Ships Dynamic on Wave-Breaking Condition

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ABSTRACT

Features of ship stability modeling in wave-breaking conditions are discussed. Analysis includes comparison of modeling results based on two various hypotheses. S.N.Blagoveschensky and A.N.Kholodilin offered the first one. It considers dynamic process as a sudden ship inclination as a result of breaking wave impact. N.B.Sevastianov formulated the second hypothesis on the basis of physical modeling results obtained in various towing tanks. In this case dynamics is represented as a result of vessel heal appearance under action of hydrodynamic moment during development of impetuous drift from breaking wave impact. The modeling was carried out for the identical initial conditions.

Keywords: *competition principle, stability, breaking waves, on-board intelligent system*

1. INTRODUCTION

Great volume of calculations is carried out in onboard intelligent systems designed for ship's seaworthiness monitoring. They include processing and analysis of measuring information coming from measuring system, construction and analysis of mathematical models, estimation and forecast of considered situations, imitating modeling of vessel-environment interaction. The hierarchy of mathematical models is expressed with the help of the various interpretation graphs describing standard and extreme situations arising in practice. As one of such examples situations tree for description of dynamics interaction of vessel with environment in storm conditions is shown on fig.1. The diagram assumes construction of models structure describing loss of oscillation stability (capsizing) depending on wind and waves features and vessel orientation (see references).

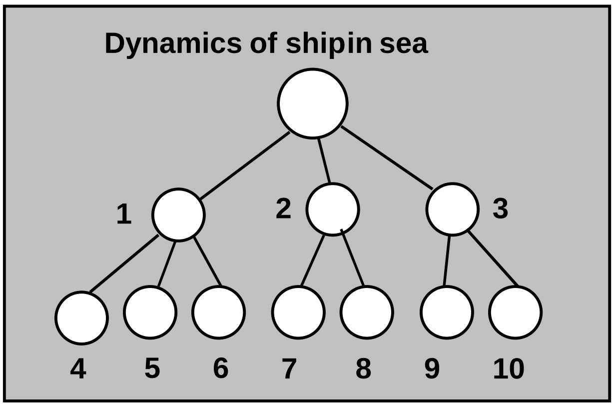


Figure 1. Decomposition tree of the system characterizing waves peculiarities and extreme situations of ship-environment interaction: 1 – random sea; 2 – breaking sea; 3 – extreme waves; 4 – pure loss of stability; 5 – resonance regimes; 6 – broaching; 7 – breaking waves in deep sea; 8 – breaking waves on shallow water; 9 – extreme wind waves; 10 – freak waves.

Methods of imitating modeling, statistical and fuzzy models (Nechaev, 2002, Intelligent systems, 2001) are applied for estimation and forecasting of extreme situations development. With the help of such models estimation of environment parameters and vessel characteristics is conducted. The problem of filtration and forecast arises at processing of measured information in problems of prediction of dynamic characteristics and time intervals evolution determining critical conditions based on ship's safety. The classification problem (images recognition) is related with estimation of situation danger and also at realization of applied control problems and decision-making (analysis of alternatives, recognition of extreme situations, etc.). Realization of specified computing technology for seaworthiness estimation is carried out on the basis of competition principle (Nechaev, 2002) providing the comparative analysis of alternatives and a choice of the preferable decision, resulting by the shortest and more reliable way to estimation of safety of considered extreme situation

2. PROBLEM TO SOLVE

The built-in procedure based on comparison (within the framework of competition principle) of modeling results based on two various hypotheses is put in a basis of analysis of ship dynamics in breaking waves in onboard intelligent system (IS):

- hypothesis of S.N.Blagoveschensky and A.N.Kholodilin (Kholodilin, Shmyrev, 1976) considers dynamic process as sudden inclination of ship as a result of breaking wave action;
- hypothesis N.B.Sevastianov (Nechaev, 1989) is formulated on the basis of results of physical modeling of situations carried out in different towing tanks. It considers ship dynamics as a result of development of very fast drift from the kick off the breaking wave.

Initial conditions and acting forces in both cases are identical. However due to use of various models results of modeling appear various. In alternatives analysis the preference is always given to the model providing better accuracy within the framework of accepted assumptions. Thus the mistake to dangerous side is not supposed, as modeling results are related with estimation of the major seakeeping qualities determining safety.

Mathematical description of situation in according with N.B.Sevastianov's hypothesis is given on the basis of differential equations system describing rolling and swaying (Nechaev, 1989), whereas within the framework of Blagoveshchensky-Kholodilin's hypothesis the only rolling differential equation (Kholodilin, Shmyrev, 1976) is used. Calculation of breaking waves elements is carried out on the basis of technique developed by B.V.Mirokhin (Kholodilin, Shmyrev, 1976).

Character of ship's inclination on breaking waves on shallow water and deep sea is practically identical. Difference is consist of only the following. Occurrence of extreme waves (which vertical sizes is more than height of vessel) of huge destructive force (freak wave) can appear in a deep sea. Getting in such sea zone with sharply changed form of a wave surface and complex hydrodynamic structure, the vessel is completely covered by the wave, involved in very fast drift and capsizes, exposing heeling loadings considerably exceeding external forces in usual operation conditions (Nechaev, 1989).

It is necessary to note, that small vessels are usually operated in a coastal zone. Waves formed on shallow water are commensurable with the vertical dimensions of such ships and sometimes surpass them. Breaking waves in a coastal zone represent terrible danger for navigation also because in this zone there can be a breakdown of large waves (for example, waves of tsunami).

3. PROPOSED ALGORITHM

3.1 Environment and considered object

Small fishing vessel is considered as the object of investigation. It is known (Kholodilin, Shmyrev, 1976) that this ship was capsized by breaking wave.

Initial data for modeling:

- Average values of waves: height - $\overline{h}_w = 1{,}65m$; period - $\overline{\tau}_w = 6s$; length - $\overline{\lambda}_w = 56m$; average wave steepness - $\overline{\delta}^* = 0{,}03$.
- Ship characteristics (Table 1): main dimensions (length, beam, depth, draught in meters); displacement, GM, metacentric radius, z-coordinate of center of gravity, waterplane area coefficient, lateral area coefficient.
- Righting arm curve (fig.2).

Table 1: Ship Characteristics

Ship characteristics

Max length of ship	19,4	(m)
Length between	18	(m)
Ship's beam	4,4	(m)
Depth	2,56	(m)
draught	1,57	(m)
Displacement	45,8	(t)
GM	0,86	(m)
Metacentric radius	4,68	(m)
Z-coordinate of center of	1,5	(m)
Waterplane area coefficient	0,8	
Lateral area coefficient	0,9	

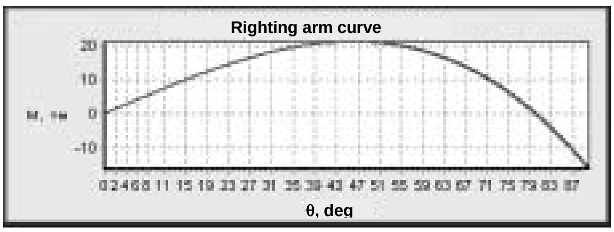


Figure 2. Form for initial data input (left) and righting arm curve (GM-curve) (right). Screen-short.

3.2 Forced impact of breaking waves

Power of breaking wave impact is

$$P_\eta = 1{,}2\lambda_{22} F_{1\max}. \qquad (1)$$

where λ_{22}– added mass calculated by the following way:

$$\lambda_{22} = \lambda_{22\,mid} L \frac{2\beta_0^2}{1+\beta_0},$$

β – lateral area coefficient; $\lambda_{22mid}=0.5\pi\rho T^2$ – added mass of middle frame; F_{1max} – maximal value of acceleration in single wave (in accordance with diagram in work (Kholodilin, Shmyrev, 1976)).

Time of power impact action

$$t_y = \psi_1 \sqrt{H_c}, \qquad (2)$$

where ψ_1 = 0,76 at relative wave height γ=0,8 (with respect to depth), H_c – depth of sea under wave base.

Impact impulse

$$I_y = 0.5 P_\eta t_y$$

Z-coordinate of wave impact center

$$z_y = 0.5\,\psi_2 (T+h) \qquad (3)$$

where h is minimal value of wave height or protected freeboard, ψ_2 = 1,14 at γ=0,8.

Z-coordinate of ship's gravity center taking into account wave added masses:

$$z_{G1} = \frac{\frac{D}{g} z_G + \lambda_{22} z_\lambda}{\frac{D}{g} + \lambda_{22}}; \quad z_\lambda = T - \frac{\lambda_{24}}{\lambda_{22}}. \qquad (4)$$

Value λ_{24} is determined in accordance with the following expression

$$\lambda_{24} = \lambda_{24mid} L \frac{1}{1-s^2}\left(\frac{2\alpha^2}{1+\alpha} - s^2\right);$$

$$\lambda_{24mid} = \frac{\rho T^3}{2}\lambda_{yz};$$

where $s=2T/B$; α – waterplane area coefficient; λ_{24mid} – static moment of added mass for midship section.

For elliptic station

$$\lambda_{yz}=1-\frac{8}{3}\frac{p}{1+p},\ \text{where } p = \mathrm{T}-0.18.$$

Initial conditions and force impact in calculations of ship dynamics on breaking waves are considered as identical in comparative analysis.

3.3 Procedure based on Blagoveshchensky-Kholodilin approach

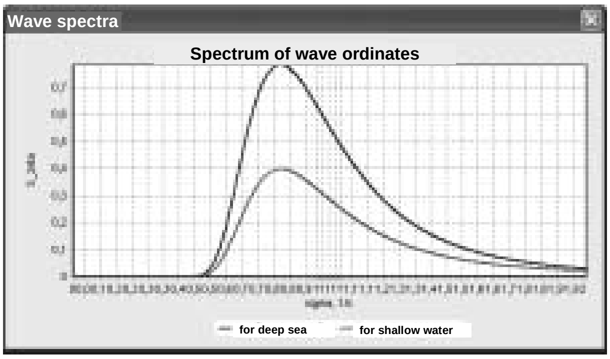
<u>Wind waves parameters.</u>

Deep water. Energy wave spectrum (fig.3):

$$S_\varsigma(\sigma)=1{,}78\frac{D_\varsigma}{\bar\sigma}\left(\frac{\sigma}{\bar\sigma}\right)^{-5}\exp\left[-0{,}44\left(\frac{\sigma}{\bar\sigma}\right)^{-4}\right] \quad (5)$$

where $\bar\sigma=2\pi/\bar\tau$ is average frequency, $D_\varsigma=\bar h^2/6.25$ - variation

Fig. 3. Spectrum of wave ordinates for deep sea (blue (upper) line) and for shallow water in breaking waves zone (green (lower) line). Screen-short.



Shallow water (breaking waves zone). Clearly that it is hard problem to describe breaking waves and to develop model of such phenomenon. It is possible to propose description of energy spectra in zone from deep water to breaking waves region. There are some well-known approximations one of which is TMA spectrum. In procedure proposed by S.N.Blagoveshchensky and A.N.Kholodilin spectrum of Yu.M.Krylov was used. He proposed to obtain energy spectrum for shallow water with the help of transfer function Π from ordinary spectrum for deep water (Krylov, 1966):

$$S_{\varsigma sw}(\sigma)=\Pi\left(\frac{\bar\tau_w}{\tau},\frac{H}{\bar\lambda_w},\alpha\right)S_\varsigma(\sigma)$$

$$\Pi\left(\frac{\bar\tau_w}{\tau},\frac{H}{\bar\lambda_w},\alpha\right)=\frac{\int_{\alpha-\pi/2}^{\pi/2}\cos^2(\theta-\alpha)\,K_h^2\left[\frac{H}{\bar\lambda_w},\frac{\bar\tau_w}{\tau},\theta\right]d\theta}{\int_{\alpha-\pi/2}^{\pi/2}\cos^2(\theta-\alpha)d\theta} \quad (6)$$

$$K_h^2=\frac{\cos\theta}{\sqrt{1-\left(\frac{c}{c_0}\right)^2\sin\theta}}\left\{\frac{c}{c_0}\left[1+\left(\frac{4\pi H}{\lambda_0}\Big/\frac{c}{c_0}\right)\sinh^{-1}\left(\frac{4\pi H}{\lambda_0}\Big/\frac{c}{c_0}\right)\right]\right\}^{-1}$$

$$\frac{c}{c_0}=\tanh\left(\frac{2\pi H}{\lambda_0}\Big/\frac{c}{c_0}\right);\quad \frac{H}{\lambda_0}=\frac{H}{\bar\lambda_w}\left(\frac{\bar\tau_w}{\tau}\right)^2$$

where h_0, c_0, λ_0 are height, phase velocity and length of spectral component on deep water; h, c are the same for shallow water; H – depth, θ - the angle between wave crest and rectilinear isobaths, α - the angle between average direction of wave crests and rectilinear isobaths.

<u>Transfer function.</u> Calculation rolling transfer function is performed by the following way:

$$\left|\Phi_{\varsigma\theta}\right|=\frac{\sigma^2\chi_\theta n_\theta^2}{g\sqrt{\left(n_\theta^2-\sigma^2\right)^2+4\nu_\theta^2\sigma^2}}, \quad (7)$$

where $\chi_\theta=1-\frac{2\pi T}{\lambda_в}\frac{r}{h}$ – reduction coefficient taking into account finiteness of ship ship dimensions (calculated in accordance with Gerasimov's formula), $n_\theta=2\pi/T_\theta$ – natural frequency of rolling, $\nu_\theta=0{,}3(\omega_0)^{1/2}$ – linear coefficient of rolling dumping, ω_0 – quadratic damping coefficient, $\lambda_в$ – wave length, r – metacentric radius, h – GM.

Natural rolling period is obtained by the formula $T_\theta = cB/\sqrt{h_0}$, where coefficient c is accepted as 0,80 — for deep water and 0,84 — for shallow water. Hence $\bar\tau_{вк}/T_\theta\approx 1{,}8$. It corresponds to negative impact phase of breaking wave.

Spectral density of rolling amplitudes and velocities (fig.4) are determined by the following way:

$$S_\theta = \left|\Phi_{\varsigma\theta}\right|^2 S_\varsigma; \quad S_{\dot\theta} = \sigma^2 S_\theta. \tag{8}$$

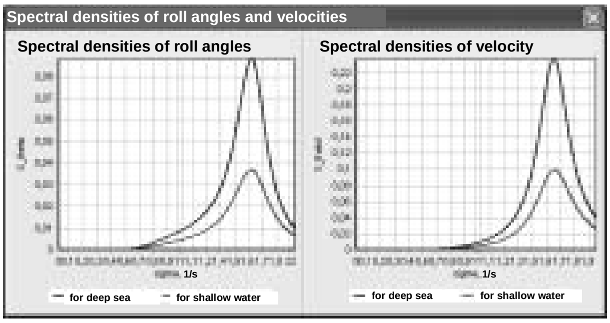


Fig.4. Spectral densities of roll angles and velocities for deep water (blue (upper) line) and shallow water (green (lower) line). Screen-short.

Ship motion. Variances D_θ and $D_{\theta'}$ are determined by the way of S_θ and $S_{\dot\theta}$ integration, rolling amplitude with 0.1% provision for deep and shallow water is

$$\theta_{0,1\%} = p\sqrt{D_\theta}, \tag{9}$$

where p=3,7 for 0.1%.

Calculated value of roll rate in the moment of breaking wave crest impact (taking into account roll decay):

$$\dot\theta_k = \dot\theta_{0.1\%} \exp(-n\nu T_\theta),$$

where n – the number of periods (for $\tau/T_\theta \approx 1{,}8$ n=1, for $\tau/T_\theta \approx 2{,}8$ n=2, etc.); T_θ – natural rolling period taking into account shallow water; ν- damping coefficient on shallow water.

Angular rolling velocity acquired in result of breaking wave action is,

$$\dot\theta_y = \frac{(z_y - z_{G1}) I_y}{I_{1мв}}, \tag{10}$$

where $I_{1МВ}=c^2B^2D/(4\pi^2)$ — moment of inertia of ship's mass relatively longitudinal axis.

Kinetic energy. Kinetic energy of rolling ship in wave impact moment is

$$K = \frac{(\dot\theta_k + \dot\theta_y) I_{1мв}}{2}. \tag{11}$$

Comparing kinetic energy with the storage of potential energy T_d, determined with the help of dynamic stability curve it is possible to determine whether ship stands simultaneous action of rolling and breaking wave impact.

3.4 Procedure based on approach of N.B.Sevastianov

The procedure consists of roll and sway differential equations integration (Belenky, Sevastianov, 2003; Nechaev, 1978; Nechaev, 1989):

$$(D/g+\mu_{\eta\eta})\eta''+\lambda_{\eta\eta}{}^{*}\eta'+\lambda_{\eta\eta}{}^{**}(\eta')^2 = P(t); \tag{12}$$

$$(J_x+\mu_{\theta\theta})\theta''+M_R(\theta')+M(\theta)=M_x(t) \tag{13}$$

where $D/g+\mu_{\eta\eta}$ – ship's mass with added mass; $J_x+\mu_{\theta\theta}$ – ship's inertia moment with added moment relative to longitudinal axes; $\lambda_{\eta\eta}{}^{*}$ and $\lambda_{\eta\eta}{}^{**}$ – coefficients of drift resistance for linear and quadratic terms; $M_R(\theta')$ – moment of damping forces; $M(\theta)$ – restoring moment; $M_x(t)$ – excitation moment inclusive moment of impact impulse $P(t)$ and moment of hydrodynamic forces of noninertial nature caused by drift.

Moment $M_x(t)$ acting on ship in drift conditions is characterized by expression

$$M_x(t) = [-P(t)z_p + Q_\eta z_q] \cos\theta - \mu_{\eta\theta}\eta \,, \qquad (14)$$

where z_p – z-coordinate of origin of force caused by impact of breaking wave;

$$Q_\eta = (a_1 v + a_2\eta)\, 0{,}5\rho\, S_o \eta \ \text{—} \qquad (15)$$

is transverse horizontal noninertial force (a_1 and a_2 – coefficients determined by the experimental way, S_o – waterplane area.; z_q – z-coordinate of origin of force Q_η (for considered hull shape the value z_q significantly depends for roll angle and determined in accordance formula (Nechaev, 1989)); $\mu_{\eta\theta}$ – added static moment for the case of steady drift.

4. RESULTS OF MODELING

Results of modeling are shown on the fig.5-7 for three different situations describing interaction of ship with breaking wave. On these pictures characteristics obtained by using of Blagoveshchensky-Kholodilin procedure are shown at the left side, the same for Sevastianov's procedure are at the right side. In all cases the impact power is 25,47 tons. However the action time is different: for the first case (fig.5) it is equal to 2,3 s, for the second case (fig.6) it is equal to 1,24 s, and for the third (fig.7) – 1,19s.

Variation of impact time resulted in different characteristics of ship's dynamics. In particular variances of rolling are 0,0397; 0,0328; 0,0286 (rad^2) – for deep water and 0,0196; 00158; 0,0135 (rad^2) – for shallow water; variances of roll velocity 0,1057; 0,874; 0,761 (rad^2/s^2)– for deep water and 0,055; 0,0442; 0.0378 (rad^2/s^2) – for shallow water. Corresponding values of $\theta_{0.1\%}$ are 42,2^o; 38,4^o; 35,8^o – for deep water and 29,7^o; 26,6^o; 24,7^o – for shallow water; $\dot{\theta}_{0.1\%}$ are 1,203; 1,094; 1,021 (rad/s) – for deep water and 0,868; 0,778, 0,719 (rad/s) – for shallow water.

Characteristics determining impact load of breaking wave are also changed:

- impact impulse 16,51; 15,74; 15,20 t·s;
- z-coordinate of center of gravity in the impact moment 2,44; 2,30; 2,21 m;
- ang. vel. after impact 1,31; 1,11; 0,98 s^{-1}.

Kinetic energy of oscillating ship at the moment of impact are equal correspondingly 23,75; 17,52; 14,03 t m, potential energy determining in accordance with dynamic stability curve in all cases is equal to 19,19 t m.

Comparative analysis of modeling results permits to propose the following conclusions:

- different interpretations of dynamics of "ship – breaking wave" interaction at the same initial conditions result in different stability parameters in such critical situation;
- taking into account drift influence originating at impact of breaking wave (hypothesis of N.B.Sevastianov) sometimes is more dangerous than dynamic inclination of ship in situation describing in frameworks of hypothesis of S.N.Blagoveshchensky and A.N.Kholodilin (see fig.6);
- detailed analysis of situation based on competitive principle is required for choosing of preferable computational technology for assessment of capsizing dangerous in breaking waves conditions. It permits to evenly assess stability and to increase efficiency of on-board decision support system providing navigation safety.

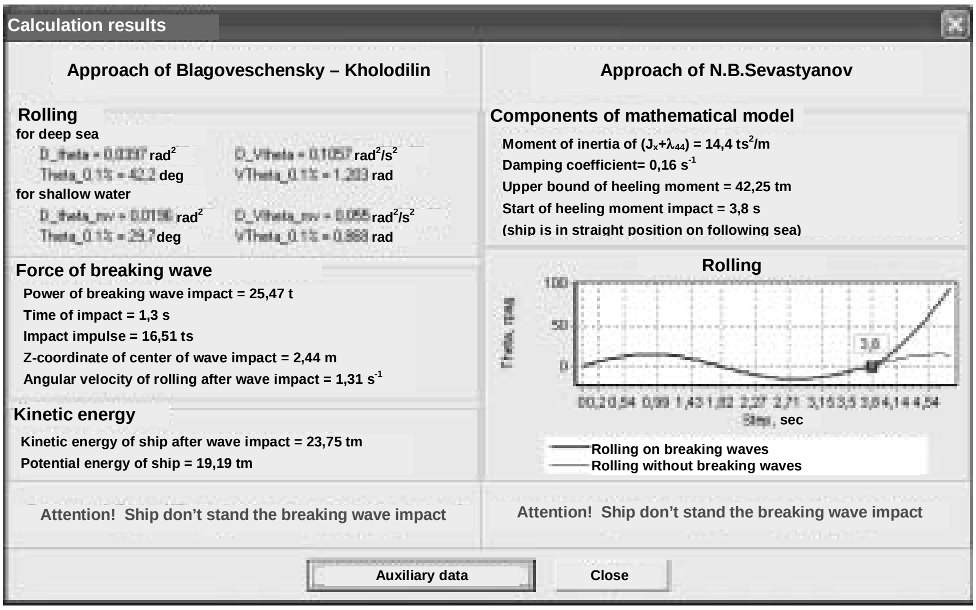


Fig.5. Modeling results. Impact time 1,3 s. Screen-short: results of approach of S.N.Blagoveshchensky and A.N.Kholodilin (left side) and approach of N.B.Sevastianov (right side).

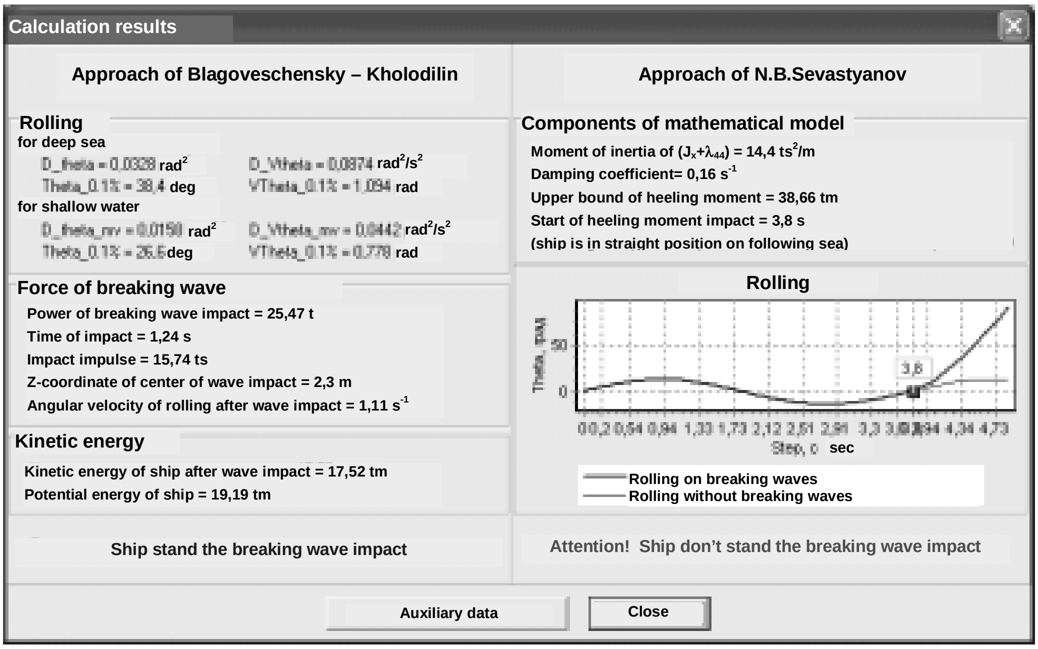


Fig.6. Modeling results. Impact time 1,24 s. Screen-short: results of approach of S.N.Blagoveshchensky and A.N.Kholodilin from the left side and approach of N.B.Sevastianov from the right side.

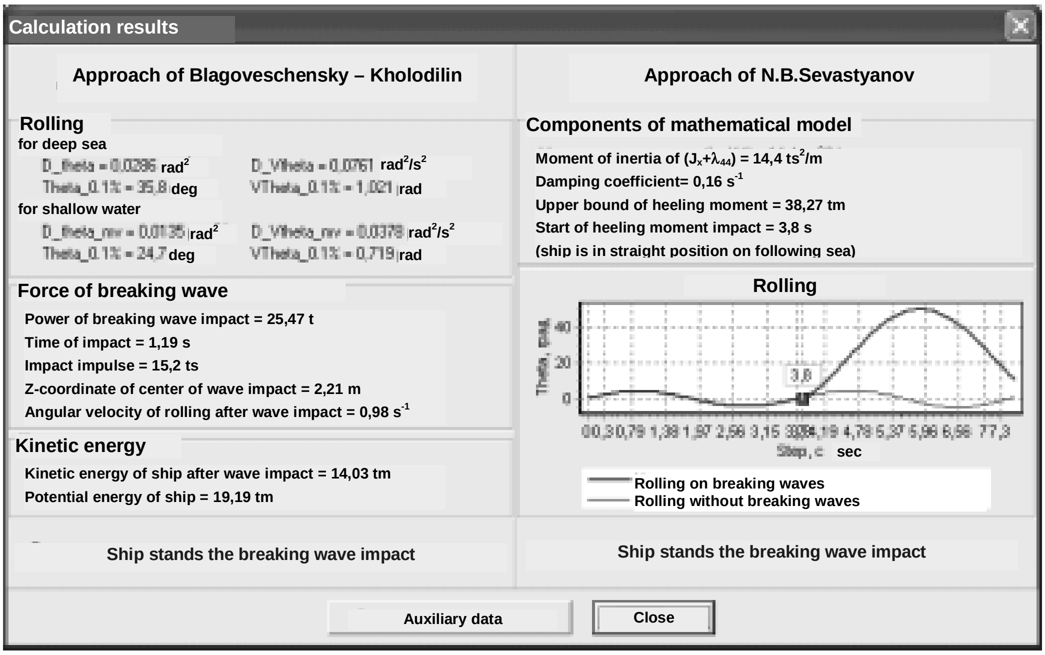


Fig.7. Modeling results. Impact time 1,19 s. Screen-short: results of approach of S.N.Blagoveshchensky and A.N.Kholodilin from the left side and approach of N.B.Sevastianov from the right side.

5. CONCLUSION

Results of carried out research show importance of competitive principle using for complicated situations analysis. Comparative analysis of different approaches, methods and models of “ship-environment” interaction in frameworks of competitive principle permits to determine more preferable computational technology that permits to obtain more reliable result. It is especially important in such situations when we have not strict theoretical models and construction of situations interpretation algorithms are based on different hypothesizes. The problem of ship’s dynamics in breaking waves conditions has such characteristics in full measure. As it has seen from the analysis results attraction of physical mechanisms for algorithms construction permits to expand possibilities of the method and to carry out complete investigation of “ship-environment” interaction.

Considered approach has important sense for stability control at the board of the ship in operational conditions. It is possible “to play” different scenarios of situation development and to present to navigator all necessary information for valid decision adoption on ship control in complex hydrometeorological situation with the help of on-board intelligent system.

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