Numerical simulation of motions of a ship with a moonpool in head waves

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Abstract. The paper shows the results of assessing the possibilities of computational fluid dynamics for predicting the motions of a ship with a moonpool and vertical water motions in a moonpool in regular head waves with a zero ship speed. A moonpool is a well which is used in different types of ships such as cable laying, drill and FPSO, survey, research and so on. This well is used for launching and lifting of different devices, divers, rescue bells, cables and risers, which are protected from outboard wind and waves. The results of the numerical simulation in the OpenFOAM software of heave and pitch motions of the DTMB 5415 model in regular head waves with and without ship speed show good agreement with the experimental data. The experiment was organized with a series 60 model, which was equipped with different moonpool shapes modules in regular head waves with a zero ship speed for determining heave and pitch RAOs and vertical water motions in the moonpool. The results do not show any influence of the moonpool for heave and pitch ship motions. These data are necessary for numerical simulation verification. The results of the numerical simulation of experimental research show good agreement, which means the good efficiency of computational fluid dynamics in heave and pitch motions and vertical water motions in moonpool calculation of a ship with a moonpool. Numerical simulation should be advised for calculations during the ship design process.

Keywords: numerical simulation; CFD; experiment; moonpool; heave motions; pitch motions; RAO; DTMB 5415; series 60; OpenFOAM.

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1. Introduction

The moonpool is a vertical well that is used on different types of ships, such as cable laying, mining and drilling, rescue, research, supply and support, is called the moonpool. This moonpool is intended for lowering and lifting various equipment, divers or rescue bells, cables or risers protected from external waves.

There are vertical water motions in the moonpool. Usually the amplitudes of water motions are no greater than the amplitudes of incoming waves. In rare cases, resonant

motions can occur, which can be four times larger than the amplitude of the incoming wave, and which can lead to the damage of the ship or the equipment located in the moonpool [1].

An experiment is organized to determine the characteristics of ship motion. The most common method for studying ship motion is forced motions in regular waves, which result RAO and phase lags of the studied types of ship motion [2].

However, the experiment is a complicated and expensive event; therefore, the use of numerical methods to solve the problems of ship hydromechanics is becoming increasingly popular.

Nowadays, methods of computational fluid mechanics (CFD) are widely used for calculating ship resistance and are also actively used for developing approaches to calculations ship motions.

In this paper, the following tasks are solved:

- The verification of CFD methods for calculations of heave and pitch motions RAO and phase lags;
- The experimental research of the motions of the ship with a moonpool without ship speed in head waves;
- The verification CFD methods for calculations of heave and pitch motions and vertical water motions RAO of the ship with moonpool.

The experimental research is needed because there are not any open experimental data of motions of ship with moonpool.

OpenFOAM software is used like CFD methods [3].

2. Preparation of numerical simulation in OpenFOAM

The Navier-Stokes equation for an incompressible fluid is defined as a system of momentum conservation equations and the continuity equation.

At high Reynolds numbers, computations with direct numerical simulations are accompanied by either large time costs or large computational powers; therefore, the time-averaged Navier-Stokes equations, called Reynolds equations, are commonly used to simulate turbulent flows. These equations are derived from the Navier-Stokes equations by splitting the pressure velocity fields into an average value and fluctuation [4].

The two-parameter turbulence model k-ω SST is used to close the system of equations [5].

Discretization of fundamental equations in the OpenFOAM software is performed using the finite volume method; the free surface is simulated using the modified volume of fluid method.

The motion of a solid body with six degrees of freedom can be described by the dynamic Euler equations [6]. The standard interDyMFoam solver was chosen for solving assigned tasks.

The internal utilities of the OpenFOAM package, such as topoSet, refineMesh and snappyHexMesh, are used to create the mesh.

Built-in boundary conditions, such as waveVelocity and waveAlpha for velocity and phase fraction respectively, at the input boundary, and functions like verticalDamping for the fvOptions file in the numerical beach zone that appeared in the OpenFOAM-5.0 version, are used to simulate regular waves.

In order to simulate the ship dynamics at sea, it is necessary to create a high-quality mesh not only in the free surface zone but also on a general scale. The recommended dimensions of the mesh in the numerical simulation of ship dynamics at sea are presented in fig. 1. In fig. 1 L is the length of ship or the wavelength, whichever is greater.

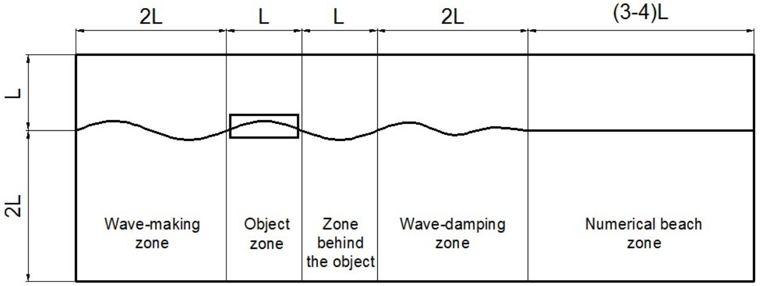

Fig. 1. Recommended dimensions of mesh for numerical simulation of ship dynamics

3. Numerical simulation of heave and pitch motions

According to the recommendations of ITTC, the study of ship motions at regular waves should be carried out under the following conditions [7]:

- the ratio of wave height to its length or wave height to model length should be constant (the recommended ratio of wave height to its length is about 1/50);
- wavelengths should vary in the range from 0.5 to 2 lengths of the model under study;
- the optimal number of motions in tests for analyzing the motion characteristics is not less than 10.

The heave and pitch motions were simulated for the DTMB 5415 model (a ship of the Arleigh Burke-class, US Navy). Experimental data used to verify the results of numerical simulations are presented in [8].

Characteristics of the DTMB 5415 hull: length between perpendiculars $L_{pp} = 3.048$ m, width B = 0.409 m, draft T = 0.132 m, displacement D = 83.5 kg, vertical center of gravity $z_g = 0.163$ m, moments of inertia $J_{44} = 1.92$ kg·m^2 and $J_{55} = 48.5$ kg·m^2.

The simulation was performed at two ship speeds corresponding to Froude numbers of Fn = 0 and Fn = 0.28. Head waves was simulated. The model had only two degrees of freedom – heave and pitch motions.

It was created the mesh with an axis of symmetry possessing the following characteristics: the number of cells was ~ 1.5 million, the maximum proportionality coefficient was ~ 57, the maximum twist factor was ~ 2.4, the average non-orthogonality was ~ 4.3, the average value of the dimensionless characteristic was y+ ≈ 1.

All calculations were made on the computer cluster of the Department of Hydro and Aeromechanics and Marine Acoustics and the Department of Applied Mathematics and Mathematical Modeling of St. Petersburg State Marine Technical University.

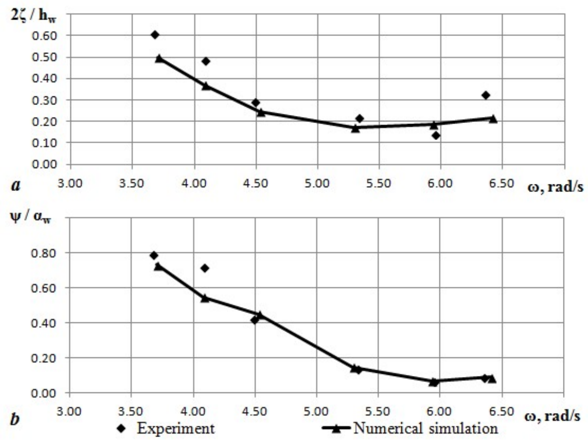

Fig. 2. RAO of heave (a) and pitch (b) motions without ship speed.

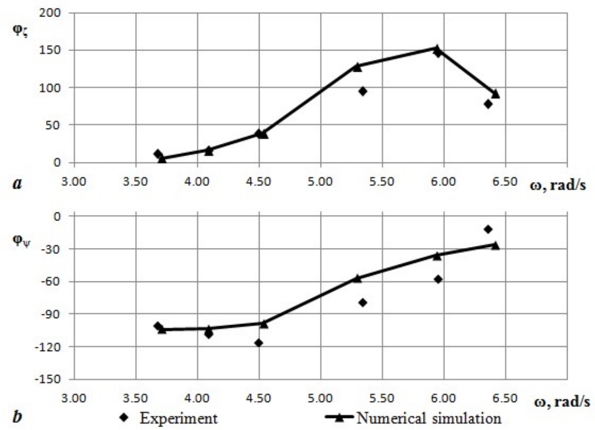

Fig. 3. Phase lags of heave (a) and pitch (b) motions without ship speed

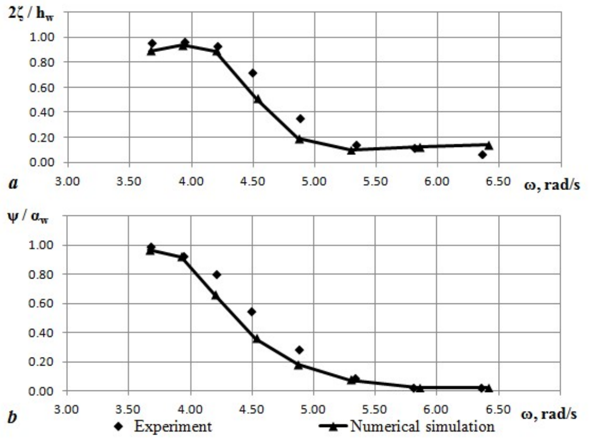

Fig. 4. RAO of heave (a) and pitch (b) motions with Fr = 0.2

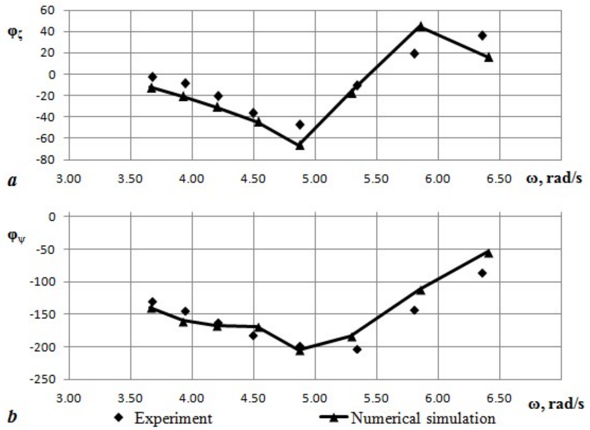

Fig. 5. Phase lags of heave (a) and pitch (b) motions with Fr = 0.28

According to the simulation results, the RAO and phase lags of heave and pitch motion are obtained and presented in figs. 2-5. In figs. 2-5, the following notation is used: $2\zeta/h_w$ – dimensionless amplitude of the heave motions of the ship (ratio of absolute heave motions ζ to the amplitude of incoming waves $h_w/2$, where h_w – height of the incoming waves), φ_ζ – the phase lags of heave motions of the ship, ψ/α_w – dimensionless amplitude of the pitch motions of the ship (the ratio of absolute pitch motions ψ to the angle of the incoming wave α_w), φ_ψ – the phase lags of pitch motions of the ship, ω – the frequency, rad/s.

Analyzing figs. 2-5, it can be concluded that numerical simulation allows estimating well enough the RAO and phase lags of heave and pitch motion both without and with ship speed.

At the same time, there is no need for additional calculations to assess the effect of grid convergence since the obtained results satisfy engineering accuracy, and the speed of calculation (about 24 hours for one RAO and phase lags) allows using this approach in the different stages of ship design process.

4. Experimental research of motions of ship with moonpool

The place of the research is the towing tank of the Ship Theory Department of the St. Petersburg State Maritime Technical University.

A plunger wave producer is used to create the incoming waves. The installed wave producer can create only two-dimensional regular waves.

In order to perform the experiment, the series 60 model was created with the following characteristics: length between perpendiculars L_{pp} = 2.09 m, width B = 0.289 m, draft T = 0.125 m, displacement D = 45 kg. In order to study the effect of the presence of moonpool, a model was created with a modular insert in the longitudinal center of buoyancy. Three modules have been developed:

- module No. 1 – no moonpool;
- module No. 2 – a circular moonpool with an internal diameter of d_m = 0.044 m and a relative diameter of d_m/B = 15%;
- module No. 3 – a moonpool of the circular cross-section with an inner diameter d_m = 0.074 m and a relative diameter d_m/B = 25%.

Three-dimensional models of the ship with different modules are presented in Fig. 6.

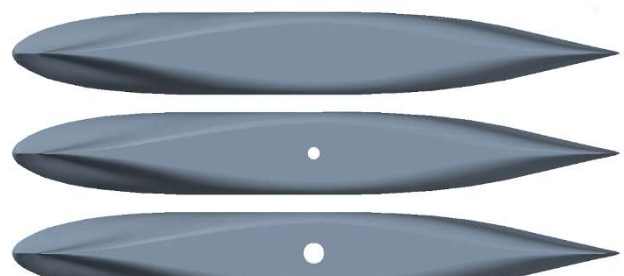

Fig. 6. Bottom view for 3D models with different moonpool modules: upper – module No. 1, middle – module No. 2, lower – module No. 3

The following model characteristics were obtained based on the results of static and dynamic calibrations: the longitudinal center of gravity from the midsection x_g = -0.03 m, the transverse center of gravity y_g = 0.00 m, the vertical center of gravity z_g = 0.10 m, the moments of inertia J_{44} = 0.8 kg·m^2 and J_{55} = 6.5 kg·m^2.

The model was tested in regular head waves with length ranging from 1.5 to 4.0 m. The image of the motions of the model on the 4.0 m wave is shown in fig. 7.

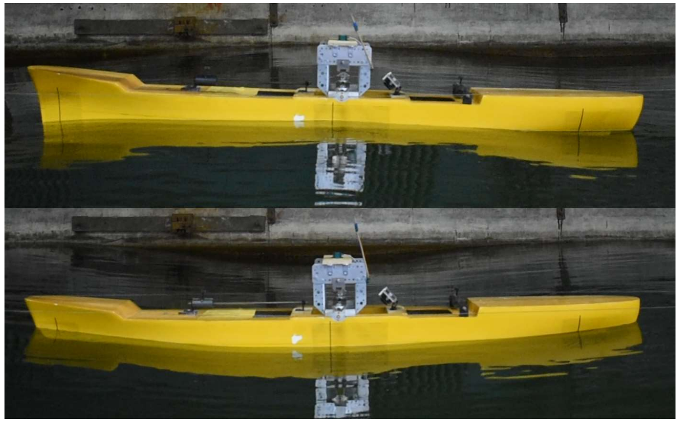

Fig. 7. Ship motions in head waves with a length of 4.0 m

As the experimental results, the heave and pitch motions data were obtained, as well as the vertical water motions in moonpool. After processing the data, RAO of heave and pitch motions of the model with different modules, as well as the vertical water motions in moonpool, which are shown in Figs. 8-10 respectively. In Figs. 8-10, approximating lines for each RAO are additionally presented.

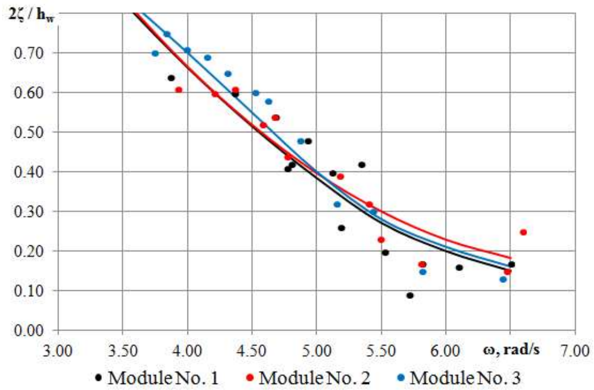

Fig. 8. RAO of heave motions for the model with different moonpool modules.

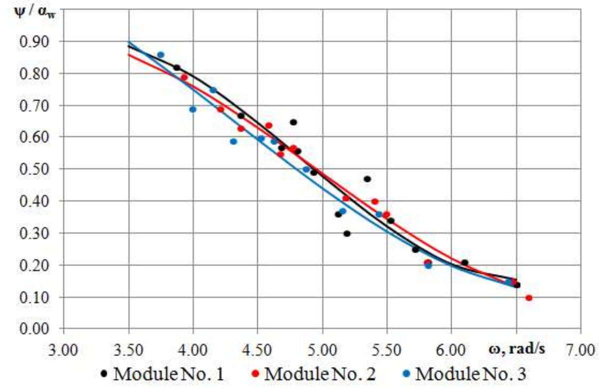

Fig. 9. RAO of pitch motions for the model with different moonpool modules.

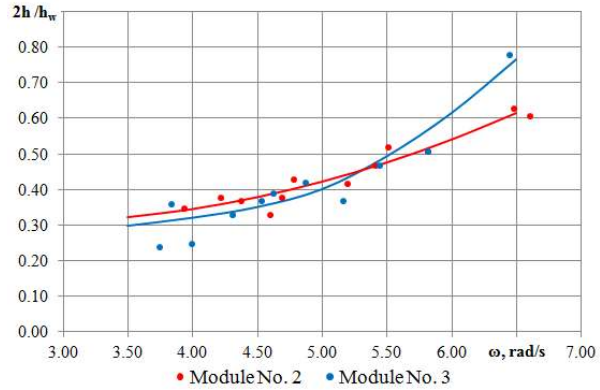

Fig. 10. RAO of water vertical motions in the moonpool for the model with different moonpool modules.

Analyzing the RAO presented in figs. 9 and 10, it can be concluded that the presence of a circular moonpool with a diameter up to 25% of the ship width does not affect the heave and pitch motions.

5. Numerical simulation of motions of ship with moonpool

In order to perform numerical simulations, three-dimensional models of the series 60 ship shown in fig. 6 were developed.

In order to study the heave and pitch motions, meshes were created with an axis of symmetry with the number of cells ranging from 1 to 1.5 million, depending on the wavelength. The characteristics of meshes are similar to those obtained in the numerical simulation of the DTMB 5415 hull.

According to the results of the numerical simulation, RAO of the heave and pitch motions of the ship, as well as the vertical water motions in moonpool were obtained and are presented in figs. 11-13 for models with modules No. 1-3, respectively.

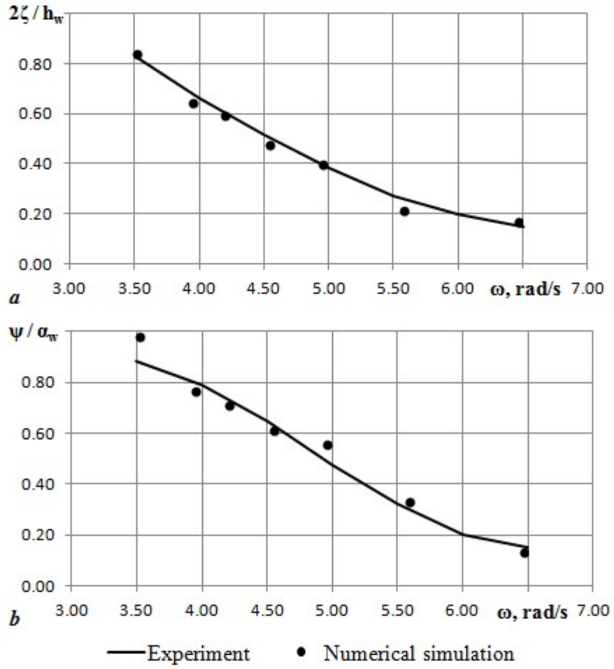

Fig. 11. RAO of heave (a) and pitch (b) motions of the model with module No. 1.

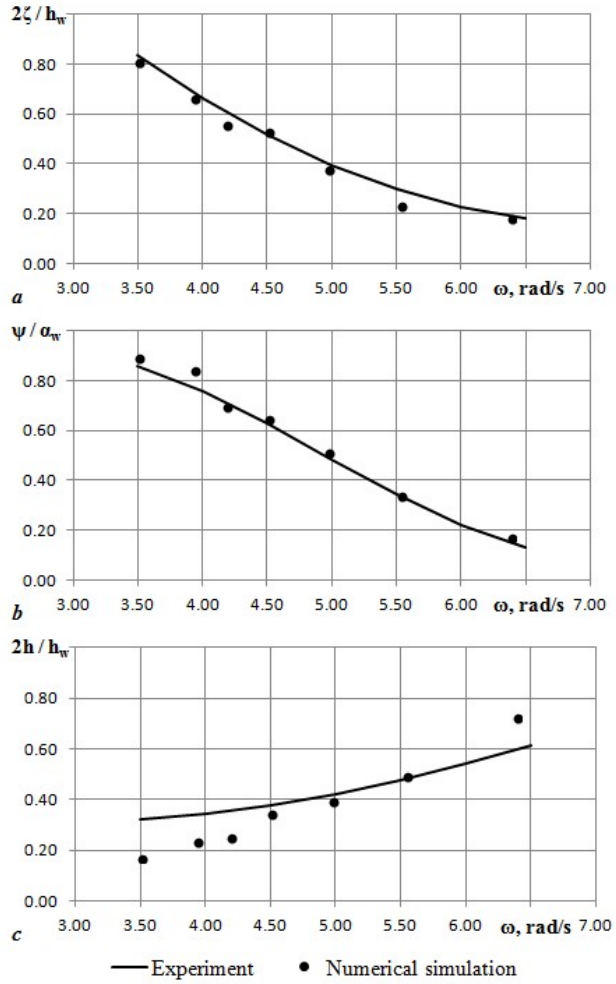

Fig. 12. RAO of heave (a) and pitch (b) motions and vertical water motions in the moonpool (c) of the model with module No. 2.

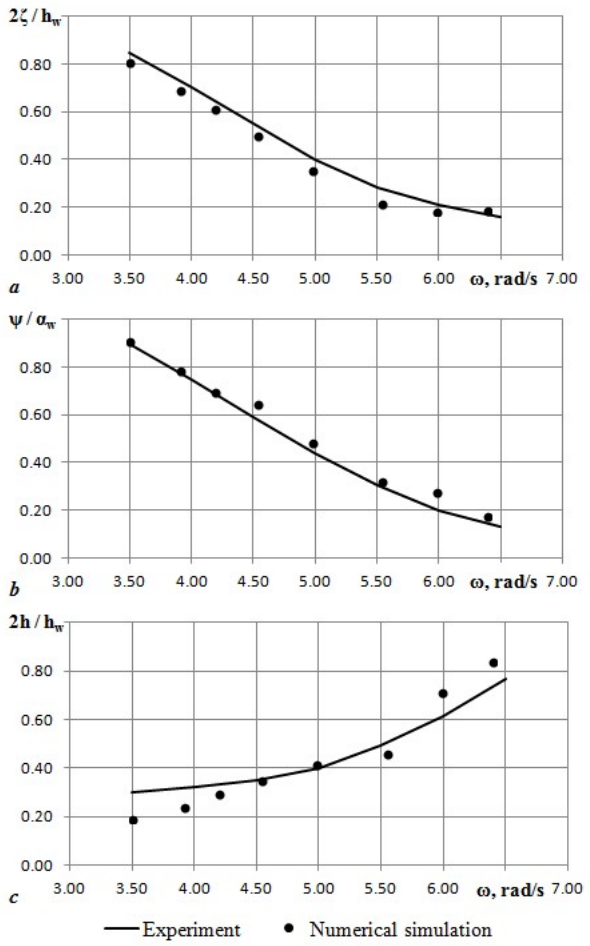

Fig. 13. RAO of heave (a) and pitch (b) motions and vertical water motions in the moonpool (c) of the model with module No. 3.

Upon analyzing the data presented in figs. 11-13, it can be concluded that numerical simulation allows determining the characteristics of the heave and pitch motions of ships with moonpools of different diameters in head sea with good accuracy.

In this case, attention should be paid to figs. 12c and 13c, which present RAO of the vertical water motions in moonpool. It can be noted here that in the considered frequency range, numerical simulation allows determining the motions characteristics of the water in moonpool with sufficiently good accuracy. However, in fig. 12b, there are differences in the trends of numerical simulation and the experimental results,

especially during subsequent extrapolation to the high-frequency zone. This remark is unfair for the results of the model with module No. 3 simulation.

Numerical simulation of the motion of ship with moonpool can be recommended in the different stages of ship design process for determining the characteristics of ship motions and the vertical water motions in moonpool.

6. Conclusion

The paper shows the results of assessing the possibilities of computational fluid dynamics for predicting the motions of a ship with a moonpool and vertical water motions in a moonpool in regular head waves with a zero ship speed.

The results of the numerical simulation in the OpenFOAM software of heave and pitch motions of the DTMB 5415 model in regular head waves with and without ship speed show good agreement with the experimental data.

The experiment was organized with a series 60 model, which was equipped with different moonpool shapes modules in regular head waves with a zero ship speed for determining heave and pitch RAOs and vertical water motions in the moonpool. The results do not show any influence of the moonpool for heave and pitch ship motions. These data are necessary for numerical simulation verification.

The results of the numerical simulation of experimental research show good agreement, which means the good efficiency of computational fluid dynamics in heave and pitch motions and vertical water motions in moonpool calculation of a ship with a moonpool. Numerical simulation should be advised for calculations during the ship design process.

Numerical simulation of the motion of ship with moonpool can be recommended in the different stages of ship design process for determining the characteristics of ship motions and the vertical water motions in moonpool.

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Численное моделирование качки судна с шахтным устройством на встречном волнении

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Аннотация. В работе приводятся результаты оценки возможности применения современных средств вычислительной гидромеханики для определения характеристик качки судна с шахтным устройством и колебаний жидкости в шахте на встречном волнении при отсутствии скорости хода. Шахтой называется «колодец», используемый на различных типах судов, таких как, кабелеукладочных, добычных и буровых, спасательных, исследовательских, снабжения и обеспечения. Эта шахта предназначена для спуска и подъема различного оборудования, водолазов или спасательных колоколов, кабелей или райзеров, защищенных от воздействия внешнего волнения. Результаты численного моделирования в программном комплексе OpenFOAM продольной качки модели DTMB 5415 на встречном регулярном волнении при наличии и отсутствия скорости хода показали, что численное моделирование позволяет с высокой эффективностью определять амплитудно-частотные и фазово-частотные характеристики вертикальной и килевой качки судна. Проведенное экспериментальное исследование модели серии 60 без шахты и с двумя шахтами круглого сечения различного диаметра на встречном волнении при отсутствии скорости хода позволило получить амплитудно-частотные характеристики вертикальной и килевой качки, а также вертикальных колебаний жидкости в шахте, которые показали, что влияние наличия шахты на динамику судна на встречном волнении пренебрежимо мало. Эти данные также необходимы для выполнения верификации численного моделирования колебаний судна с шахтой на встречном волнении. Численное моделирование экспериментального исследования показало, что современные средства вычислительной гидромеханики позволяют с хорошей эффективностью решать задачи по определению характеристик продольной качки судна, снабженного шахтным устройством, и вертикальных колебаний жидкости в шахте на встречном волнении при отсутствии скорости хода. Численное моделирование качки судна с шахтным устройством может быть рекомендовано на начальных стадиях проектирования для определения параметров качки и вертикальных колебаний жидкости в шахте.

Ключевые слова: численное моделирование; эксперимент; шахта; вертикальная качка; килевая качка; амплитудно-частотная характеристика; DTMB 5415; серия 60; OpenFOAM.

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