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Methods of system analysis in problems of navigation

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Abstract. *The paper proposes a method of reliable system of prevention and detection of the beginning of the parametric pitching of a sea vessel, based on measured signals. This approach allows us to make decisions during the operation, as well as to predict susceptibility to parametric pitching at the ship design stage. The problem of forecasting of random forces and their impact on the state of the marinee evessel is reviewed. It is noted that chaos theory and the discovery of the fractal nature of many natural systems is one of the possible approaches to solving this problem.*

Keywords. fuzzy logic, sistem analyze, chaos, entropiya, parametric pitching vessel, shipbuilding, waves

Mathematics Subject Classification (2010): 37N30

1 Introduction.

A description of all the processes taking place around the moving sea vessel by means of traditional mathematics is impossible due to the presence of the principle of incompatibility [39] stated by L. Zadeh, which states that the increase in complexity of the system decreases the possibility of its precise description up to a certain threshold beyond which the accuracy and relevance of information become incompatible and mutually exclusive characteristics. In the event that all researchers manage to write a mathematical model of the ship, its practical use is difficult because of the complexity of the mathematical description of the processes, the availability of inadequacy.

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Based on the above said, it can be concluded that one of the most correct possible directions of development of the theory of ship control systems is renunciation of the traditional mathematics, replacing it with the device originally adapted to work in conditions of uncertainty, such as fuzzy logic [40].

According to L. Zadeh, the presence of the human factor significantly limits the application of mathematical methods for constructing a mathematical model of the object [39, 40]. That is why, still the question remains to develop alternative methods that can be effectively used to analyze the processes taking place around the moving sea vessel.

To understand the processes and phenomena occurring around the vessel under the influence of wind and sea waves and for ship management, it is necessary to study the behavior of the whole system, taking into account the relationship of external forces, not only the individual parts of the system.

Thus, in order to understand how to steer a boat, you need a systemic, holistic view of the processes taking place around him. In other words, a systematic analysis which can be viewed as another possible area of research is needed.

System analysis examines the causes and mechanisms of emergence of new modes and structures, exploring the characteristic scale and speed of transient and steady-state processes, predict the likely changes to the system and indicates how it would be possible to manage the unexpected dynamic modes that arise in complex systems. These modes include the so-called parametric resonance on vessels.

In 1970 several fishing vessels overturned on the west coast of Canada under conditions which are not considered to be particularly dangerous. To account for these unusual events in the report [28] has been tasked to determine the nature of the stability of the common structures used in these vessels. By means of the use of a specific hull form via the theory of calculation of diffraction waves, taking into account fluid pressure to the vessel, etc. Within the framework of the six degrees of latitude, a full dynamic analysis of ship movements was made in order to calculate the non-linear time history.

This work identified three separate tipping mechanisms corresponding to resonance and subharmonic pitching of beams at sea and buckling on the crest of a wave. The last of these mechanisms is of a particular concern, as there is a lack of time and it is impossible to warn of the impending rollover.

In the paper [11] other rollover mechanisms were analyzed, one of which is associated with pitching, caused by parametric resonance in the head waves.

As in the solution of the technical problems while trying to solve the problem of motion of a ship at sea, it is impossible to accurately determine the condition of the vessel at any time. Thus, initial conditions for the modeling are not always known and instead of focusing on the same trajectory, the stability of the ship may be estimated by analyzing the ensemble of decisions.

Chaos theory and the discovery of the fractal nature of many natural systems in recent years is one of the most common approaches to the study of such processes.

In the problems of navigation, to determine the wind-wave losses of the ship speed is of considerable interest, as the master shall have reasoned understanding of the real-time leeway in case of unfavorable prognosis or actual bad weather.

Thus, the problem of the forecast of random forces and their effect on the condition of the vessel is not only of scientific, but also of practical interest.

2 Statement of a problem.

Experimental work in the field of maneuvering and control of vessels shows that it is difficult to predict the characteristics of the vessel from the model tests due to the lack of accurate data on the steering control and the on board state of the ship. In the paper [2] a lot of research work has been done to analyze the dynamics of the condition of the vessel.

Ships, even in calm water, may fall out of equilibrium by an external force, such as wind. This may result in vessel movement. If the vessel is subjected to pitching because of the wind, thanks to damping, pitching will decay and tend to zero through several periods of oscillation (Fig. 1). However, if the sea is turbulent, the pitching side of the ship may lead to instability in the behavior of the vessel and, as a consequence, to the parametric resonance. The ship begins to oscillate until being tipped or stabilized to a certain roll angle (Fig. 2, [21]). Because of this phenomenon, swimming in the sea can be dangerous.

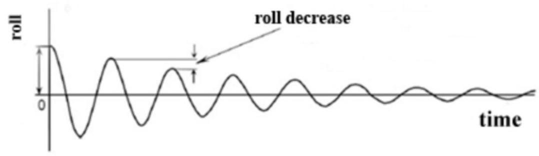

Fig.1. Pitching at a calm sea.

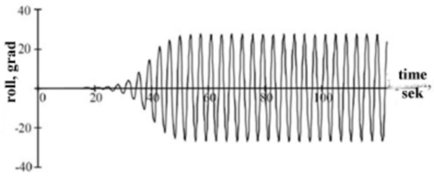

Fig.2. An example of parametric resonance of the ship pitching.

In the maritime practice cases of increase in parametric resonance amplitude of pitching from 15^0 to 60^0 in less than 6 minutes are known.

Parametric resonance on ships was first observed by Froude, who said that the ship, on which the oscillation frequency in the vertical and keel pitching is equal to double the natural frequency of the pitching side, showing degraded characteristics of seaworthiness, which can lead to the excitation of large lateral oscillation. Theoretical proof appeared in the 20 th century [12], [37].

Report about the incident with the ship in China in October 1998 by W. France and others. [6] reinforced the interest in parametric resonance in the side roll. K. Dohlie [5] described the parametric resonance as a very real phenomenon that will be able to threaten the ship even in normal conditions of navigation in the sea, which were previously considered safe.

The publications devoted to parametric pitching on container include [13] - [16].

Papers [32] [33] are devoted to the study of parametric pitching on fishing vessels.

3 Theoretical research.

The main focus of this study is to analyze the nonlinear interactions between the onboard pitching roll and the other parameters of vessel traffic and the development of models that can help in decision-making during the operation, as well as to predict susceptibility to parametric pitching at the design stage. Such attempts were made in [34], [14].

The recommendations of these studies are effective, but only to prevent the excitation of regular waves. Irregular waves of the sea were reviewed in McCue and Bulian [25], who used a finite time of Lyapunov to detect the start of the parametric pitching. Subsequently, the results of this method have not been confirmed experimentally.

In contrast to the results presented in [7-9], this paper suggests methods based on the measured signals for detecting parametric pitching. The technique of a reliable system of prevention and detection of the beginning of the parametric pitching is offered. It is shown that this problem can be solved only based on the signals.

The point of the method consists of two detection circuits, one in frequency, the second in time range. The method is based on the frequency of the sensor spectral index of correlation between the vertical or keel and on board pitching. The method based on the time sensor uses phase synchronization between the square of on board pitching and keel pitching.

The paper [10] proposes the results of the experiment for determining the dynamics of the angle of on board pitching during the onset and development of the parametric pitching (Fig. 3 - Fig. 6).

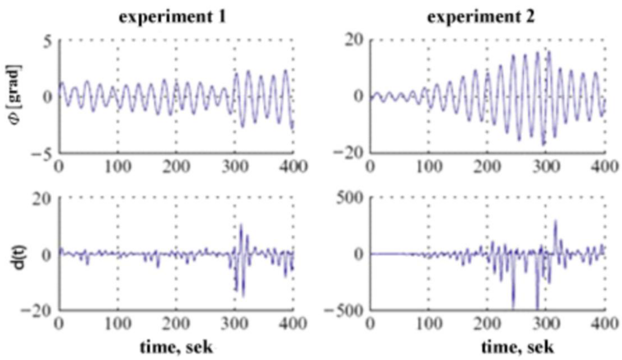

Fig.3. Dependence of the amplitude of onboard oscillation on time. Data from experiments in the pool, $d\,(t)$- the control signal (driving signal).

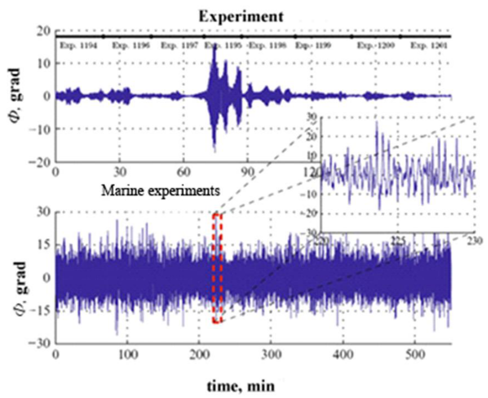

Fig.4. Dependence of the amplitude of the on board oscillation on time (time series recorded from experiments).

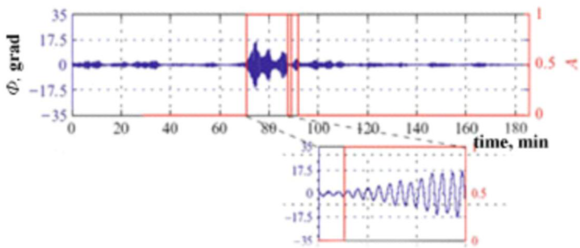

Fig.5. The data obtained on the experimental setup.

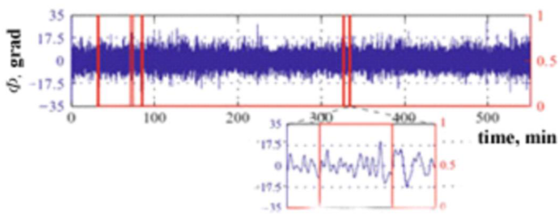

Fig.6. The results of the movement trials.

Dependence of the amplitude of the on board oscillation on time (time series recorded from experiments). The experiment on the top Fig. 4 is the only one in which parametric pitching clearly developed. Dependence of the amplitude of the on board oscillation on time on the bottom Fig. 4 were recorded during navigation in the North Atlantic Ocean.

The onset of parametric pitching on the experimental setup shown in Fig. 5 is detected in a timely manner when the roll angle is only about 3^0.

For the case illustrated in Fig. 6, emergency alarm was given. Visual inspection shows that in this case there was a false alarm, there is no parametric resonance.

The nature of these measurements on Fig. 5 shows that the parametric pitching occurs between $T = 70$ min and $T = 90$ min and detected in a timely manner when the roll angle is about 3^0. Loss of phase synchronization is also found, then the detector Weibull GLRT relieves alarm $T = 90$ min after pitching splits, and the parametric resonance is over. However, as it is seen from Fig. 6, there is a sudden alarm again when new resonance oscillations occur.

Calculation and prediction of extreme perturbation parameters of pitching. Practical use of entropy in problems of navigation. Recent studies with a model of one degree of latitude of vessels‘ pitching at sea shows how new theory of dynamical systems can be used to study the quality of long-term forecasting of the behavior of the vessels. [6]

We will highlight the calculation methodology only for on board pitching, as it is similar for other types of vessel fluctuations. In modern software when calculating the reaction of the vessel to a mixed swell, two of the spectrum - the spectrum of wind waves and swell spectrum are used. The response to the impact of a mixed swell of the vessel is the sum of responses to its components. The formulas for calculating the reaction vessel on the swell and wind waves are almost identical, which makes it possible to describe an algorithm for obtaining parameters of pitching, using only wind component of the swell.

Prediction of vertical and keel pitching according to the swell is similar. However, it should be used in the amplitude-frequency characteristics of the vessel, appropriate to all these types of pitching.

The paper [24] proposes the results of model experiments of ships, subject to parametric pitching. The purpose of these tests lies in the characteristic of its dynamic behavior in such situations, as well as to check the system of forecasting side pitching in real conditions, developed by the author. Furthermore, the results of these predictions for some tests given in this paper are proposed.

Current work has two main objectives. On the one hand, it studies the dynamic behavior of the vessel in the conditions of parametric resonance of pitching. This information will be crucial to define the parameters under which the vessel is becoming close to the danger of resonance, which requires alarm.

On the other hand, short-term prediction algorithms developed by authors have currently been tested on the mathematical model with three degrees of latitude at the head end of stationary waves [31]. Nevertheless, it is also necessary to study their suitability for more realistic conditions, for example, stationary waves. This analysis was also carried out in this work.

An extensive testing program was carried out in Spain in order to solve both problems (Technical University of Madrid).

A wide scale model of average trawler with a high propensity to the action of parametric pitching was used. The tests were carried out at different speed of longitudinal wave types (both stationary and non-stationary), resulting in resonant and nonresonant behavior.

As is evident from Fig. 7 [27] nonparametric pitching (stationary waves) does not develop, there is only a small pitching with small amplitude due to the natural decline of the vessel and the effects of external disturbances (tow bar).

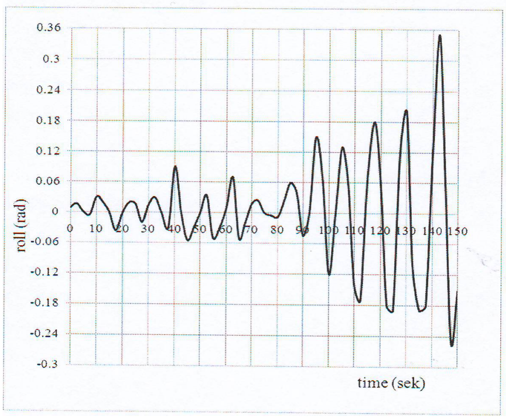

Fig.7. The tests data $\phi(t)$ [31] (table 1).

Table 1.

t (sek)	pitching (rad)	t (sek)	pitching (rad)	t (sek)	pitching (rad)
0	0,01	50	0	100	-0,12
2,5	0,016	52,5	0,034	102,5	0
5	0	55	-0,05	105	0,13
7,5	-0,005	57,5	-0,029	107,5	0,058
10	0,03	60	0,009	110	-0,14
12,5	0,02	62,5	0,07	112,5	-0,17
15	0	65	-0,05	115	0,065
17,5	-0,037	67,5	-0,02	117,5	0,18
20	0	70	0,017	120	0,057
22,5	0,02	72,5	0,025	122,5	-0,18
25	0,016	75	0	125	-0,19
27,5	-0,02	77,5	-0,006	127,5	0,12
30	0,015	80	-0,009	130	0,2
32,5	0,03	82,5	0,023	132,5	-0,1
35	0	85	0,06	135	-0,19
37,5	-0,03	87,5	0,04	137,5	-0,18
40	0,09	90	-0,045	140	0,12
42,5	0	92,5	0	142,5	0,35
45	-0,055	95	0,15	145	0,06
47,5	-0,03	97,5	0,059	147,5	-0,25

This paper has two main objectives: on the one hand, the study of the behavior of the ship in real terms in parametric resonance, on the other hand, the verification of the method for forecasting the resonance of the side pitching in such conditions.

Let‘s consider the task of describing and predicting parametric pitching on ships based on the theory of information with using entropy. For this purpose we use the measurement data shown in Fig. 7.

The traditional theory of information, issued as a scientific direction in the 50s of the 20 th century, almost immediately attracted the attention of scientists and experts from various fields of science. Suffice it to say that already in 1956 K.Shennon wrote: ”Information theory has been applied in biology, psychology, linguistics, theoretical physics, economics, the theory of production and in many other areas of science and technology.”

There is reason to expect that the synergetic theory of information will find a broader scope of application and will be able to face new cognitive tasks, both of theoretical and applied nature, inaccessible to traditional information theory [3,17,22].

One of the possible areas of application of synergetic theory of information can be ship navigation theory. With this aim we will use an entropy approach in this paper. We will use the numerical series of the test data shown in Fig. 7.

We perform the entropy sequentially increasing the data numbers for 10 points up to 150 seconds. (Fig. 7). We describe in detail the procedure for the calculation of points for the first interval (interval 0 - 22.5 seconds, the first 10 pixels).

If the number of points $n(\phi)$<100, the number of groups N_{gr} of data calculated by the formula:

$$N_{gr} = 1 + 3,32 \cdot \lg n(\phi) \tag{3.1}$$

Otherwise, if$n(\phi)$>100, calculated by the formula

$$N_{gr} = 5 \cdot \lg n(\phi) \tag{3.2}$$

In this case, $n(\phi)$= 10 <100, so $N_{gr} = 1 + 3,32 \cdot \lg 10 \approx 4$, i.e. the number of groups of data considered N_{gr} is 4.

Let's calculate the difference between the minimum and the maximum value of the side pitching:$\Delta\phi = \phi_{\max} - \phi_{\min}$ = 0,03-(-0,037)=0,067. Then

$$h = \frac{\Delta\phi}{N_{gr}} = 0,01675 \tag{3.3}$$

Let's create a table in which we show the number of the group, the range of the data $\phi(t)$ in each group, calculated using the formula$[\phi_{\min};\ \phi_{\min} + ih]$ $(i = 1, 2, 3, 4)$, the amount of data $\phi(t)$allocated in each of the resulting intervals $n(\phi_i)$ and the corresponding probabilities $p_i = n(\phi_i)/n(\phi)$.

Entropy is calculated as follows:

$$I = -\sum_{i=1}^{N_{gr}} p_i \log_2 p_i \tag{3.4}$$

In the works [29-31] systems analysis was applied to problems of oil mechanics.

Table 2.

of group	Intervals $\phi(t)$	$n(\phi_i)$	p_i
1	$[-0,037;\ -0,02025]$	1	0,1
2	$[-0,02025;\ -0,0035]$	1	0,1
3	$[-0,0035;\ 0,01325]$	4	0,4
4	$[0,01325;\ 0,03]$	4	0,4

In works [18-20] it is proposed that all of the system formations to be classified, depending on the quality of their separate parts and the type of ratio of additive negentropy I_Σ and entropy I into 5 types:

$$\begin{array}{l} -ordered: N_{gr} < \sqrt{n(A)}, I_\Sigma > I; \\ -randomly-ordered: \sqrt{n(A)} \le N_{gr} \le \frac{n(A)}{4} + 1, I_\Sigma > I; \\ -equilibrium: \sqrt{n(A)} \le N_{gr} \le \frac{n(A)}{4} + 1, I_\Sigma = I; \\ -orderly-chaotic: \sqrt{n(A)} \le N_{gr} \le \frac{n(A)}{4} + 1, I_\Sigma < I; \\ -chaotic: N_{gr} > \frac{n(A)}{4} + 1, I_\Sigma < I; \end{array} \tag{3.5}$$

In addition to the given classification, any system formation can be compared to each other for information and entropy ratio, referred to as R-function:

$$R = \frac{I_\Sigma}{I} \tag{3.6}$$

Additive Gentry I_Σ and entropy I are measures of order and randomness of the system, respectively. That is, R-function is a generalized informational-entropy characteristics of structured systemic formations, the value of which suggests what prevails in their structural organization and to what extent: the order (negentropy) and chaos (entropy). For example, if $R>1$, the order is dominant in the structural organization structure, otherwise when $R<1$ – chaos is dominant. When $R= 1$, chaos and the order equilibrate each other, and the structural organization of the system formation is an equilibrium.

It has been shown that in any system (in the notation of this paper) $\phi$with a fixed number of elements $n\left(\phi\right)$ always observed equality:

$$\log_2 n\left(\phi\right) = I_{\Sigma} + I, I_{\Sigma} = \sum_{i=1}^{N_{gr}} p_i \log_2 n\left(\phi_i\right), I = -\sum_{i=1}^{N_{gr}} p_i \log_2 p_i \tag{3.7}$$

In other words, for any structural changes of the system, occurring without changing the number of its elements, the amount of order and chaos retains its constant value.

Analyze and discussions of results. The entropy I of reflection is equal to the interval in question is equal to $I = -\sum_{i=1}^{N_{gr}} p_i \log_2 p_i = 1,721928$, and the additive negentropy to $I_{\Sigma} = \sum_{i=1}^{N_{gr}} p_i \log_2 n\left(\phi_i\right) = 1,6$. Moreover, $\log_2 n\left(\phi\right) = \log_2 10 = 3,32192809514303$. It is easy to see that condition (7) is satisfied, i.e, $\log_2 n\left(\phi\right) = I_{\Sigma} + I$.

According to (6) and (7), we have:

$$R = \frac{I_{\Sigma}}{I} = \frac{\log_2 n\left(\phi\right) - I}{I} = \frac{\log_2 n\left(\phi\right)}{I} - 1 \tag{3.8}$$

For the interval in question is equal function$R$ is equal.

$$R = \frac{order}{chaos} = 0,929190949 < 1,$$

For this period of time, the conditions $N_{gr} > \frac{n(A)}{4} + 1$, $I_{\Sigma} < I$ are fulfilled, so the system can be described as chaotic.

On Fig. 8 a chart of dependence of the values of R - function, entropy and negentropy of time for the entire observation period.

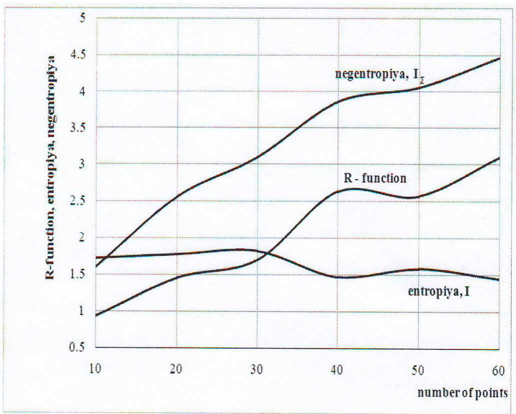

Fig.8. Dependence Chart R-function, entropy and negative entropy of the time.

As is evident from Fig. 8, starting from the time t= 72 sec. (30th point), entropy I begins to decrease and reaches a minimum at t= 90 seconds. (37th point). Point t= 72 sec. corresponds to the start of increase of pitching amplitude and, consequently, the point of minimum entropy t= 90 and on the maximum observed amplitude of pitching. Parametric resonance occurs.

Physical interpretation of the phenomenon is explained as follows.

The vessel in question is an example of open systems, i.e, is a system that is supported in a certain state by a continuous inflow of external energy or information. This is an irreversible system. Time factor is important in it.

As we know, in open systems, along with natural and necessary factors, random factors and fluctuation processes also can play a key role. Sometimes fluctuations may become so strong that the existing organization is destroyed.

Change in entropy is studied in detail above. In other words, we studied the dimension, inverse of energy.

The vessel - sea system is designed so that the continuous order in it is destroyed if the system is not fueled by energy. Orderliness is maintained by a certain level of energy, so before time t= 72 seconds, the $R = \frac{order}{chaos}$ function increases (Fig. 8).

In the considered time intervals t= 72 seconds, chaos is not observed, because a slight increase in entropy I (chaos) is offset by a strong growth of additive negentropy I_{Σ} (order) because of the favorable conditions of the vessel operation. Therefore, we should not expect chaos.

Conclusion. From the results and figures above, we can conclude that the model predictions are very accurate and the model can accurately track the reaction of the vessel pitching.

Thus, the proposed approach can not only explain, but to predict the onset of critical on board pitchings on behavior of R- function or entropy.

Results of the calculation of the proposed model confirm the possibility of predicting the pitching resonance 18 seconds ahead. However, for the detection of parametric pitching further work is needed to get accurate results for a longer period of time.

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