problem is that the value of KG_{CR} can be exceeded with the given probability P_0:

$$R(Z_G > Z_{CR}) = P_0. \tag{5}$$

Therefore, the problem formulation (1), (2) consists of developing an algorithm for the analysis and judgment of stability in waves with an estimate of correctness of formulation of criteria in the conditions of uncertainty and incompleteness of the initial information.

The following theoretical principles are formulated for the research of ship stability in waves and further development of stability standards. Consider an information operator processing information on dynamics of interaction of a ship with environment. A structure of this operator should reflect the following properties of information flows [26]:

- Relatively small uncertainty in input may be related with significant uncertainty of the output. This uncertainty must be accounted correctly, as the output represents vital stability information.
- Formulation of stability criteria should take into account properties of a ship as dynamical system under external excitation. A normal operating area is around stable equilibria with a corresponding safe basin parameter space. The behavior of system on and in vicinity of the boundaries depends on the physics of the problem. Uncertainty leads to appearance of a “gray” area limited by “safe” and “unsafe” boundaries. Small excursions through the “safe” boundary lead to equally small changes in the state of the dynamical system, while similar

excursions through the “unsafe” boundary lead to a qualitatively different state of the system that is incompatible with safe operation.

Practical implementation of these theoretical principles for setting boundary values for criteria results in difficulties caused by the uncertainty and incompleteness of the input data. The generalized model developed within the framework of this approach allows formal consideration of ship stability in waves, including both analysis and criteria.

Research of ship stability in waves includes consideration of direct and inverse problems. The solution of a direct problem is the transition from a known structure and inputs of a dynamical system to the characteristics of output and stability criteria. The objective of the inverse problem is synthesis; it is transition from the desirable characteristics and known criteria to unknown structure of the dynamical system and characteristics of its components. These models characterize the theoretical *formalized core* of stability regulations.

Formulation of the problems of the control and prediction of stability in waves is inherently related with conditions of uncertainty and incompleteness of the input data. Therefore, the problem of *validity* of the mathematical models becomes the most important. Let $F_i(a),\ \ (i=1,\dots,n)$ be a criterion of validity defined from the analysis of a mathematical model describing a certain type (or types) of ship motions. This criterion is either a function of parameters $a_j,\ \ (j=1,\dots,k)$, or a function of the solution of differential equations. The coefficients of mathematical model a_j, satisfying given parametrical, functional and criteria restrictions, make an allowable area E_a in a space of criteria $F(E_a)$. Setting the accuracy of approximation of parameters a_j as $\varepsilon_j,\ \ (j=1,\dots,k)$, and the accuracy of criteria $\varepsilon_i,\ \ (i=1,\dots,n)$, it is possible to present criterion for the proximity of the data from mathematical modeling to data from physical experiments, which is the criterion of validity of the mathematical model [16]:

$$F=\left(\left\|F_1^P-F_1^E\right\|,\dots,\left\|F_n^P-F_n^E\right\|\right), \qquad (6)$$

where index P stands for calculation and E for experiment.

The approximation of area E_a is necessary for the evaluation of coefficients of a mathematical model with the given accuracy. It is achieved by finding values such as:

$$\min F(a)=F(a^r),\ a\in F(a),\ r=1,\dots,N \qquad (7)$$

under conditions for determining allowable area E_a

$$\left\|F_i^P-F_i^E\right\|\in F_i^{**}. \qquad (8)$$

Here a_1 parameters that are within the boundaries $a_j^*\le a_j\le a_j^{**}$, N — number of experiments; F_i^{**} — allowable criteria limits (level of validity), assigned with account for accuracy of the experiment.

Attempt to make dependences (6)-(8) specific, leads to the following formulation. Let's present mathematical model (1) as local discrete transformation:

$$S_i=\Phi_m(W_i,S_{i-1},V_i)\ , \qquad (9)$$

where S_i is the modeled state of a ship in the *i*-th instant of time; while S_{i-1} is the state corresponding to the pervious instant of time $i-1$; W_i and V_i are variables discriminating state of environment and internal state of the dynamical system in the *i*-th instant of time.

The condition of validity is determined as

$$Y\in S\quad \forall c\in C_m\ , \qquad (10)$$

where S is a domain limiting meaningful behavior of model; C_m is a set of objectives for modeling. For example, if a model of ship motions is linear and its domain of meaningful behavior is limited to relatively small-amplitude motions, it is valid if the objective is a conventional seakeeping analysis.

Development of the model, indeed, includes a choice of the type of the model and its domain. To quantify deviation from a penalty function is introduced:

$$\Phi(Y,S)=\begin{cases} 0 & \text{if} \quad Y\in S \\ \varphi(Y,S) & \text{if} \quad Y\notin S \end{cases}. \tag{11}$$

The discussion in IMO during 1965-67 was focused on the problem of validity of mathematical models of stability and the correct design of physical experiments.

Observed differences between the theoretical and experimental data may be used as criteria of validity with the peak data of motion time history (deterministic or probabilistic expressions for linear or angular motions, velocities and accelerations), as well as the limitation of divergence between time histories of phase trajectories. Alternatively, the applicability of theoretical distributions (Gaussian, Rayleigh, Weibull, etc) can be tested against the empirical data.

The improvement of mathematical models of ship stability in waves can be facilitated by improvement of the theoretical background and experimental technology of hydro-aerodynamic research, the use of effective methods for processing and analyzing experimental results. The validity of mathematical models can be improved by the development of more reliable ways of evaluation of components of these models by better accounting for distortions that a moving vessel introduces into the wave field (interference and diffraction of waves, change of a field of pressure), as well as a more complete description of the spatial and temporary structure of wind air-flows and roll damping forces.

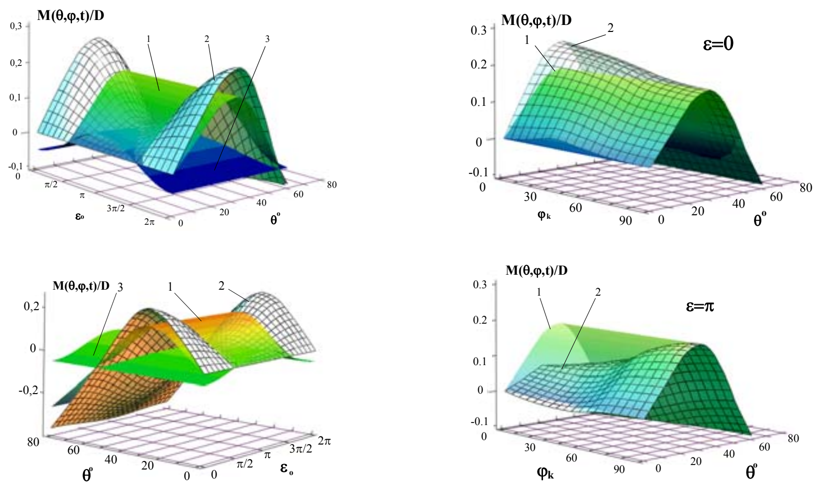

Figure2. Nonlinear function, describe of righting component:
1 – initial function; 2 – transform function; 3 – wave shape.

Mathematical models for stability in waves [9]-[11], [18]-[20], [23], [24] are usually developed for extreme situations. The background of these models is a description of the ship interaction with environment, so it is a nonlinear dynamic system with six degrees of freedom [16]. A specific type of mathematical model is determined by the physics which are observable during experiments. For example, when considering stability in following waves or stability in breaking waves it is enough to use the differential equations of drift and roll. While considering broaching, it is necessary to use a system of at least four differential equations, including the surge, sway, roll and yaw. In more complex situations, it is necessary to formulate hypotheses with all six degrees of freedom included. It is important to include a term describing continually changing stability in waves in the equation of roll motions. The nonlinear spatial function of the righting moment in waves is represented by the following formula: [23], [24]

$$\begin{aligned} M_W &= M(\theta,\varphi,t) = \\ &D[l(\theta,\varphi) + \Delta l(\theta,\varphi)\cos(\sigma_k t - \varepsilon)]; \\ l(\theta,\varphi) &= 0.5[l(\theta,\varphi)_{\max} + l(\theta,\varphi)_{\min}], \\ \Delta l(\theta,\varphi) &= 0.5[\Delta l(\theta,\varphi)_{\max} + \Delta l(\theta,\varphi)_{\min}]; \\ M_W &= \Phi(\theta,\varphi_k,t) = D\,l(\theta,\varphi,t), \end{aligned} \tag{12}$$

where $\Delta l(\theta,\varphi)_{\max}$ and $\Delta l(\theta,\varphi)_{\min}$ are the magnitude of stability changes while the ship is on a wave crest or a wave trough, at various course angles φ; $l(\theta,\varphi)$ is the righting arm determined by interpolation on θ and φ for the various moments of time, ε is the phase of a ship relative to a wave.

The geometric interpretation of function $M(\theta,\varphi,t)$ is given in a fig. 2.

4. METHODS FOR THE ANALYSIS OF NONLINEAR DYNAMIC SYSTEMS IN THE MODELING OF SHIP STABILITY IN WAVES

The research of ship stability in waves as a complex nonlinear dynamic system requires understanding of physics governing the phenomena. These problems are not always can be resolved within the frames of existing concepts and approaches and may require development of the new approaches, methods and models. Nonlinearity is, probably, one of the most important properties of the system, which defines the methods applicable for analysis, such as: method of Monte-Carlo, method of the moments, method of action functional, equation of Fokker-Plank-Kholmogorov, method of a phase plane and theory of catastrophe. These methods are helpful in both the qualitative and quantitative interpretation of complex physical phenomena associated with stability of ship in waves.

The author applied the Monte-Carlo method for stability and roll of a ship in waves in 1975; it is described in the monograph [23]. This method plays a role of a bridge between theory and experiment. Being quite a powerful tool of research in statistical dynamics, the Monte-Carlo method is related with handling rather extensive volumes of data. It requires high speed of computation and a large volume of memory. For the solution of such problems, high-performance computers with parallel data processing technologies are best.

The mathematical model for the application of the Monte-Carlo method is transformed into a dynamical system containing stochastic nonlinear function representing the righting moment. This function can be presented as

$$\begin{aligned} \frac{M(\theta,\varphi,t)}{J_x + \Delta J_x} &= \{1 + \mu(t)\cos[k\,t + \varepsilon_0(t)]\} \times \\ &(\omega_\theta^2\theta - a\,\theta^2\,\mathrm{sgn}\,\theta). \end{aligned} \tag{13}$$

Parameter $\mu(t)$ and phase $\varepsilon(t)$ are considered random variables with normal and uniform distribution, respectively.

$$\mu(t) \in \{M^*[\mu(t)],\ D^*[\mu(t)]\},\ \ \varepsilon_0(t) \in [0, 2\pi] \tag{14}$$

The hypothesis of Gaussian distribution of the process μ(t) is checked by the analysis of the time history of process. The correlation function $R^*_\mu(t)$ of the process $\mu(t)$ is estimated using the data of real sea waves. Calculations show, that the function $R^*_\mu(t)$ can be presented with the following approximation:

$$\begin{aligned} &R^*_\mu(\tau) = \\ &D^*[\mu(t)]\exp[-\alpha(\mu)\,|\,t-\tau\,|]\cos\beta(\mu)(t-\tau), \end{aligned} \tag{15}$$

where $\alpha(\mu)$ and $\beta(\mu)$ — parameters to be found by the calculations.

For modeling the stochastic process $\mu(t)$, the method of forming filters is used in time domain. The parameters of the filter can be found from variance $D^*[\mu(t)$ and autocorrelation function $R^*_\mu(\tau)$.

The filter is described by system of the differential equations:

$$\frac{d\mu}{dt} = -\alpha(\mu)\,\mu(t) + \beta(\mu)\,\nu(t) + \sqrt{2\alpha(\mu)D\,\mu^*}\,W_1(t);$$
$$\frac{d\nu}{dt} = -\beta(\mu)\,\mu(t) - \alpha(\mu)\,\nu(t) + \sqrt{2\alpha(\mu)D\,\nu^*}\,W_2(t), \tag{16}$$

where

$$\begin{aligned}
&M^*[W_1(t)W_1(\tau)] = \delta^*(t-\tau);\\
&M^*[W_1(t)W_2(\tau)] = 0;\\
&M^*[W_2(t)W_2(\tau)] = \delta^*(t-\tau);\\
&M^*[\nu(t)] = 0, \quad M^*[\mu_2(0)] = D\,\mu^*;\\
&M^*[\nu_2(0)] = D\,\nu^*, \quad D\,\mu = D\,\nu;\\
&M^*[\mu(0)\,\nu(0)] = 0.
\end{aligned} \tag{17}$$

Here $W_1(t)$ and $W_2(t)$ are white noise stochastic processes; $\alpha(\mu)$ and $\beta(\mu)$ are parameters of the autocorrelation function; ν(t) is the auxiliary stochastic process; M^* and D^* are operators of mean and variance; δ^* is the delta function.

This mathematical model is a part of practical procedure of modeling the system with the given initial conditions. An important point here is the necessity of formation of the random initial conditions determined by expressions (17). As shown by calculations, the Monte-Carlo method has a number of advantages over other methods of solution (method statistical linearization, theory of Markov processes) for problems of statistical dynamics of nonlinear systems. The principle advantages are compactness of the calculation scheme, stability of results in a case of hardware failure, and a rather simple way to estimate the accuracy of results. Another convenient feature is that there is no limitation on the structure of differential equations as any type on nonlinear terms can be included.

A traditional approach of classical dynamics considers either deterministic (regular) or stochastic (irregular) processes described by the appropriate nonlinear differential equations of roll motions. However, the nonlinear deterministic dynamical system can exhibit chaotic behavior, when phase trajectories that were initially close, become divergent in the limited area of phase space. This phenomenon of the nonlinear system is known as deterministic chaos [25], [49].

Nonlinear dynamics makes a clear distinction between simple (usual) and strange (chaotic) attractors. The simple attractors are encountered quite frequently when describing nonlinear roll and capsizing of a ship on waves. The geometrical interpretation of a simple attractor describing a dissipative system represents on a phase plane either focus or limit cycle. For both these cases, all phase trajectories have a shape of spirals that converge to a stable equilibrium or to steady-state stable cycle. Strange attractors have more complex structure, as they contain both stable (attractors) and unstable (repeller) trajectories. Essentially, they are saddle-type trajectories that are being attractors in one dimension and repellers in another; they form a set of layers connecting to each other in quite complex way.

The works [46], [49] describe the development of parametric resonant motions of a ship caused by passage of group of waves. It is shown, that complex structures of oscillatory roll modes are formed in this case. These structures are sets of attractors looking like unstable limit cycles. The cycle-attractor can lose stability through several scenarios. A passing group of large waves stabilizes the limit cycle described due to the nonlinearity of large-amplitude response (fig. 3). This cycle appears when the wave height in a sequence of waves in a group exceeds the critical value of creating enough parametric excitation to reach practically constant amplitude of response. However, the subsequent gradual reduction of wave heights, breakes the conditions for parametric resonance and the cycle disappears.

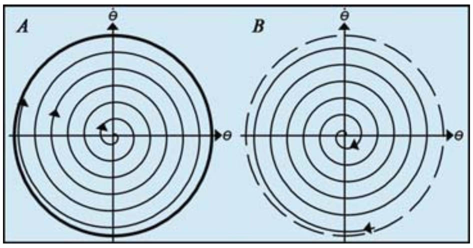

Figure 3. Formation of a limiting cycle caused by of group waves.

A more complex scenario is realized when the stable cycle collides with an unstable cycle (fig. 4). Such a situation is much rarer and it can be generated by a consecutive passage of waves groups containing wave of significantly different height. The first wave group with small heights results in a relatively small-amplitude limit cycle, while the second group generates large-amplitude cycle. Appearance and loss of stability of an oscillatory mode ("birth and death of a cycle" using a terminology by A.A. Andronov) occur due to limitedness of a rolling resonant zone on a rather small time interval where large-amplitude motions are generated by a passage of wave groups.

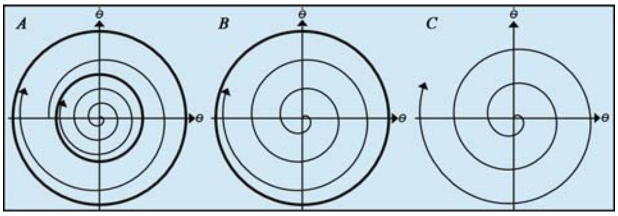

Figure 4. Appearance (A) and of loss of stability of a cycle (B) (C).

The problems and methods of controlled chaos is an area of intensive research in recent decades. In the beginning, the concept of deterministic chaos was considered as an exotic phenomenon that is of interest to mathematicians only; the very possibility of occurrence of chaotic response in practical applications was doubtful. However, later on, chaotic dynamics was found to be present in many dynamical systems across disciplines: in mechanics, laser physics and radio-physics, chemistry and biology, economy, and health science. Systems with chaos demonstrate both good controllability and surprising flexibility: the system quickly reacts to external excitations, while keeping a mode of motions. The combination of controllability and flexibility in part is the reason why chaotic dynamics is a characteristic type of behavior for many dynamical systems describing ship motions in waves.

From the point of view of the synergetic approach, chaotic systems represent possibilities for realization of self-organizing processes. One of the most typical scenarios for the transition to chaos is through a sequence of period-doubling bifurcations, which is observed for systems with viscous friction under action of excitation forces. The research of chaotic behavior of a nonlinear dynamical system describing roll motions was carried out by systematic variation of control parameters. The result was shown on Poincare map, allowing to clearly see the period-doubling and sub-harmonic bifurcation [25], [46]. Another scenarioіs the mechanism of transition to chaotic response, known as *intermittency*, where intervals of deterministic chaos alternate with almost periodic motions (fig. 5).

The Lyapunov exponent is an important tool for study of behavior of chaotic systems. It can be demonstrated with the Duffing equation, which is one of the interpretations of nonlinear rolling [49]. Introduction of the third dimension for the independent variable allows presentation of the Duffing equation as a system of the third order:

$$f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{pmatrix} = \begin{pmatrix} x_2 \\ -x_1^3 - k\,x_2 + B\cos x_3 \\ 1 \end{pmatrix} \quad (18)$$

This system is defined with two positive parameters: coefficient of linear damping k amplitude of excitation B. Negative divergence is also is determined by damping (dissipation)

$$\frac{\partial f_1}{\partial x_1}+\frac{\partial f_2}{\partial x_2}+\frac{\partial f_3}{\partial x_3}=-k<0\,. \qquad (19)$$

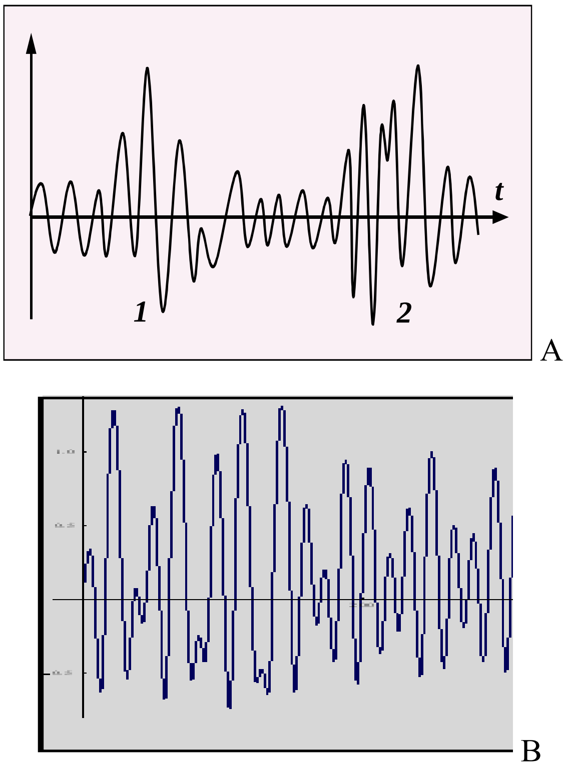

Figure 5. Occurrence of chaos of an alternated type: A – Duffing model; IB – Mathieu model at presence of an initial of heel.

The linearized system (7) leads to the following matrix

$$A=\begin{pmatrix} 0 & 1 & 0 \\ -3x_1^2 & -k & -B\sin x_3 \\ 0 & 0 & 0 \end{pmatrix}. \qquad (20)$$

The results of calculations for $B=10$, $k=0.1$ are shown in a fig. 6. These parameters leads to appearance of chaotic behavior of the system (18), which is confirmed by time histories, phase trajectories, and the Lyapunov exponent [49].

Theoretical development of chaotic dynamics has revealed a series of possible practical applications, including ship motions and stability in waves, where the chaotic responses may be encountered as a result of complex interaction of the ship and environment. Moreover, there are possible practical applications, where the control over nonlinear system is realized by changing a degree of its "chaoticness". Methods for the solution of similar problems have been developed recently, especially for application of different control algorithms for chaotic systems [49].

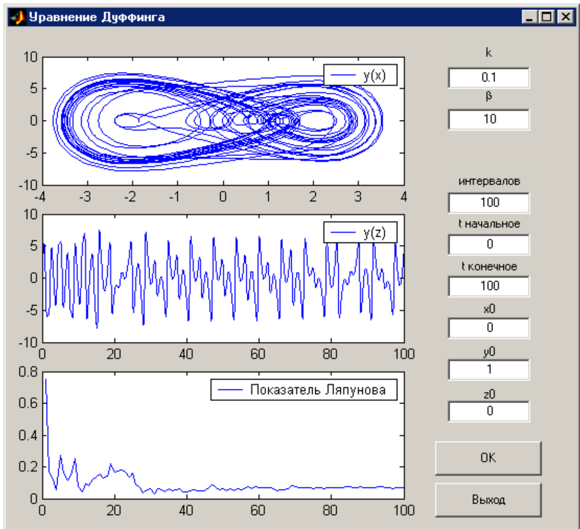

Figure 6. Attractor and Lyapunov exponents for the Duffing equation.

5. ANALYSIS OF EXTREME SITUATIONS AND CONTROL OF SHIP STABILITY IN WAVES

The evaluation and prediction of stability changes for motion control of a ship in waves are carried out using the information from acting sensors [16]. In this case, the extreme situation caused by deterioration of stability can be described in compact set with variable $z\in(1,\,\dots\,,m)$. The analysis produces scenarios for the possible development of extreme situations, taking into account physics of the interaction between a ship and environment. When the probabilities of encounter of extreme situations are estimated, measures of statistical uncertainty have to be evaluated as well. Let number of situations be N, while $M(w)$ is an average estimate, and $D(w)$ is the variance estimate of a value representing possible consequences of the situation.

$$N_j^0 = q_j N^0 \quad (j = 1, \dots, m). \tag{21}$$

where N^0 is the predicted total number of extreme situations for the considered period of time; q_j is the fraction of situations for the *j*-th class in the distribution *F*(*w*), determined on the formula

$$q_j = P(w_{\min j} < w < w_{\max j} . \tag{22}$$

The value q_j is calculated with known distribution *F*(*w*) and its parameters *M*(*w*) and *D*(*w*). The accuracy of the forecast under the formula (21) is characterized by the standard deviation:

$$\sigma[N_1^0] = \left\{ \left(q_j \sigma[N^0]\right)^2 + \left(N^0 \sigma[q_j]\right)^2 \right\}^{1/2}. \tag{23}$$

random deviation $\left(q_j \sigma[N^0]\right)^2$ and $\left(N^0 \sigma[q_j]\right)^2$ included in the formula (23) are determined by statistical processing of results from the mathematical modeling.

The development of an algorithm for the extreme situation prediction is carried out using the information from a measuring system. This information is pre-processed and represents a time-series reconstructed on the basis of the Takens' theorem [49]. According to the Takens' theorem, a phase portrait restored as:

$$\begin{aligned} Z(t) &= \Lambda[y(t)] = [y(t), y(t-\tau), \dots,] \\ y[t-(m-1)\tau] &= [z_1(t), \dots, z_m(t)] \end{aligned} . \tag{24}$$

is equivalent topologically to the attractor of initial dynamic system.

6. METHOD OF ACTION FUNCTIONAL

The search of a universal principle that could help to describe behavior of a dynamic system, has resulted in discovery of a principle "of least action", similar to a principle of "minimum potential energy" that determines the position of equilibria. According to a principle of the least action, the variation problem is a search of a stationary value of the action integral, defined on the interval (t_1, t_2). Responses of the dynamical system corresponding to all possible initial conditions are compared. If the interval of time $(t_2 - t_1)$ is small enough, the action integral has a minimal value as well as the stationary value.

The implementation of the algorithm of functional action for ship dynamics in waves is considered in [28]. The advantages of the method can be summarized as follows:

- use of the information for an external disturbance, received during real-time measurements;
- taking into account significant nonlinearity of a problem for any kind of function – possibility of the solution without use of a priori data on behavior of system and its initial conditions.

Functional action is defined by an asymptotic expression [16], [28]:

$$\begin{aligned} &\lim \varepsilon^2 \ln P_x\left\{X_t^\varepsilon \in \partial D\right\} = -\min S_{0T}(\varphi) \\ &\varphi \in C_{0T}\left(R^{r+n}\right), \varphi_0 = (x, \xi), (\varphi_t)_1 \in \partial D \end{aligned} \tag{25}$$

It allows estimating probability P_x that critical set ∂D (capsizing) will be achieved. This estimation is carried out using optimum control for the stability criteria formulated above. The solution of such problem (25) is given by the main term of logarithmic asymptotic expansion of the probability at $\varepsilon \to 0$.

This approach makes possible the development of new methods for analysis and prediction of behavior of nonlinear dynamical systems in real-time, including stability control in waves. The results of a method of functional action are presented as a probability of capsizing as a function of time (fig. 7A, B). Then interpretation of the results for the given external conditions allows "drawing a picture" of capsizing for a ship in a considered extreme situation. Additionally information on heeling moment leading capsizing can be made available on the screen.

Using the method of the functional action it is possible to evaluate combinations of dangerous speeds and headings relative to waves and present those in a form of a polar diagram (see Fig. 7C)

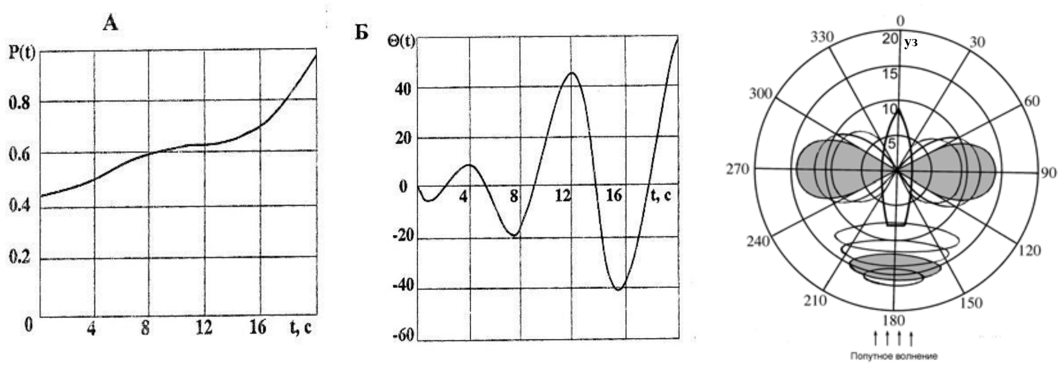

Figure 7. Probability of capsizing as a function of time (A), dynamics of roll of a ship on waves (B) and polar diagram (C).

7. STUDY OF SHIP STABILITY USING CLIMATIC SPECTRA AND SCENARIOS OF EXTREME SITUATIONS

Modelling the environment is one of the most complex problems that need to be solved while developing procedures for onboard IS. Contemporary approaches to the solution of these problems requires new presentations of wind-wave fields in the ocean. These include the conception of climatic officially accepted on 18th Assembly of IMO in 1993 along with the concept "wave climate" [12]. These concepts open the opportunities for more detailed description of waves in different part of the World Ocean.

The hydrodynamic model of waves in the spectral form is represented as the equation of the balance of wave energy:

$$\begin{aligned}&\frac{\partial N}{\partial t}+\frac{\partial N}{\partial \varphi}\dot{\varphi}+\frac{\partial N}{\partial \theta}\dot{\theta}+\\&\qquad\frac{\partial N}{\partial k}\dot{k}+\frac{\partial N}{\partial \beta}\dot{\beta}+\frac{\partial N}{\partial \omega}\dot{\omega}=G\end{aligned}\quad. \qquad (26)$$

Here N is the spectral density of wave action; it is function of latitude φ, longitude θ, wave number k, and the angle between a wave direction and a parallel β, as well as frequency ω and time t. The equation (26) relates inflow of energy from wind, dissipation and redistribution, as well as nonlinear interaction between frequency components of the process. Often, the source function G is written as a sum of three components $G = G_{in} + G_{nl} + G_{ds}$ (incoming energy from wind to waves, weak nonlinear interaction in a wave spectrum, and dissipation of wave energy).

Examples of classification of wave spectra are shown in Fig. 8. There are six classes of spectra: A — swell; B — wind waves; C — combined swell and wind waves systems with prevalence of swell; D — combined swell and wind waves systems with prevalence of wind waves; E — combined swell and wind waves systems without clear division and with prevalence of swell; F — E - combined swell and wind waves systems without clear division and with prevalence of wind waves.

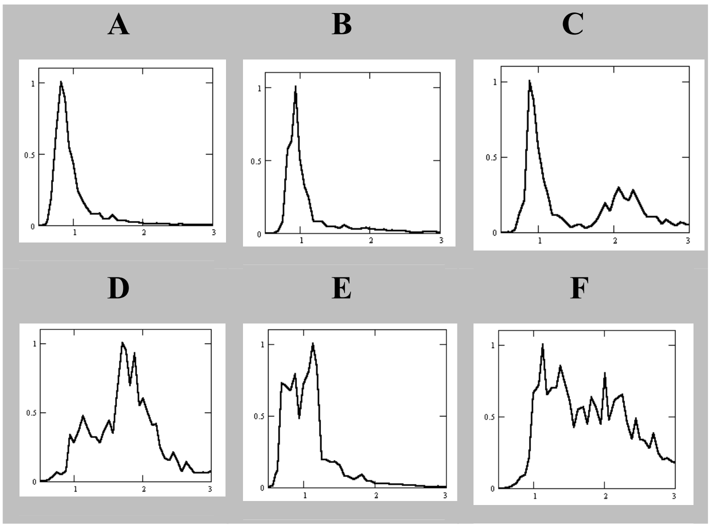

Figure 8. The typical normalized spectra of sea waves; vertical axis is value spectral density $S(\omega)/S_{max}$ and horizontal axis is circular frequency ω, in sec^{-1}.

It is important to note that the standard calculation of dynamics of complex objects in real sea waves is done with a one-peak-spectrum, which may result in a type II error in comparison with climatic spectrum. Therefore, climatic spectra must be used for development of onboard IS, as type II errors may result in catastrophic consequences.

8. PARADOXES OF STABILITY STANDARDS

The concepts of complexity and randomness- are closely related. Simple criteria are often preferred over the complex ones. However, while gaining better understanding of physics of ship/environment interaction, it becomes clear that the problem of a choice of criteria is a very complex one. That's why sometimes that are unexpected results and paradoxes [29].

Paradox of "ideal" norms. It is known, that the guarantee (defined as a probability that failure will not occur if an object satisfies the norms, see also [4, 61]) for any, even most primitive, norms can be made very close to unity (ideal norms), if

$$\frac{1}{y\sqrt{2\pi}}\int_{-\infty}^{0}\exp\left[-\frac{(\varphi-\overline{\varphi})^2}{2y_x^2}\right]d\varphi = 0, \quad y \to 0$$

$$\varphi_i = \left(\frac{KG - KG_{CR}}{KG}\right)100; \qquad (27)$$

$$y = \sqrt{\sum\frac{(\varphi_i - \overline{\varphi})^2}{N-1}}, \overline{\varphi} = \frac{1}{N}\varphi_i$$

where KG, KG_{CR} are the actual and critical of position of center of gravity.

It can only be achieved by making norms stricter. Simple calculations show that considerably more physically valid stability criteria may result in further deviations from the ideal, compared to simplified IMO criteria. The paradox is that the result is achieved by the extremely uneconomical way, at the expense of making a norm stricter than the average norms, even when it is not really necessary.

Paradox of zero probability. The paradox of zero-probability is directly related to probabilistic stability criteria. Practically, the probability of capsizing equals to zero (based on casualty statistics, probability of capsizing is about 10^{-4}, i.e. corresponds to a range of risk (1-10) 10^{-4} similar to landing helicopters, horse races with obstacles, and sport car races), but this event is not impossible. There is a paradox, whether it is possible to compare "chances" of events having zero-probability. Also whether it is real when the conjunction of events having zero-probability can result in finite-value probability, i.e. the addition of many “nothings” results in “something”. Probabilistic analysis of stability failures leads to a concept of rare events coming from “unusual occurrences” (combination of external conditions for assumed situations, encounter with extreme waves, etc.). The small probability of such events may make a false impression that simultaneous combination of many adverse factors is practically impossible, like conditions that lead to large-amplitude rolling (synchronous and parametrical resonance). This paradox is also closely related to the problem of rarity [62].

Paradoxes of the distributions. Many paradoxes are related with the application of theoretical distributions. One such peculiarity is caused by asymptotic properties of theoretical distributions and results in insensitivity of the probability of stability failure to the large changes of the centre of gravity in the vicinity $P_0 \to 1$. Other problems are related to the change of distributions by a nonlinear dynamical system, depending on the level of excitation.

It is known that for the normal distribution, the average $\theta^* = \sum \theta_i / N$ of a random variable θ is an unbiased estimate $E(\theta^*) = 0$ and converges $P(|\theta^* - \theta| < \varepsilon) = 1 \quad \forall\theta$ at the large values *N*. However if the distribution is not known *a priori*, the estimate θ^* may end up being biased with the minimum variance; in case of multi-dimensional distributions, such an estimate may simple not exist for quadratic loss function $\sum(\theta - \theta^*)^2$. If such a check was not performed during the statistical analysis the resulting criteria may be not valid.

Paradox of a choice of boundaries for a criterion. The paradox of rational choice boundaries for a stability criterion is very important. Use of fuzzy boundaries for stability criteria makes sense due to the random nature and uncertainty of the input data that is used as a basis for calculation scheme of evaluation of stability (fig. 9) [29].

The errors of an inclining experiment, limited accuracy of data on loading conditions of a ship, as well as the uncertainty of other factors, may result in the true value of the parameter *X* actually belonging to the interval $[X_0 - \varepsilon;\ X_0 + \varepsilon]$. Then according to the requirements when $X^* = X_0$, the norm is observed exactly, while in reality $X_0 = \pm\varepsilon$. The area of acceptance of a hypothesis $X = X_0$, i.e. the interval ($X_{1-\alpha}$, X_α) equals β (α — significance value). Then the probability of a type II error for deviation from hypothetical value X_q equals β; the value 1 – β characterizes “power of the criterion”. Reducing α leads to a reduction in the probability of a type I error (the zero hypothesis is rejected, when it is correct). However, the probability β is increased of the type II error and the “power” of criterion is reduced.

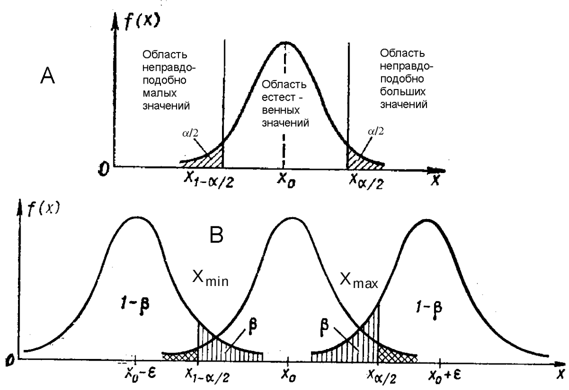

Figure 9. Errors of practical use of stability criteria: X_0 – parameter; (X_{max}, X_{min}) — area of actual change *X*; A — area zero-hypothesis (1) and alternative hypotheses (2); B — areas corresponding to an type II error.

Paradoxes of computer implementation. Many paradoxes are related to computer implementation of stability problems. Any statistical solution, which can be implemented on the computer, now becomes available. As a result, “stable” and multi-dimensional methods, requiring huge number of operations, have entered engineering practice without a sufficient theoretical justification. Meanwhile, it is possible to justify many empirical collisions, using robust statistical methods. Unfortunately this is a common practice in assessment and regulation of stability of ships [29].

9. FUTURE DIRECTIONS

The further developments of the analysis and criteria of stability can be achieved by advancements in the following strategic directions:

1. Development of hydrodynamic model of the interaction of a ship with external environment while under action of extreme waves.
2. Study of physical response of roll and capsizing of a ship in extreme situations using climatic spectra.
3. Development of a hydrodynamic model for nonlinear interaction of ship waves with incident waves in storm conditions.
4. Further development of criteria for ship stability in waves using new approaches for description of uncertainty in complex dynamic environments.
5. Development of effective means of the control of ship stability in waves using algorithms, which take into account the change of ship dynamics in time.

10. CONCLUSION

The considered problems of the analysis and criteria of ship stability in waves reflects only a small portion of the research applications, in which the ideas developed by the author, his students and colleagues have found a place. The foundation for these works combines stability and the theory of oscillators and offers a methodology for better understanding how both these concepts are applied for modeling. Thus the author emphasizes applications that attract both scientific and practical interest while researching complex behavior ships in various extreme situations. Making decisions for the control of these situations may benefit from the new approaches based on formulations of uncertainty and construction of system of knowledge using artificial intelligence and fuzzy mathematics.

Advancements in cybernetics, information technology, and the general theory of systems led to a new scientific picture of the world. This picture has found its reflection in new approaches to the problem of stability of a ship in waves. The leading role belongs to nonlinear dynamics and is related to the concept of synergy that has changed the understanding of the relation between chaos and order, entropy and information. The theory of synergy came from works on the theory of bifurcation of dynamical systems and was further developed by new generations of researchers. Complexity of structures and processes plays a key role for modeling of the stability of a ship in waves. Their instability, randomness, and transitive nature led to new scientific paradigm. Changes of the structure of a dynamical system are studied within this paradigm, rather than a behavior of a system with unchangeable structure.

The problem of analysis and development of stability criteria is one of important avenues for ensuring safety of operation. Uncertainty and incompleteness of the input information are inherent for the complex problem of ship stability. Information technology for monitoring ship dynamics in waves being developed by the author and his colleagues may be implemented into on-board intelligent systems. Such technology should not be reflected in the final form of criteria, as a mathematical formulation allows more flexible analysis of stability in complex situations.

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