CRITERIA BASIS FOR ESTIMATION OF CAPSIZING DANGER IN BROACHING EXTREME SITUATION FOR IRREGULAR FOLLOWING WAVES

Yu.Nechaev, O.Zavyalova
State Marine Technical University,
St.-Petersburg, Russia

Abstract

The problem of creation of criteria basis for an estimation of a broaching extreme situation, connected with occurrence of capture and unguided turn of a ship on following sea is discussed. The analysis is carried out on the basis of mathematical modelling data of broaching dynamics in conditions of irregular waves at a various level external influence. The modelling data processing has allowed to allocate the characteristics of dangerous conditions connected to occurrence of the phenomenon of capture and overturning of a ship during unguided turn.

1. INTRODUCTION

A number of works is devoted to research of a ship dynamics in conditions of "capture" and non-control turn on following waves (situation «broaching») [1]-[13],[16]. At the given stage of researches of broaching dynamics on irregular waves there is a formation of theoretical basis of a problem. The complexities arising on a way of its research are connected to the adequate mathematical device, incompleteness of the initial information and uncertainty of external conditions, in which the concrete situation proceeds. Among works of such direction the special interest represents [13], in which the problems of nonlinear broaching dynamics are discussed.

Actual condition of a problem and the complexities of its decision have found reflection in the national and international specifications at the formulation of stability criteria in this extreme situation. The requirements and offers on broaching standardisation consist of ship speed restriction on following waves. But they don't take into account actual of a ship stability in broaching conditions and don't reflect of physical essence of phenomenon. Besides the quantitative estimations of Froude numbers according to the specifications of the different countries also essentially differ. It creates the certain difficulties of the analysis of a broaching situation in research designing and by development of intelligence systems of safety navigation [8].

Present work contains the approach to the analysis of features of occurrence and development of a researched extreme situation. The conceptual and computing features of such approach have required creation of the special mathematical device, algorithms and software. They allow more deeply understanding physical processes in a considered critical situation.

As illustration offered theoretical decisions the data of simulation modelling of dynamics of "capture" and non-control turn of a ship on following waves are considered. The processing of the received data has allowed to determine of the probability characteristic of a ship capsizing in a broaching regime and to construct criteria system.

The difference of considered research from works of other authors consists in the following:

1. The initial mathematical model contains nonlinear function describing the righting moment on following waves.
2. The analysis of mathematical model is carried out on the basis of representation of irregular waves as consecutive wave packages.
3. The system of the criteria equations determining of a ship safety in a broaching regime is offered.
4. The algorithm of management of a ship on following waves passing allowing excluding an opportunity of occurrence this extreme situation is offered.

The received data characterise of broaching dynamics for small ships. They can be used in tasks of safety navigation.

2. MATHEMATICAL MODEL

Let' s consider a ship as dynamic system with six degrees of freedom. The ship's behaviour can be described by system of the nonlinear differential equations:

$$F_i\left[\ddot{x}_i, \dot{x}_i, x_i, t, X_{i1}, \ldots, X_{im}, Y_{i1}, \ldots, Y_{in}\right] = 0, \quad (1)$$

where $F_i(\cdot)$ – nonlinear functions; x_i – linear and angular moving; $X_{i1},\ldots,X_{im}$ – parameters describing a ship as dynamic system (inertial, dampfer and righting components); $Y_{i1},\ldots,Y_{in}$ – disturbance forces and moments; i=1,2, …, 6.

An extremely complex picture of change cinematic and hydrodynamic parameters characterises the ship's behaviour in conditions of «capture» by a following wave and non-control turn. For the description of ship's movement from a condition of "capture" the system of four differential equations can be used [1]. Three of which are the known equations of the theory of controllability and describe of a ship's trajectory (longitudinal–horizontal, transversal–horizontal oscillations and yawing), and fourth – inclination of a ship concerning a longitudinal central axis:

$$\left.\begin{aligned}
&\left[\left(\frac{D}{g}\right)+\mu_{\xi\xi}\right]\left(\dot{v}\cos\beta^* - \beta^* v\sin\beta^*\right)+\\
&+\left[\left(\frac{D}{g}\right)+\mu_{\eta\eta}\right]v\dot{\chi}\sin\beta^* = F_x = X(t)+P_e-R,\\
&\left[\left(\frac{D}{g}\right)+\mu_{\eta\eta}\right]\left(\dot{v}\sin\beta^* - \beta^* v\cos\beta^*\right)+\\
&+\left[\left(\frac{D}{g}\right)+\mu_{\xi\xi}\right]v\dot{\chi}\cos\beta^* = F_y = Y(t)+R_{yB}+R_{yR},\\
&\left(J_z+\mu_{\chi\chi}\right)\ddot{\chi} = M_z = M_z(t)+M_{zB}+M_{zP},\\
&\left(J_x+\mu_{\theta\theta}\right)\ddot{\theta}+M_R(\dot{\theta})+M(\theta,\varphi,t) = M_G+M_A,
\end{aligned}\right\} \quad (2)$$

where β^* – drift angle; χ – angle of yawing; $D/g+\mu_{\xi\xi}$, $D/g+\mu_{\eta\eta}$, $J_x+\mu_{\theta\theta}$, $J_z+\mu_{\chi\chi}$ – inertia components; X(t), Y(t), $M_X(t)$, $M_Z(t)$ – disturbing forces and moment; $M_R(\dot{\theta})$ and $M(\theta,\varphi,t)$ – damping and righting moment; $R_{y\hat{a}}$ and $M_{z\hat{a}}$ – force and moment called by a rudder action; $M_{x\hat{a}}$ – moment of a rotational nature called by a drift and rotation of a ship concerning a vertical axes; M_G – hydrodynamic heeling moment; M_A – wind heeling moment [6].

For the description of general ship's behaviour on waves in broaching conditions the systems of coordinates are entered: $\xi O_1 \varsigma$ – motionless in space, $x_1 G y_1$ – mobile system rigidly connected to the centre of weights of a ship (a point G); v – speed of a vessel; β – drift angle; φ – course wave angle; ω_z – angular speed of yawing. The definition of ship elements is conducted in usual system of coordinates accepted of the ship static.

The nonlinear space-time function of the righting moment at various course angle φ on following waves is represented by the formula [5]:

$$M_W = M(\theta,\varphi,t) = D[l(\theta,\varphi) + \\ + \Delta l(\theta,\varphi)\cos(\sigma_k t - \varepsilon)]; \qquad (3)$$

$$l(\theta,\varphi) = 0{,}5\,[l(\theta,\varphi)_{\max} + l(\theta,\varphi)_{\min}], \\ \Delta l(\theta) = 0{,}5\,[\Delta l(\theta)_{\max} + \Delta l(\theta)_{\min}]; \qquad (4)$$

where $\Delta l(\theta,\varphi)_{max}$ and $\Delta l(\theta,\varphi)_{min}$ – extreme meanings of arm stability, appropriate to a ship situation at wave crest and wave trough at various course angles φ; ε – phase (ε=0 and 2π – ship on a wave trough, ε=π/2 – ship on an upslope, ε=π – ship on a wave crest, ε=3/2π – ship on a down-slope).

The general expression for function $\Delta l_w(h_w/\lambda,\theta,\varphi)$, determining influence of waves at various parameters of shop's form and Froude number, looks like [5],[7]:

$$\Delta l_W(h_W/\lambda,\theta,\varphi) = B\,[\Phi\left(\frac{h_W}{\lambda},\theta,\varphi_k\right) + \\ + \sum_{m=1}^{6} A_m f_m(\theta,\varphi_k) + \sum_{n=1}^{8} B_n F_n(\theta,\varphi_k) + \\ + \sum_{p=1}^{3} C_p E_p(\theta,\varphi_k)], \qquad (5)$$

where

$\Phi(h_W/\lambda,\theta,\varphi_k)$, $\sum_{m=1}^{6} A_m f_m(\theta,\varphi_k)$, $\sum_{n=1}^{8} B_n F_n(\theta,\varphi_k)$, $\sum_{p=1}^{3} C_p E_p(\theta,\varphi_k)$

– function describing data's of standard model and sums of the corrections on influence of linear, square-law and cubic terms of Taylor series decomposition to magnitude of an aggregate increment of an arm of stability, defined in view of diffraction and interference component at driving a ship with an arbitrary course angle on waves [5]. The geometrical interpretation of function l(θ,φ,t)=M(θ,φ,t)/D is given in a fig.1.

Thus, as against the earlier researches, in discussed work more severe mathematical model of a ship's inclination in broaching conditions, taking into account a real picture of change of space-time nonlinear function of the righting moment is used.

3. RESULTS OF MODELLING

The mathematical modelling is carried out on the basis of the following approach:

- Researches of behaviour of self-propelled radio-controlled models on natural waves [5], [11] testify that the broaching situation at ship's movement on irregular waves arises at influence of packages of dangerous waves. The parameters of waves and configuration of packages depend on width of a spectrum and intensity of waves. The conditions of "capture" and non-control turn of a ship occur during a time interval not exceeding time of passage of a dangerous package. The phenomenon of "capture" of a ship comes at performance appropriate of a criteria ratio [1].

- Dynamic roll and capsizing of a ship in a broaching regime it are marked during one – three amplitude rolling at increase of the heeling moment from drift and yawing and also disturbing moment from waves.

The inclinations of a ship get the obviously expressed dynamic character only in a final stage of evolution, when the ship appears at a situation of board to waves.

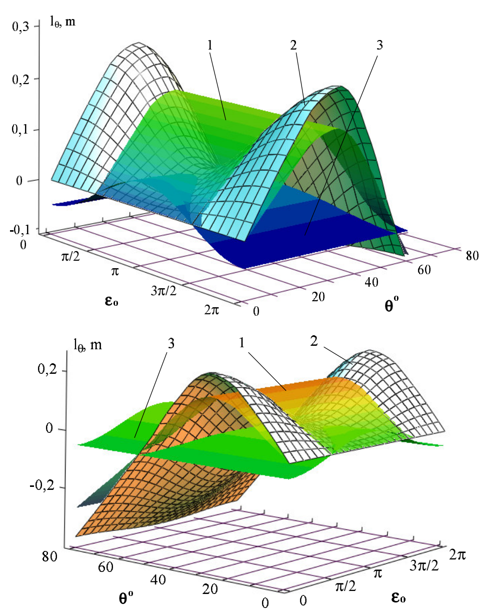

Fig.1. Nonlinear function of a righting moment (1 – on still water; 2 – on wave; 3 – wave profile).

The mathematical modelling is carried out in such sequence. The irregular wave of the given intensity was generated. Then ship dynamics was simulated and the condition of capture was checked. At occurrence of capture the ship began to move together with a wave. At the certain angle of drift occurred unguided turn and inclination of a ship on waves. During the analysis the moments of capture and capsizing were fixed. As a result of research of ship's behaviour at influence of sequences of wave systems with packages of the various form and intensity were determined probability of occurrence of capture and probability of capsizing. Thus the cases of capsizing were marked much less often, than cases of occurrence of capture. The statistical processing of these data has allowed constructing the appropriate experimental dependencies (fig.2).

The carried out researches of broaching dynamics on the basis of mathematical model (2) have allowed to clear a real picture of a ship behaviour and to receive an extensive experimental material for criteria system determining [17]. This material allows to present a general picture of characteristics change describing probability of "capture" and ship capsizing depending on intensity of waves (fig.2). The given data testify that a researched probability characteristic essentially change. The growth of waves results in decrease of probability of "capture" and increase of probability of a ship capsizing during of non-control turn.

The results of research have allowed to establish the following facts and laws:

- At the analysis and stability standardisation in a broaching regime it is necessary to take into account interrelation of the phenomenon of "capture" and subsequent non-control turn of a ship on following waves. Standardisation only of mode of "capture" doesn't give an objective estimation actual of a ship stability.

- The occurrence of the phenomenon of "capture" is observed after performance of criteria determining a condition of ship movement with speed of a wave run. The probability of such phenomenon on steep waves of dangerous length is high enough.

- Dynamics of a ship in a broaching regime is characterized by many factors and not is always finished by process of a ship capsizing. The probability of capsizing in a broaching regime practically on the order is less, than probability of occurrence of "capture". Actual specifications connected to restriction of Froude number on following waves don't reflect essence of the phenomenon and are subject to updating on the basis of new experimental data.

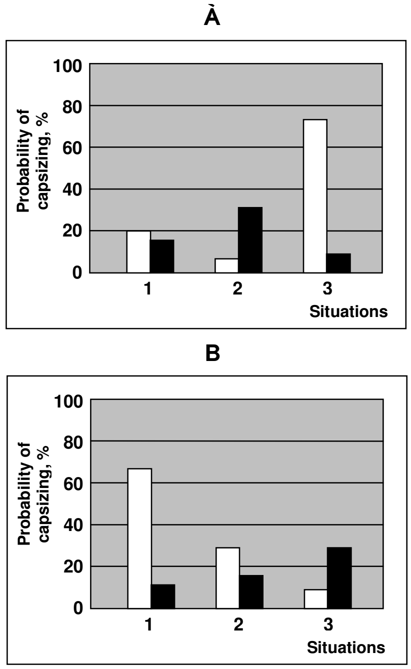

Fig.2. Experimental data of the probability characteristics estimations (average distribution and factor of a variation) "capture" (À) and capsizing (Â) for various meanings of waves parameters (wave height of $h_{3\%}$ and average period τ^*): 1) $h_{3\%}=1.5$, $\tau^*=5.7$; 2) $h_{3\%}=2.5$, $\tau^*=7.6$; 3) $h_{3\%}=3.5$, $\tau^*=8.8$.

Thus, the new facts established during the analysis and laws allow:

- To modify of information on interaction of a ship with external environment;
- To formulate criteria basis for development of the system of stability standardisation in this extreme situation.

4. THE BROACHING DIAGRAM

The results of modelling have allowed developing the broaching diagram. As against the diagram [1] new interpretation of the diagram is offered below. Its basic difference is that as the basic characteristic of the diagram instead of a dimensionless way the dimensionless time is used. The dimensionless time it is the relation of time of a ship inclination to the rolling period. The application of such characteristic considerably facilitates practical use of the diagram at the analysis of a ship's behaviour in a considered extreme situation. On the diagram change of relative radius of trajectory curvature of ship weights-centre is entered during uncontrollable turn. The offered diagram represented in a fig.3 in the dimensionless shape as following functional connections:

$$(S/L,\ v/c,\ R/L,\ \varphi,\ \beta^*,\ \theta,\ \varepsilon) = f(t/\tau_\theta),$$

where S/L and R/L – dimensionless path and turn radius; v/c – dimensionless velocity of ship; θ and β^* – angles of heel and drift; ε – phase; φ – course angle.

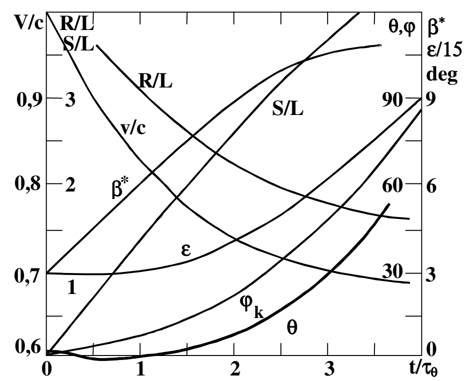

Fig.3.The broaching diagram.

At construction of the broaching diagram original values of a dimensionless velocity v_0/c_0 and the phases ε_0 determine also, as well as for the diagram [1] – from conditions providing "capture" of a ship. In this case $v_0/c_0=1$, calculate significance $\varepsilon_{îí}$ on the basis of a stability criterion [1]. Original values of angle course φ, angle of drift $\beta_í$ * angular velocity $\Omega_í$ accept on data's of physical simulation.

5. ÒHE CRITERIA BASIS

The features of a ship's behaviour on following waves at estimation of broaching danger in the formalized of knowledge system requires creation of two systems criteria of estimations (fig.4). The first system provides check of a condition of capsizing and is developed as precise and fuzzy criteria systems. The precise system is formulated on the basis of the traditional approach and assumes use threshold criteria estimations as global and local systems. The global system of criteria includes the national and international requirements, which are provided independent of ship's type. The local system is developed during creation of knowledge system and takes into account characteristics of a researched ship. The fuzzy system is based on more perfect methods of the information formalisation in view of its incompleteness and uncertainty within the framework of the soft computing concept.

The practical realization of such approach is connected to creation of fuzzy system of logic rules. One group of rules allows to determine an estimation of a situation danger, another - is directed on prevention strong yawing and is realised directly in control IS (decrease of speed of a ship speed, change of a course angle).

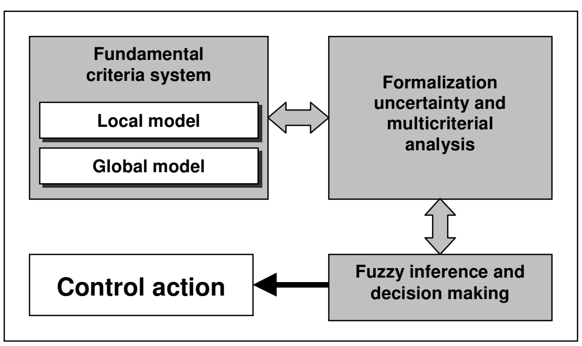

Fig.4. Criteria system of broaching extreme situation.

On the basis of the carried out researches the estimation criteria of danger of a broaching situation were developed. This task can be formulated as follows. Let there is some information operator allowing to carry out transformation the information on dynamics of a ship's interaction with external environment. The structure of such operator should take into account two aspects the determining basic requirements to the contents of information flows. First aspect is connected to a problem of uncertainty. Correct registration of this feature requires allocation of the essential factors determining dynamics of a roll and capsizing. Second aspect is a choice and formulation of criteria of ship's safety. These criteria are connected to an estimation of stability of oscillatory movement of a ship in broaching situation. The ship's behaviour on border of areas of stability and near to them depends on conditions of a task. The small infringements of safe borders result in small changes of a condition of system, and small infringements of dangerous borders - to essential to a new condition of system which is not allowed in exploitation practice. The realization of this theoretical principle in conditions of uncertainty and incompleteness of the initial information is connected to difficulties in definition of threshold meanings of the criteria characteristics.

At a substantiation and choice of the stability characteristics it is necessary to realise the main principle standardisation - tolerance to uncertainty and partial validity for achievement interpretation, flexibility of the decision. The generalized model, created on the basis of such approach, allows to proceed to construction of models of the formalized tasks of the analysis and safety standardisation in a considered extreme situation.

The analysis of modelling results has allowed to find out the essential factors determining conditions of capsizing and to formulate the requirements to ship's safety in a broaching situation. These requirements are reduced to check of dynamic criteria and limiting meaning of Froude number:

$$(\grave{I}_{\tilde{n}})_W \geq M_R,\ Fr \leq (Fr)_{CR}, \qquad (6)$$

where $(M_c)_W$ – minimum capsizing moment on following waves; M_R – heeling moment arising in process of a unguided turn of ship; $(Fr)_{CR}$ – critical Froude number.

The meaning of the capsizing moment is determined as (fig.5):

$(M_c)_W = 0,5[M(\theta,\varphi t)_{max} + M(\theta,\varphi,t)_{min}] =$
$= 0,5D[l(\theta,\varphi,t)_{max} + l(\theta,\varphi,t)_{min}]$, (7)

where $M(\theta,\varphi,t)_{max}$, $M(\theta,\varphi,t)_{min}$ – extreme meanings of the minimum capsizing moment at a ship situation on a wave trough and wave crest; $l(\theta,\varphi,t)_{max}$, $l(\theta,\varphi,t)_{min}$ – appropriate meanings of arm stability, φ - course angle of a wave.

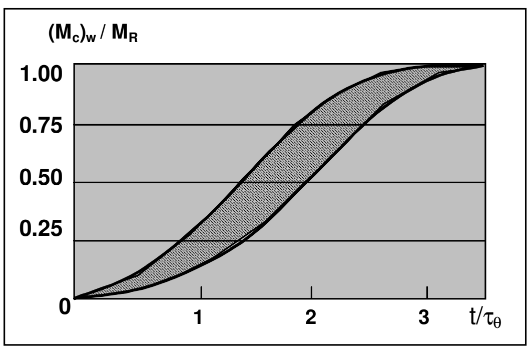

Fig. 5. Change of the minimum capsizing moment in process of a unguided turn of ship

Calculated length of a wave corresponds to length of a ship (λ=L), and the steepness is characterized by the formula [5],[7]:
$h_w/\lambda = 0,05[1+(160-\lambda)/135]$. (8)

The meaning of the heeling moment in broaching conditions is determined with the help of regression model:

$M_R = F(L)Dl_R = D[1+0,023(30-L)+$
$+0,0005(30-L)^2]\,(0,15 - 0,05\tilde{O}_1 - 0,02\tilde{O}_2 +$
$+0,03\tilde{O}_3 - 0,19\tilde{O}_4 + 0,06\tilde{O}_5 + 0,007\tilde{O}_2^2 +$
$+0.018\tilde{O}_3^2 + 0,12\tilde{O}_4^2 + 0,43\tilde{O}_5^2)$, (9)

where D – ship displacement; l_R – heeling arm; $\tilde{O}_1$–$\tilde{O}_5$ – dimensionless characteristics calculated on the formulas:

$\tilde{O}_1$ = L/B – 4,0; $\tilde{O}_2$ = B/T–3,0; $\tilde{O}_3$= Í /Ò– 1,4;
$\tilde{O}_4$ = δ/α–0,7; $\tilde{O}_5$ = (Fr)î – 0,32;
L/Â,B/Ò,Í /Ò,δ/α – ratio of main dimensions and factor of vertical fullness. (Fr)î=v/(gL)$^{1/2}$; v – the maximal of a ship speed on still water.

The expression (7) is fair for ships of length smaller then 60m, i.e. covers the most important range of the characteristics of small ship subjected danger of capsizing in broaching conditions.

The critical Frood number is under the formula

$(Fr)_{CR} = k_B(Fr)o$,
$(Fr)_{CR} \notin \{(Q(Fr)^*),(Q(Fr)^{**})\}$; (10)

$$(Fr)^* = \sqrt{\frac{\lambda}{L}}\left(\frac{1}{\sqrt{2\pi}} - \frac{k_\theta^*}{C\sqrt{g}}\sqrt{\frac{\lambda}{L}\frac{L}{B}\frac{h_\theta}{B}}\right),$$
$$(Fr)^{**} = \sqrt{\frac{\lambda}{L}}\left(\frac{k_\theta^{**}}{C\sqrt{g}}\sqrt{\frac{\lambda}{L}\frac{L}{B}\frac{h_\theta}{B}} - \frac{1}{\sqrt{2\pi}}\right). \quad (11)$$

where $k_B = f(L/B)$ – numerical factor; k_θ^*, k_θ^{**} – factors describing areas Q(Fr)* and Q(Fr)** of occurrence of resonant regime of a ship rolling on longitude waves: $k_\theta^* = (0,8\div1,2)$ for the basic resonance; $k_\theta^{**} = (1,95\div2,05)$ for a parametrical resonance; $h_\theta = 0,5[(h_o)_{min} + (h_o)_{max}]$ – average meaning of metacentric height on longitudinal waves; $(h_o)_{min}$, $(h_o)_{max}$ - extreme meanings of metacentric height at crest and trough of a waves designed for conditions, at which the capsizing moment $(M_c)_w$ was determined.

The physical sense of considered formulas is explained by the following reasons. The capsizing moment at movement of a ship in conditions unguided turn on following waves continuously changes depending on instant situations of a ship concerning a wave. Thus the ship moves from a situation with some small course angle on following waves to a situation board to waves (usually capsizing comes a little bit earlier, than the ship will achieve this situation). The capsizing moment during evolution appears close to average meaning on waves approximately at a course angle 45 degrees. It is necessary to note, that approach offered in works of other authors based on use of the stability diagram of a ship on still water, does not reflect a real picture of change of the capsizing moment in waves, and results in mistakes in an estimation of a situation.

6. PRACTICAL REALIZATION

The practical realization of safety criteria in a broaching regime can be carried out in control system of ship on waves.

Algorithm of a ship control. The control algorithm on the basis of a normal functioning principle is realised in onboard system of safety navigation and it is represented by a set of logic rules "IF – THEN". Each rule contains in the left part variable condition, and in the right part variable, describing control (action). As the initial information angle of yawing χ and speed of change of this angle $d\chi/dt$ are used. The control in a considered critical situation is accepted as change (decrease) of ship speed V proceeding from maintenance of the given system of criteria. The algorithm is represented as control matrix of dimension 5×5. Elements of a matrix are the meanings of an fuzzy variable task (fig. 6).

X_2 \ X_1	NM	NS	ZE	PS	PM
NM			PM		
NS			PS	NS	
ZE	PM	PS	ZE	NS	NM
PS		PS	NS		
PM			NM		

Fig. 6. Algorithm of control ship on following waves

From figure follows, that the considered fuzzy set is broken on five classes for everyone fuzzy variable. For a set of meanings considered linguistic variable " yawing angle" and "angular yawing speed" the following standard designations are entered: PS – positive small, PM – positive medium, ZE – zero, NS – negative small, NM – negative medium.

The empty cells of a matrix in a fig.6 specify, that any actions for the given condition of system don't undertake. For example, if a angle of a ship yawing on following waves NS and yawing speed NM, any influences on system do not appear.

Let' s consider work of a ship control system in conditions of following waves with use of fuzzy logic rules:

Rule 1: IF X_1 is NM AND X_2 is ZE
THEN Y is PM; (12)
Rule 2: IF X_1 is NS AND X_2 is ZE
THEN Y is PS. (13)

where $\tilde{O}_1$ and $\tilde{O}_2$ – fuzzy standardisation of meaning of a angle and angular speed of yawing, given by the appropriate meanings of membership functions.

Let at some moment of time by results of measurements the meanings of the criteria characteristics $\tilde{O}_1$ and $\tilde{O}_2$ are calculated. Using conjunction for the left parts of rules 1 and 2, we receive [14]:

$(X_1)^*= \min\{\mu_{NM}(X_1),\mu_{ZE}(X_2)\};$ (14)
$(X_2)^*= \min\{\mu_{NS}(X_1),\mu_{ZE}(X_2)\}.$ (15)

In result we have:

$y_1= \mu_{c1}^{-1}(X_1)^*,\ y_2 = \mu_{c2}^{-1}(X_2)^*,$ (16)

where μ_{c1} and μ_{c2} is result of calculation (14) and (15).

Then average weighted value of contribution of the rule 1 and 2 with used defuzzyfication calculation to formula:

$y^*=\sum_{i=1,n}(\tilde{O}_1)_i^*\acute{q}/\sum_{i=1,n}(X_1)_i^*$, will determine clear definition of the output characteristic (control influence Y), where n - number of rules in system.

Elements of a matrix in a fig.6 corresponds to one of five possible condition of control influence Y. They can be generated through artificial neural network (ANN) [14]. The scheme of knowledge base control on a ANN basis is submitted in a fig.7 In system there are two control inputs X_1 è X_2 and one control output Y.

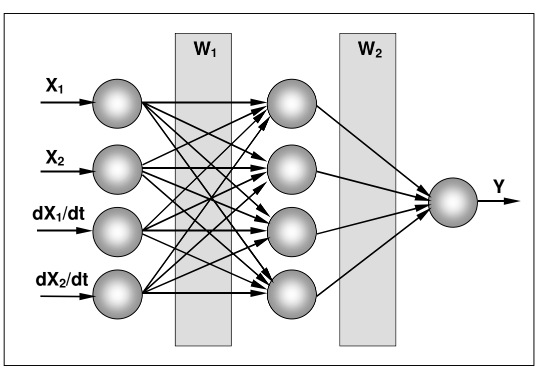

Fig. 7. ANN, ensuring control of a ship in yawing conditions on following waves

The training of a network is made with the help of genetic algorithm (GA) on meanings of membership functions for $\tilde{O}_1$ and $\tilde{O}_2$, which move on an input of system, and meanings Y on an output. As a result of GA use is formed complex many-dimensional surface of a control mistake as the function of parameters of the control law. GA finds a global minimum of this surface.

7. CONCLUSION

The carried out research of a ship dynamics in a broaching situation allows to make the following conclusions:

1. Dynamics of a ship during non-control turn substantially is determined by character of nonlinear function of the righting moment continuously varied in time and in space. The presence of this function results in qualitatively other picture of oscillatory movement of a ship at rolling on waves and to decrease of stability during non-control turn. The replacement of this function by the stability diagram on silent water results in an error in the dangerous party.

2. The analysis of modelling results of broaching dynamics has allowed to develop system of criteria determining of a ship safety in this extreme situation. The criteria provide an estimation of an opportunity of a ship capsizing and prevention of hit of a ship in area of occurrence strong rolling in a regime of the basic and parametrical resonance.

3. On the basis of the developed criteria to construct algorithm of a control ship at movement on following waves. This algorithm can be realised at creation of onboard of real-time intelligence system. The functioning of such system is provided on the basis of the concept "soft computing", based on principles of construction of fuzzy systems, ANN theory and GA.

Thus, the results of research can be used both in research designing, and by development of intelligence systems of a safety of navigation.

8. REFERENCES

1. **Ananyev D.M. Gorbacheva L.M.** Applied tasks of seaworthiness. – Trans. of ÊTIRPKH. Cdiningrad, 1993.

2. **Ananyev D.M., Loseva L.** Vessels heeling and stability in the regime of manoeuvring and broching in following seas/ STAB-94.Melbourne.Florida.USA.

3. **Du Cane.** The following sea, broaching and surging. TINA. v.104. ¹ 2. 1962.

4. **Grim O.** Surging motion and broaching tendencies in a irregular sea// Deutche hydrographische Zeitschrift, 1963, ¹ 5, p.p.201-251.

5. **Nechaev Yu.** Modeling of ship stability on waves. Modern tendency. - Leningrad: Sudostroyenie, 1989.

6. **Nechaev Yu.I.** Standartization of stability Problems and perspectives // Proc. of 6^{th} international conference on stability of ships and ocean vehicles STAB-97. Varna. Bulgaria. 1997. Vol.2,, p.p.39-45.

7. **Nechaev Yu., Makov Yu.** Algorithm of calculating righting moment when ship sails on arbitrary course in rough seas // Proc. îf third International conference on marine industry MARIND-2001. Varna Bulgarià 2001. vol. 1, p.p.213-217.

8. **Nechzev Yu., Zavyalova O.** The broaching interpretation in learning intelligence systems // Proc. of 14^{th} International Conference on Hydrodynamics in Ship Design. Szcecin-Miedzyzdroje, Poland, 2001, p.p.253-263.

9. **Nechaev Yu., Zavyalova O.** Stability estimation in the non control of ship on broaching regime // Proceedings of science national conference «Problems of seaworthiness and ships hydrodynamics» (Krylov reading). St.Petersburg. 2001, p.p.114-116.

10. **Neves M.S., Perez N, Lorca O.** Roll motion and stability of ship in waves// Proceedings of fourth international conference on marine industry MEET/MARIND'2002. Varna. Bulgaria, 2002, p.p.127-139

11. **Pauling J., Kastner S., Schafran S.** Experimental studies of capsizing of intact ships in heavy seas. IMCO. STAB/7. 1973, P.p.1-54.

12. **Renilson M., Tuite A.** Broaching simulation on small vessels in severe following seas // Proceeding of International Symposium «Ship stability in a Seaway»: Stability, Maneuverability, Nonlinear approach. Kaliningrad. 1995. Vol.1. ¹ 15, p.p.1-14.

13. **Spyrou K. J.** The nonlinear dynamics of ship in broaching // Proc. of First international congress on mechanical and electrical engineering and technology «MEET-2002» and Fourth international conference on marine industry «MARIND-2002».Vol.3. Varna. Bulgaria. 2002, p.p.51-57.

14. **Wasserman F.** Neurocomputer techniques. – Moscow. World.1992.

15. **Zadeh L.** Fuzzy logic, neural networks and soft computing // Commutation of the ACM-1994. Vol.37. ¹ 3. 1994.

16. **Zavyalova O.** Mathematical modelling of conditions of imitation and development of extreme situation on irregular waves // Proceedings of third international shipbuilding conference –ICS'2002. St.Petersburg. 2002. Section B, p.p.224-228.