

Virtual Testbed: Computational Component of Wind Waves – Ship Interaction

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Abstract. Marine virtual testbed is a problematic solving environment for virtual experiments conducting to study the behavior of marine objects in various conditions. These conditions may cover cases that are either very difficult or dangerous for model or natural experiments. In addition, the numerical experiment is always cheaper. To ensure the necessary accuracy at the reproduction of maritime object behavior under the action of external excitations it is necessary to have appropriate mathematical models. For effective apply of these models, numerical implementation using the advantages and features of the hardware is needed.

This article discusses the interaction of wind trochoidal waves with the maritime object in a complete formulation, taking into account the forces of Frouda-Krylov, and the diffraction component. Mathematical description of wind waves and subsurface currents is given. Modeling of vertical fluid particle oscillations is considered using finite differences. Full-fledged trocoidal waves are considered taking into account the dispersion of visible and group velocities of waves.

As a result, both the hydrostatic formulation of ship moving by arbitrary course on a stormotable waves, and complete hydrodynamic modeling, taking into account the local flow rates near the ship hull and reflection of waves are modeled in the numerical experiment.

Keywords: Virtual testbed · Hydrodynamics · Direct computational experiment · Trohoidal waves · Efficiency of ship sailing in stormy conditions

1 Introduction

The problems of the virtual testbed presented earlier in a number of articles [1–4]. Noted that the main computational task of the virtual testbed is the implementation of a complex mathematical model of an object, environment and their interaction. With a modern level of hardware development, this task is solvable at the well-known physics of the phenomenon under consideration. The second task of implementing the virtual testbed is the effective numerical implementation of mathematical models, taking into account the architecture of computing systems. The latter is possible in case of effective implementation of basic computing operations and transformation of mathematical models

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for these purposes. This level of operations can be attributed, for example, multiplication of the matrix to the vector, the transition from one coordinate system to another, interpolation, etc. In earlier works, we paid special attention to this topic [5–7].

In this paper, it presents and discusses tools for construction of direct computing experiments for visually demonstrative computer experiments of ship stormy seaworthiness within the marine virtual testbed. In the development of mathematical models and algorithmic solutions, special attention is paid to the efficiency of computing operations.

At the basis of stormy sea computing models, theoretical results and mathematical solutions for trochoidal big waves were used [8]. In these solutions, the parametric determination of the kinematics of the fluid particles is comparable to a corpuscular approach to the waveforming model. The conditionally free movement of cyclic displaceable cells of calculated mesh is dynamically reinterpolated to the coordinates associated with the vehicle body. This is required for the unambiguous permission of the problem of the ship's hydromechanics in stormy conditions.

The computational experiment was originally designed in the concepts of separation of solutions on physical processes [9–12]. This simultaneously allows you to use an interactive selection of both the actual models of sea waves and the nature of the power interaction of ship hull with intensive excitation.

1.1 Basic Notations

r_w [m] – local radius on the path of wave movements of fluid particles;

$\tau = 2\pi/\omega$ [s] – wave period, $\lambda = 2\pi/k$ [m] – wave length;

$C_w = \lambda/\tau = \omega/k$ [m/s] – phase speed;

$C_w = \sqrt{g/k} = \sqrt{g\lambda/2\pi}$ – phase/visible speed of trochoidal waves on deep water;

$\varphi_w = 2\pi\,(s + tC_w)/\lambda_w$ – phase angle for determination of displacement of trochoidal waves basis, where: s [m] – space distance, t [s] – time countdown at speed C_w [m/s];

$\omega = 2\pi \cdot C_w/\lambda = 2\pi/\tau$ [1/s] – circular frequency of wave pulsations;

$\rho = 1025$ [kg/m^3] – fluid density; g – gravity acceleration [m/s^2];

$\overrightarrow{\zeta}$ [m] – vector of fluid particle displacement in vertical plane;

$\overrightarrow{v}$ [m/s] – vector of fluid particle velocity in movement along trochoidal path.

Volume – ship displacement; *vW* – underwater ship hull volume; $\overrightarrow{vB}$ – current coordinates of center of buoyancy, $\overrightarrow{Gravity}$ – current coordinates of center of gravity; $\overrightarrow{B}$ – vector of Archimedes force; $\overrightarrow{iV}$ – normal to wave slope; $\overrightarrow{V}$ – vector of linear velocity, $\overrightarrow{\Omega}$ – vector of angular velocity; $\overset{\times}{inMass}$ – mass (volume) tensor; $\overset{\times}{r}$ – ship coordinate basis; $\overrightarrow{R}$ – distance between centers of buoyancy and gravity.

General notations using at algorithms description are shown in [7, 9].

2 Analytical Description of Computational Experiment

Sea waves in open water quakes can be modeled in various ways. One of the effective computing models reflecting all the physical characteristics of real waves is ARMA [13, 14]. For this reason, this model is implemented in the structure of the marine virtual testbed [1, 3]. Conducting serial calculations using real oceanological data on

the structure of sea waves, as well as numerous data from the open sea, shows that the sea surface is most often observed wave fronts. This makes possible mathematical description of waves using simplified two-dimensional profiles of trochoid waves, which also allow you to take into account the nonlinear nature of sea waves. In this case, the distribution of current speeds can only be considered relative to the gravitational vertical.

Numerical schemes for the free propagation of surface perturbations of an arbitrary shape with a strictly specified speed C_w. are used in a computational experiment on sea waves modeling. The inclusion of high-amplitude trochoidal waves in the boundary conditions leads to the reproduction of group structures of storm waves and subsurface currents throughout the water area of the computational experiment.

The fixed phase velocity of waves C_w means the use of analogues of long-wavelength or gas-dynamic finite difference schemes, in which the dynamics of the calculated cells is strictly determined by the local rheology of an inseparable continuous medium. A similar difference solution for trochoidal and strongly swirling marine gravity waves is still unknown.

It is assumed that the waves reflected from the moving ship retain free propagation speed. This is formally acceptable for an elongated ship if the longitudinal components of the Doppler frequency shifts are neglected. The reflection of storm waves from a ship moving under its own power will, on average, be compensated by relatively small transverse displacements of the ship's hull.

In any case, the algorithms for generating shipwalking with Doppler effects are required for the existence of a numerical solution. A fixed phase speed of waves will not prevent with adequate changes in the amplitude-frequency characteristics of the reflected waves. We can consider incorrect distortion as insignificant if we exclude second action on the ship's hull.

The storm observation of waves in open sea shows the existence of several stable group structures: steep waves under the action of wind and two-three swell systems. Group structures are determined in the form of a surface rhombic network from packets, on average, of nine wave fronts. They are running in the group with a double phase rate. At the borders of the wave packets, the phase references are cyclically changed. The relative length of the fronts or the relative width of the rhombic packets increases with a decreasing of wave slops, and the line of crests of particularly steep waves are partly bending in the direction of phase velocity.

In the computational model defined in this way, sea waves are given by a superposition of three (or more) independent wave systems. These are group structures with fixed phase velocities. They are separately affect the ship. A fundamental feature of this model is the accounting of reflected waves from the oscillated ship hull. All of these independently existing wave processes are summed up to recreate the resulting surface of the storm seas and subsurface flows. Ship dynamics modeling (ship performance and motion) is carried out on the basis of this surface similarly [1, 3].

3 Mathematical and Computational Models of Trochoidal Waves

Mathematical model of trochoidal waves $\overrightarrow{\zeta}$ (t, s, z) [m] is presented in vector form on profile plate $w \in \{s, z\}$ in direction of wave front propagation s [m] with gravity vertical z [m]. Phase start of wave front in computational experiment comes from zero initial time t [s] and half-length of diagonal of model water area Lb [m].

$$\varphi_w = 2\pi\,(t \cdot C_w - s - Lb/2)/\lambda \text{ [rad]} \tag{1}$$

where: λ [m] is wave length moving with velocity C_w [m/s] in profile plane $w \in \{s, z\}$ at time moment t [s], from initial position s [m], taking into account the centering of initial position relatively half-length of basin diagonal Lb [m].

In the initial data, half-height of the wave is set using the trochoid radius r_w [m] at the level of the undisturbed surface of the sea $z = 0$ [m], from which the radius with depth is performed r_z [m]:

$$r_z = r_w \exp(2\pi z/\lambda)[\text{m}] \tag{2}$$

Believing the movement of particles of fluid on its own trocoidal trajectories, on which water pressure is leveled in depth under the slopes of wave ridges, a work is made for the first amendment on a local breaking:

$$r_z \times = \exp(2\pi r_z(\sin\varphi_w - 1)/\lambda)[\text{m}] \tag{3}$$

If it necessary we introduce asymmetric correction to wave profile for taking into account wind stresses Wd $[0 \div 1]$ and alignment of the middle sea level Cr $[0 \div 1]$:

$$r_z \times = \exp(2\pi r_z(Cr(\sin\varphi_w - 1) + Wd\cos\varphi_w)/\lambda)[\text{m}] \tag{4}$$

It is important to note that in the case of modeling of group wave structures with a speed dispersion, difference schemes incorrectly recreate subsurface flows of water.

The trochoidal wave profile in the mathematical model is written in vector form for a simple harmonic displacement of water particles from their initial neutral position:

$$\overrightarrow{\zeta} + = r_z\overrightarrow{\{-\cos\varphi_w, \sin\varphi_w\}}[\text{m}] \tag{5}$$

By definition, in a purely trochoid wave, fluid particles move through circular orbits with strictly equal angular velocities: $V_r = \omega \cdot r_z$ [m/s] defining phase velocity of wave crest free motion: $C_w = \lambda/\tau = \omega/k$ [m/s]. Taking the above-water space (air) conditionally weightless, the immersion of the liquid particle is counting on the level of active wave slopes, while the trochoid radii and the curvatures of the particle trajectories are scalable in the geometric proportions of the trocoidal wave as a whole (2) and (3): $V_r = \omega{\cdot}r_z = \omega{\cdot}r_w{\cdot}e^{kz}$, or for sea surface:

$$V_w = \omega \cdot r_w \cdot \exp(2\pi/\lambda \cdot (z + r_w \cdot (\sin\varphi - 1))), \text{ [m/s]} \tag{6}$$

where z is appliqued in the global Cartesian reference system.

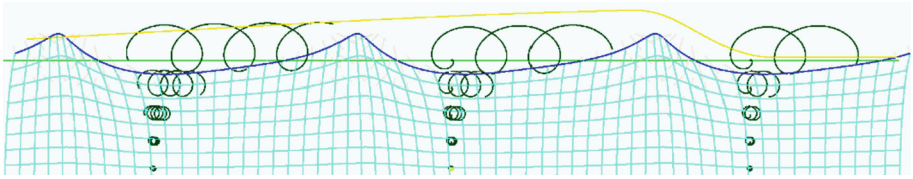

Fig. 1. Modeling of regular tropoidal waves under the action of near-water wind with correction of sea level.

Maximum amplitude in wave crest $\approx 1{,}134 \cdot r_w$ is noticeably more than in wave trough $\approx 0{,}614 \cdot r_w$. Ratio wave length to wave height $h = \lambda/\pi$ or $r_w = \lambda/2\pi$ corresponds to simple cycloid and approximately equal to $h \cdot k \approx 0{,}75$ or $\lambda/h \approx \pi \cdot 8/3 \approx 8{,}38$, where h is visible height of progressive wave from trough to crest.

Trochoidal trajectories of fluid particles illustrated dependence of drift flows from the relative height of the wave crest are show on Fig. 1. Maximum velocity of surface flows is achieved in the crest of braking progressive wave, which is approaching the value of the single wave phase velocity.

Coefficient $H_w = 8/3 \cdot \pi \cdot h/\lambda$ normalized relative to the maximum permissible height of trichoidal waves ($h = 2 \cdot r_w$ [m] is conditional wave height as doubled surface trochoid radius) is used for description of wave processes. Rhombic cell of the group structure has a length in the direction of movement: $L_g = \lambda \cdot 8.89$ [m]. Largest front length (width of the rhombic water area fragment is $F_g = \cdot 2\pi \cdot \lambda/H_w$ [m]) is inversely proportional to the relative height of the maximum wave in the center of the group structure.

3.1 Features of Algorithmic Representation of Storm Wave Models

Analysis of the stability of computational processes in time and preliminary coordination of the approximation smoothness of the simulated hydrodynamic fields precedes the construction of a computational model in finite differences.

Stability of wave equation is controlled by Courant criterion. The essence of the criterion is to prevent the intersection of the simulated perturbations of the calculation cell as a whole in one calculated cycle in time.

$$C_w < \delta s/\delta t \tag{7}$$

where C_w [m/s] is the set phase velocity of the simulated wave; δs [m] is the mesh step (common for all computational area); δt [s] is the time step for one cycle of computational experiment.

To achieve equal efficiency in modeling of three wave fields with different wavelengths, it is possible to establish as an initial condition for calculated time step δt [s]. This will naturally correlate with the ideas about the approximation smoothness of wave processes, which natural period of oscillations should be at least an order of magnitude longer. Then the spatial grid step will be assigned dynamically, as $\delta s = C_w \cdot \delta t$. This will create equally optimal simulation conditions for independent wave fields with predetermined phase velocities.

In practice, for a stable solution, it is necessary to slightly reduce the calculated time step δt. Usually it is enough to bring the crossing of one cell diagonally by the wavefront in two time steps ($tKrat \approx \sqrt{2}$ is the multiplicity of the time step splitting) for a rectangular grid. In a computational experiment, a change in the calculated time step does not lead to visible changes in the results of the simulation, except for a slight negative effect on the radiation conditions of the waves at the free boundaries. These are the Sommerfeld radiation conditions [15], in which for the normal component of the emitted wave it is necessary to make an adjustment to the step time form $tK = tKrat/(tKrat + 1)$.

To simplify the algorithmic writing, a dimensionless parameter-characteristic of the wave $kW = C_w \cdot \delta t/\delta s/tKrat$ (the ratio of the wave velocity to the grid speed) is introduced.

Extrapolation radiation conditions at free boundaries in accordance with Sommerfeld are determined only from sea level with respect to the normal component of the progressive wave running away from the calculated region:

$$\begin{aligned} \overset{+}{0}\vec{\zeta} \mathrel{+}= kW \cdot (\vec{1\zeta} - \vec{0\zeta}) \cdot tK &= C_w \cdot \frac{\delta t \cdot (\vec{1\zeta} - \vec{0\zeta})}{\delta s \cdot (tKrat + 1)} \quad [m] \\ \overset{+}{n}\vec{\zeta} \mathrel{+}= kW \cdot (\vec{n-1\zeta} - \vec{n\zeta}) \cdot tK &= C_w \cdot \frac{\delta t \cdot (\vec{n-1\zeta} - \vec{n\zeta})}{\delta s \cdot (tKrat + 1)} \end{aligned} \tag{8}$$

where low left indexes n are used for grid knots marking; symbol (+) as left upper index shows the next time indicator.

Dynamics of liquid particles is constructed in the vertical plane of the wave profile, where grid differences divided by half of spatial step provide synchronous interaction of the displacement vectors of the liquid particles $\vec{\zeta}$ [m] (local velocities $\vec{v}$ [m/s], phase velocity of wave propagation C_w [m/s] and angle rotation ω [1/s]).

$$\begin{aligned} \overset{+}{}\vec{\zeta} &= kW \cdot (\vec{v} - \vec{v}) / \omega = C_w \cdot \frac{\delta t \cdot (\vec{v} - \vec{v})}{\delta s \cdot tKrat} / \omega \quad [\text{m}] \\ \overset{+}{}\vec{v} &= kW \cdot (\vec{\zeta} - \vec{\zeta}) \cdot \omega = C_w \cdot \frac{\delta t \cdot (\vec{\zeta} - \vec{\zeta})}{\delta s \cdot tKrat} \cdot \omega \quad [\text{m/s}] \end{aligned} \tag{9}$$

All particles of the liquid are synchronously rotated along trochoidal radii in the direction of wave crest movement. This doubles the phase velocity relative to the group velocity. Thus, the wave packet propagates twice slowly as the apparent phase velocity. At the same time, the phase is constantly changing at the point of its first entry into the unperturbed water area:

$$\begin{aligned} \overset{+}{}\vec{\zeta} &= \delta t \cdot \omega \cdot \{-\vec{\zeta_z}, \zeta_x\} = \delta t \cdot \omega \cdot \{-\zeta_z + \zeta_x \cdot \delta t \cdot \omega / 2, \ \zeta_x + \zeta_z \cdot \delta t \cdot \omega / 2\} \quad [\text{m}] \\ \overset{+}{}\vec{v} &= \delta t \cdot \omega \cdot \{-\vec{v_z}, v_x\} = \delta t \cdot \omega \cdot \{-v_z + v_x \cdot \delta t \cdot \omega / 2, \ v_x + v_z \cdot \delta t \cdot \omega / 2\} \quad [\text{m/s}] \end{aligned} \tag{10}$$

3.2 Possible Variants of Virtual Testbed Functioning with Sea Waves Models

The undoubted advantage of computational experiments in hydromechanics is the possibility of preliminary or interactive selection of various mathematical models. This approach is in demand in many practical tasks. A variety of built-in methods for modeling sea waves is certainly useful when debugging the software that ensures the operation of the virtual testbed.

The following computational experiments with storm waves are implemented in the software package "Vessel":

1. The version of the calm sea without waves. It is necessary for experiments with the ship differentiation when gaining momentum and active braking; when simulating the heel and motion of the ship on circulation; to visualize the free or residual vibrations of the hull when sea waves excitation extracts from the calculations; as well as for observations of the ship motion under the influence of external impulse heeling moments.
2. A purely mathematical wave field of full-fledged trochoidal waves (2,3,4) and subsurface velocities of currents at uneven regularized design nodes. Such model of an unchanged storm sea allows you to work out in detail the dynamics of storm propulsion and motion of the ship without the complicated influence of high-altitude waves reflected from the ship hull.
3. The same space-temporary wave field on strictly uniform nodes with identical calculation cells. In this variant, the resulting wave field is immediately simulated without involving extra layers with fixed wavelengths. In optimized modeling of sea waves, a single vector array is used in which the z component includes sea level, and along the horizontal axes $\{x,y\}$ averaged velocities of subsurface currents. Thus, a simulation option with minimal use of computer computing resources is implemented.
4. A direct computational experiment with trochoidal wave on uneven regularized nodes, with the possibility of turning on dispersion for phase and group velocities, with showing of ship wave formation and a full reflection of external storm waves from the hull of the ship.
5. The same computational experiment, taking into account the subsurface velocities of currents, which partially reduce the force effects of storm waves on the hull of the ship by reducing water pressure while taking into account the caused currents near the hull of the ship. In this case, the computing resources of the computer are maximized.
6. Computational experiment using wave mode in full streams on uniform regular grids, with guaranteed compliance of stability criteria and approximation smoothness of differential approximations. Thus, the requests for computing resources of the computer are optimized and significantly reduced, but at the same time, the determining part of the hydrodynamic processes in the experiment is implemented quite correctly (Fig. 2).

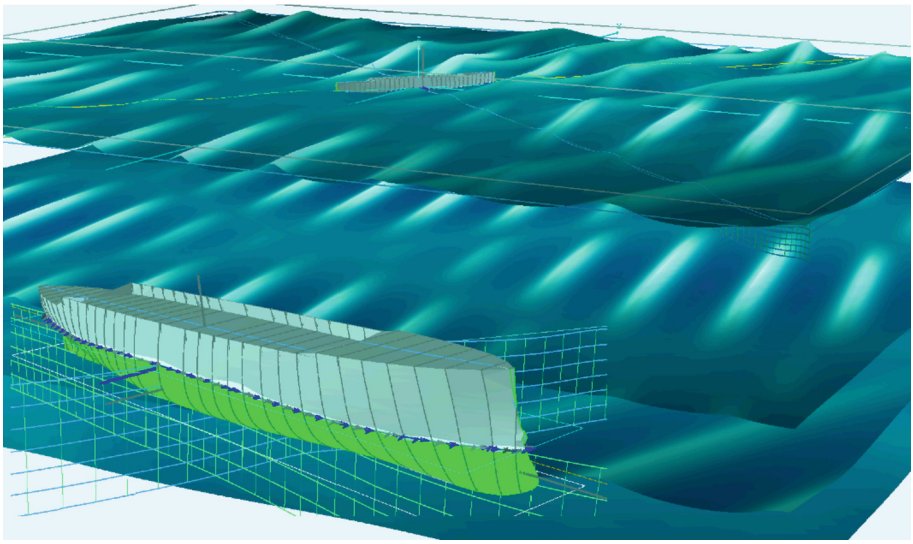

Fig. 2. Example of computational experiment with visualization of wave fields and ship dynamics.

4 Variants for Experiments in the Field of Stormy Seaworthiness

A virtual model of the ship is built in full-scale digital theoretical drawings. The surface of the general ship architecture, with mass and dynamic characteristics of the hull, propulsion and rudder control are considered. It is also possible to interactively change the application of the center of gravity directly during the experiment. This is necessary to assess the nature and intensity of the ship motion in various stormy navigation scenarios, and it can be used to return the vessel to its operating position in the event of emergency capsizing.

The virtual numerical model of the ship is digitized by full-scale theoretical drawings. This allows you to conduct simulations in real time in compliance with inertial characteristics, speed pulsations and motion periods of a real ship. During the experiment, an interactive change in the metacentric height *GM* is allowed.

Ship maneuvers in computational experiment are performed along smooth circulation trajectories. Gain and loss of speed also occur smoothly. This generally corresponds to real sailing with six degrees of freedom, occurrence of heel on the circulation and running trim during acceleration and braking of the ship, that is, with a variable speed depending on the nature of the interaction of the hull with specific crests of storm waves.

The course of the ship is held by the automatic pilot system with a limit on speed of circulation according to two conditional options for transferring the rudder to the "half-side" and "to the side" (*the angular velocity on the circulation does not depend on the travel speed*). The speed of travel is regulated by propulsion tools and the resistance in case "still water", which allows both the loss of the storm motion on intense waves, and acceleration on crests of the following waves (*when engines are stopped the damping is applied to the full drift speed*).

In the computational experiment, hydrodynamic models of ship motion of varying complexity are involved, as well as in the simulation of sea waves.

1. The simplest or test version is based on the kinematic sliding of the ship hull relative to two pairs of points along and across the hull. In the simplest case, no hydrodynamic calculations are performed at all. Graphical visualization of wave structures and ship hull sliding along the chords of the resulting wave field is performed.
2. In the simplest version of ship dynamics modeling only the vertical components of external storm forces are considered. Formally, from such vertical external forces, pitching, rolling and heaving are formed. Regardless of wave nature, the calculations involve the entire complex of finite-difference operations. They include simulations of both ship wave formation and the reflection of storm waves from the ship hull.
3. Involvement of all external forces and heeling moments. This means simulating all six components of the ship's degrees of freedom on the way of stormy conditions.
4. In variants 2 and 3, the calculations are supplemented by subsurface current velocities, which formally reduces the external force effect of storm waves by reducing the hydrostatic pressure on the ship hull while taking into account the fast currents under the crests of the waves near and along the ship hull. In this version of the simulation, additional memory resources are requested to build three-dimensional current fields near the ship hull, and, accordingly, requests for computational resources increase significantly.

4.1 Hydrodynamic Model of Ship Propulsion and Motion in Intensive Waves

The moving model of the ship interacts separately with each of the wave fields with predetermined phase velocities. This hydrodynamically correctly determines the geometric transformations and kinematic processes of waves reflection from ship hull. The resulting wave field (Fig. 3) is obtained by simply summing the sea levels and vector velocities of subsurface currents, and serves to recalculate the instantaneous force effects on all hull, including the freeboard, decks and superstructures.

At each step of the computational experiment, the geometric characteristics and hydrodynamic parameters of the hull are recalculated, taking into account the kinematics on the waves. Wave field is not created at the first cycle of calculations. The results of calculations are re-assigned to the original numerical objects to fix mass, inertial and hydrostatic parameters of the ship on still water without motion.

A computational experiment is formed by a sequence of algorithms with vector and tensor quantities: $\vec{B} = vW \cdot \overrightarrow{iV}$ is vector Archimedes forces; $\overrightarrow{W} = \{0, 0, Volume\}$ is vertical vector of mass (volume) of ship hull; $\overrightarrow{V} + = g\left(\overrightarrow{B} + \overrightarrow{W}\right)\delta t/Volumer$ is speed of forward ship hull movements in the ship's coordinate system. After applying the damping coefficients that affect viscosity, such caused velocity is simply summed up with the current speed of the vessel. $\vec{R} = r \cdot \left(\overrightarrow{vB} - \overrightarrow{Gravity}\right)$ is moment arm of Archimedes; $\overrightarrow{\Omega} + = \left\{\left[g\left(\overrightarrow{R} \times \overrightarrow{B}\right)\delta t\right]/r\right\}/inMass$ is renewed vector of angle velocity of ship motion. Here, damping coefficients are also used, and Archimedean force vector is supplemented by an inertial component from the current accelerations on the trajectory of the ship's mass center.

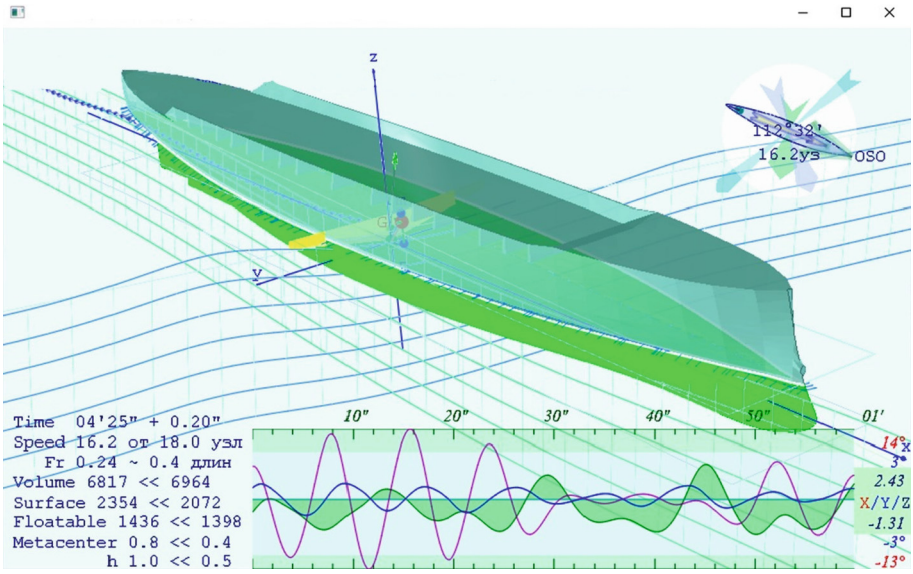

Fig. 3. Screen shot of graphical window with the characteristics of the ship hull. At the top right is a cartouche with the course of the ship and arrows of characteristic lengths, heights and directions of group wave structures movement. At the bottom of the screen are graphics of rolling, pitching and heaving are showed.

An important element of the computational experiment is the limitation of acceleration when ship becomes a given speed and two circulation modes are installed ("rudder on board" and "half-board"). This allows you to simulate the occurrence of heel on circulation and motion loss on a storm wave, the capture of the hull by a following wave and other effects of motion and propulsion on all six degrees of freedom.

To speed up the calculations, numerical structures ordered by frame-space are used that describe the hull surface. This makes it possible to enable reenterable procedures to parallelize the calculation process. At each step of the experiment, the current waterline is re-interpolated and beams are placed to dynamically separate the underwater and overwater volumes of the hull. Modified submerged hull volumes, shifted centers, and new moments of inertia are calculated. The metacentric characteristics of the hull are used only to formally control the dynamics of the ship within the framework of traditional representations of ship theory. To do this, the area, position of the center and moments of inertia of the current waterline area are additionally calculated.

5 Conclusion

Direct computational experiments within the framework of the marine virtual testbed are widely used in practice. The obtained results can serve as an experimental justification for technical proposals in the design of promising ships and vessels of increased storm seaworthiness. The described approach can also be useful as part of on-board navigator counting and solving devices or expert information systems in the maritime services

of captains-mentors, for the synthesis of operational recommendations to navigators in strong and stormy seafaring conditions.

The experimental computing environment has a full three-dimensional visualization of all structures of the sea wave. It shows the trajectory of movement and instant positioning of the virtual model of the ship with visualization of hydrodynamic characteristics and parameters. OpenGL's standard graphics tools make it possible to adjust the transparency of sea waves with a choice of options for continuous or contour drawings of ship contours and surface architecture of the ship. This gives the user of the virtual testbed the opportunity to visually analyze and predict in advance the conditions and effectiveness of the storm seagoing, including to prevent potentially dangerous or emergency situations on the high seas.

The new toolkit opens up a popular area of research in the field of ship fluid mechanics, the significant advantages of which are a completely optimal requirement for RAM and performance of computers, which makes it possible to recommend new software complexes for widespread use in production, research and academic purposes.

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