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SIMULATION OF SHIP TRAJECTORY IN WAVES BASED ON STAR-CCM+

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МОДЕЛИРОВАНИЕ ТРАЕКТОРИИ СУДНА НА ВОЛНАХ НА БАЗЕ STAR-CCM+

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Abstract. The reliable ship motion trajectory signal provides a basis for six-degree-of-freedom test bench to simulate ship motion in waves. The characteristics of ship motion in waves were analyzed. Aiming at the problem of complex hull shape and large displacement at sea, the dynamic overlapping grid technique was used. Based on STAR-CCM+, the free surface was solved by CFD (Computational Fluid Dynamics) numerical simulation method. The numerical model of ship motion in waves was established, and the DFBI (Dynamic Fluid Body Interaction) method was used to simulate the ship motion in the waves. The ship's motion trajectory was obtained in the regular and irregular heading waves, which provides important support for the six-degree-of-freedom test bench wave simulation system.

Аннотация. Надежный сигнал траектории движения судна является основой для испытательного стенда с шестью степенями свободы для моделирования движения судна на волнах. Проанализированы характеристики движения судна на волнах. Для решения проблемы сложной формы корпуса и большого водоизмещения в море использовалась методика динамической сетки с перекрытием. На основе STAR-CCM+, свободная поверхность была решена методом численного моделирования CFD (*Computational Fluid Dynamics — вычислительная гидродинамика*). Создана численная модель движения судна на волнах с использованием метода DFBI (*Dynamic Fluid Body Interaction — динамическое взаимодействие тел с жидкостью*) для моделирования движения судна на волнах. Траектория движения судна была получена в регулярных и нерегулярных волнах курса, что обеспечивает существенную поддержку системы моделирования волн на испытательном стенде с шестью степенями свободы.

Keywords: six-degree-of-freedom test bench, dynamic overlapping grid, Computational Fluid Dynamics, Dynamic Fluid Body Interaction.

Ключевые слова: испытательный стенд с шестью степенями свободы, динамическая сетка с перекрытием, вычислительная гидродинамика, динамическое взаимодействие тел с жидкостью.

Introduction

Ships will face complex sea surface conditions in the actual navigation. Under the action of waves, the ship body will have complex space swing motion [1]. These swing motions put forward higher requirements for the installation and operation of ship equipment, and seriously affect the normal work and service life of deck machinery and other equipment. The six-degree-of-freedom test bench can simulate the ship's motion with the change of sea waves during the navigation, test the reliability of ship equipment in complex sea conditions, reduce the number of real ship test, and save the time and cost of research and development.

The researcher Wei L in our laboratory used the existing Stewart platform to simulate the motion of ocean waves and designed a method of tuning PID parameters based on SOA algorithm to improve the control accuracy of the motion system [2]. The purpose of this paper is to provide a signal source for that system which can truly reflect the trajectory of the ship.

There are many parallel degrees of freedom in the structure of the parallel six degree of freedom experimental platform, so it can move in multiple degrees of freedom direction, with compact structure, high bearing capacity, fast response and high precision [3]. This paper uses a typical Stewart mechanism, as shown in Figure 1. The mechanism is mainly composed of two platforms: upper (moving platform) and lower (fixed platform), six hydraulic cylinders and other support and control components. The hydraulic cylinder connects the upper and lower platforms in parallel through the ball hinge. The coordinated motion of six hydraulic cylinders drives the attitude change of the upper platform in space [4].

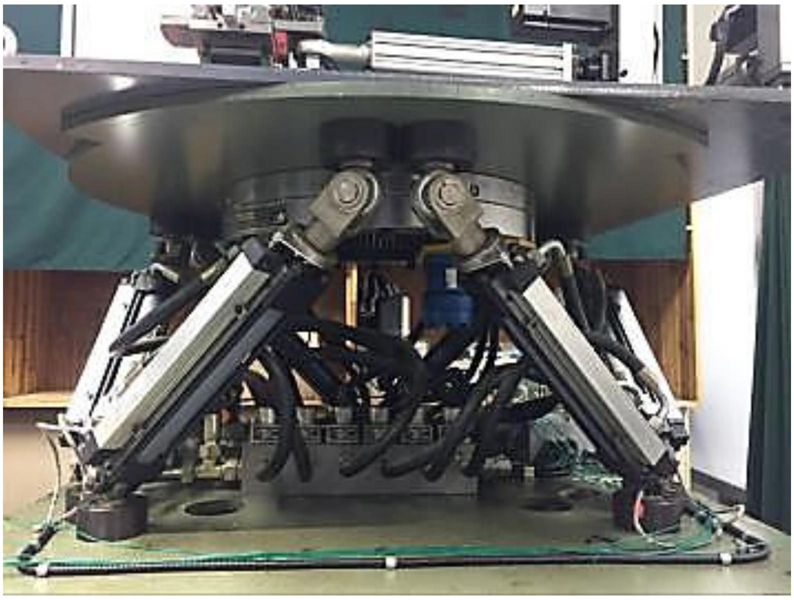

Figure 1. Six-degree-of-freedom test bench

In order to make the 6-DOF test bench reflect the swaying motion of the ship in the waves as truly as possible, it is necessary to obtain the trajectory signal of the ship. The STAR-CCM+ is a leading computational fluid dynamics software, which can simulate any engineering problem including liquid flow or gas flow (or a combination of both) and all associated physical fields. In this paper, based on STAR-CCM+ software, the CFD (Computational Fluid Dynamics) numerical simulation method is used to establish the numerical model of ship motion in the waves, and get the trajectory of the ship, so as to provide the closest signal source to the actual situation for ship equipment testing.

Modeling

Coordinate system. In order to describe the motion of the ship in the waves, two coordinate systems need to be established, one is geodetic coordinate system, the other is the hull coordinate system with the center of gravity as the origin [5]. As shown in Figure 2, the positive direction of the x-axis of the hull coordinate system is from the stern to the bow, the positive direction of the y-axis is from the port to the starboard, and the z-axis is perpendicular to the deck and points to the bottom of the ship.

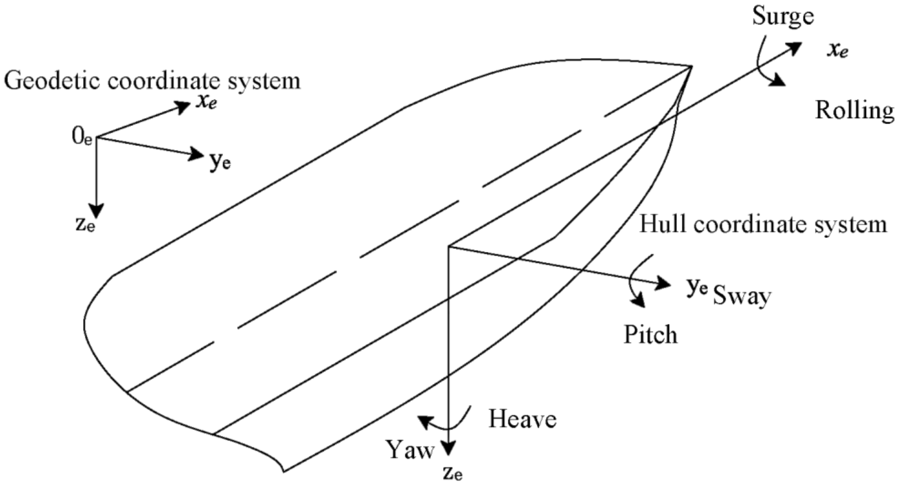

Figure 2. Characterization of ship motion

The periodic displacement of the ship along the three axes is called surge, sway and heave, and the periodic rotation around the three axes is called rolling, pitching and yaw.

Governing equation. The hydrodynamic control equations, including momentum conservation equation, energy conservation equation and continuity equation, are used in the simulation of sea water and air.

The continuity equation is derived from the law of conservation of mass. Different flow models has different continuity equation. The continuity equation of unsteady flow of compressible fluid is [6]:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

Where: ρ is fluid density, t is time, u, v and w are velocity components of velocity vector in x, y and z directions.

In order to simplify the calculation, seawater is considered as an incompressible flow:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{2}$$

The momentum conservation equation is derived from Newton's second law, which means that the sum of external forces acting on the control body is equal to the change of fluid momentum by time [7]. N-S equation is generally used to describe incompressible viscous fluid.

$$\mathbf{F}-\frac{1}{\rho}\nabla P+\upsilon\nabla^{2}\mathbf{V}=\frac{\partial\mathbf{V}}{\partial t}+\left(\mathbf{V}\cdot\nabla\right)\mathbf{V} \tag{3}$$

Where: F is the body force, V is the velocity vector, and υ is the kinematic viscosity coefficient. The ideal fluid has no viscosity:

$$\mathbf{F}-\frac{1}{\rho}\nabla P=\frac{\partial \mathbf{V}}{\partial t}+\left(\mathbf{V}\cdot\nabla\right)\mathbf{V} \tag{4}$$

The standard κ-ε model is the simplest and most widely used complete turbulence model. It is a semi empirical formula . The standard κ - ε model is very popular in industrial applications because of its good convergence rate and relatively low memory requirement.

$$\mu_i=\rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

Where: μ_i is turbulent viscosity, κ is turbulent kinetic energy, ε is turbulent energy dissipation rate, and C_μ is empirical constant.

Dynamic overlapping grid. High quality grid generation can greatly improve the computational accuracy and efficiency of CFD numerical simulation. When the ship is sailing in the waves, the motion amplitude will be very large. At this time, the topological structure of the free surface of the water in contact with the air is very complex. If we use the traditional regional grid, we cannot solve the problem of overlapping of each block. Dynamic grid technology based on structure nesting, namely dynamic overlapping grid technology [8], can solve this problem well.

The dynamic overlapping grid allows each sub grid area to overlap each other, and there is no special requirement for sub grid area, every sub grid is isolated, which reduces the difficulty of grid generation [9]. The coupling relationship between regions and data interpolation transfer relationship are obtained by digging holes and finding points [10], which are suitable for complex hull shape and large displacement at sea.

Volume of fluid model. When a ship is sailing at sea, it is always affected by water and air. For two-phase flow, the N-S equation of each phase can be solved directly, but when the free surface has large deformation, the amount of calculation will increase sharply, and it is difficult to get the result. In this paper, VOF (volume of fluid model) method is used to solve the free surface, that is, the interface between sea water and air. In the whole computational domain, two or more fluid bodies are not mixed with each other, seawater and air are regarded as two-phase flow of the same equation group respectively, and the motion of the interface between air and seawater is determined by the ratio of the volume fraction of two-phase fluid to the volume of cell.

The VOF method divides the computational domain into three regions: two single-phase regions and one transition layer region. Three regions are defined by water fluid volume fraction β_w and air fluid volume fraction β_a [11]:

$\beta w=1$, $\beta a=0$ water fluid region,
$\beta w=0$, $\beta a=1$ air fluid region,
$0<\beta w$, $\beta a<1$ transition layer region.

Research

In the selected calculation domain, there are a lot of gas and liquid flows at the same time, so the Eulerian two-phase flow model is established with seawater as the main phase and air as the secondary phase. The viscosity of seawater cannot be ignored. The governing equation of the model is composed of momentum conservation equation and continuity equation. Reynolds time average method is used to solve the turbulent motion of the fluid, and VOF model is used to simulate the motion of the interface between seawater and air.

Table shows the dimensions of the 11000kW ocean rescue tug, and Figure 3 shows the overall view of the tug's geometric model.

Table 1.

MAIN SCALE OF 11000KW MARINE RESCUE TUG

Length overall, L_{OA}	89.9m
Length between perpendiculars, L_{BP}	80m
Moulded breadth, B	17.2m
Moulded depth, D	8.5m
Scantling Draft ,T	6.5m
Loaded displacement ,M	4000t

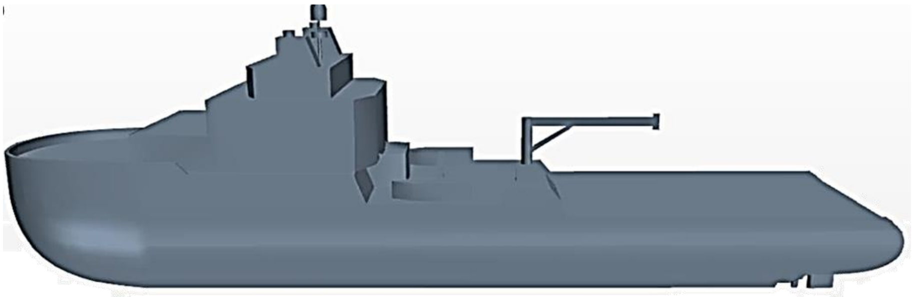

Figure 3. Geometric model

Boundary condition. The calculation area and boundary settings are shown in Figure 4, in which the surface boundary of the floating body can be regarded as a fixed wall without sliding; the inlet boundary and outlet boundary are set as velocity inlet and pressure outlet; the side boundary, top boundary and bottom boundary are set as velocity inlet. The velocity, direction and pressure of each boundary are determined by the wave model.

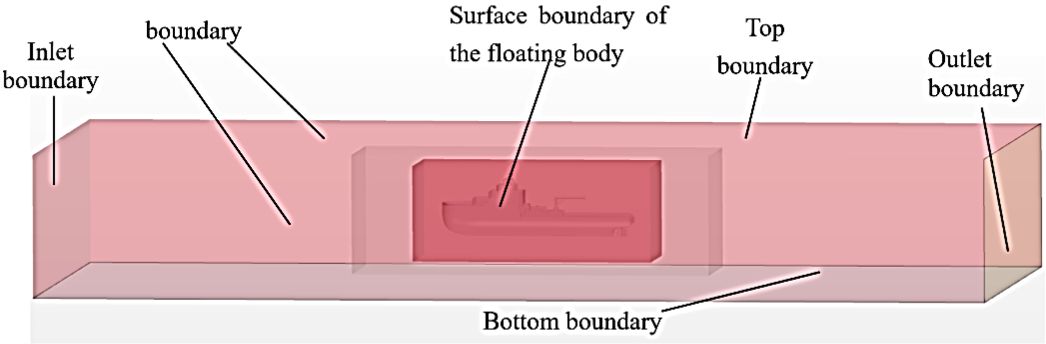

Figure 4. Model computing domain and boundary conditions

Computing domain and grid

Figure 5 is the model grid. Compared with the polyhedral mesh, the overlapping mesh technology can better deal with the motion of the ship with the complex fluid changes. As shown in the figure, the size of the external background pool is $-200 \text{ m} < x < 200 \text{ m}$, $-100\text{m} < y < 100 \text{ m}$, $-30 \text{ m} < Z < 30 \text{ m}$, the basic size of the grid is set to 1m, and the minimum size is 0.5 m; a cuboid area is established to include the hull, and then the interior of the hull is stripped.

The ship motion simulation calculation is two-phase flow, and the free surface is the interface between air and water. In order to capture the change information of free surface and the interaction between fluid and hull, the grid near the free surface and the hull are densified [12]. In this paper, the overlapping grid technology is used, as shown in Figure 5 (b). The physical information exchange between the overlapping grid and the background grid is completed by interpolation [13]. The mesh size of each area is the same as that of the encrypted area.

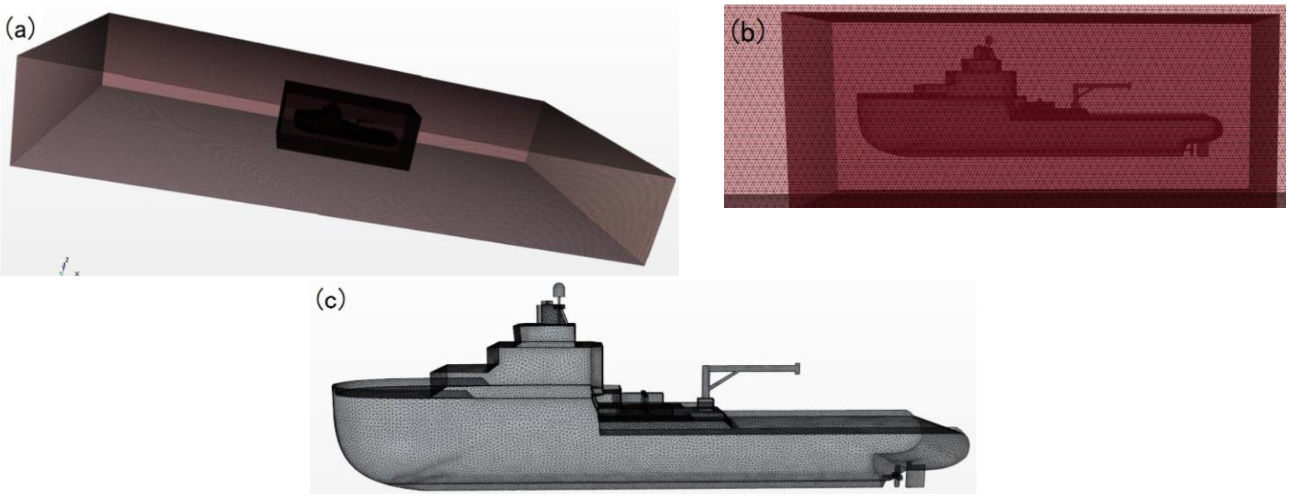

Figure 5. Model grid

In order to prove that the simulation results have nothing to do with the grid size, the basic grid sizes of the external background calculation domain are set as 0.75 m, 1 m, 1.25 m, 1.50 m, 1.75 m, 2 m respectively, and the wave model is set as the regular facing wave. The pitch angle of the ship in stable driving is obtained as shown in Figure 6. It can be seen from the figure that when the grid size is less than 1m, the pitch angle basically does not change with the grid size. Therefore, it can be considered that when the basic grid size is set to 1m, a good balance can be achieved between the calculation accuracy and the calculation cost.

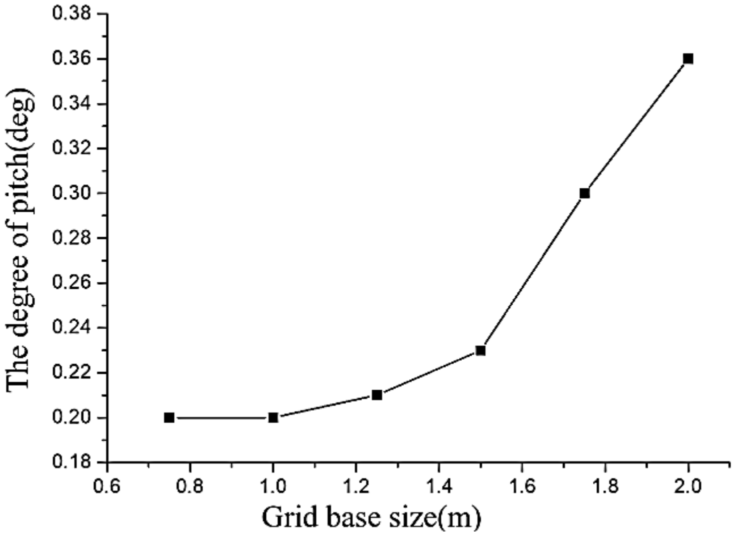

Fig 6. Grid independence verification

The dynamic fluid body interaction (DFBI) method is used to simulate the motion of a ship in waves. Six degrees of freedom can fully describe the motion of a rigid body under the action of fluid, and the combination of rotation and translation can contain all six degrees of freedom. In this paper, the overlapping mesh and DFBI six degree of freedom motion method are used to avoid the computational efficiency degradation caused by mesh adaptation and solve the contact problem. When a ship moves in regular waves, the rolling, sway, surge and yaw motions are small, which have little impact on the ship. Therefore, numerical simulation is mainly carried out for pitching and heave [14].

In the solver, the implicit unsteady solution is adopted, the time step is set as (t is the period of incident wave, n is the number of single wavelength grid nodes), the maximum number of internal iterations is set as 10, and it stops when the ship moves stably on the water. Release time, hull mass, center of gravity and moment of inertia are defined in the software.

Results

The ship's pitching and heave motions are simulated in regular facing waves. The wave parameters are set as wave height 2 m and period 4.5 s. As shown in Fig. 7, the pitching and heave motion trajectories are obtained after stable operation.

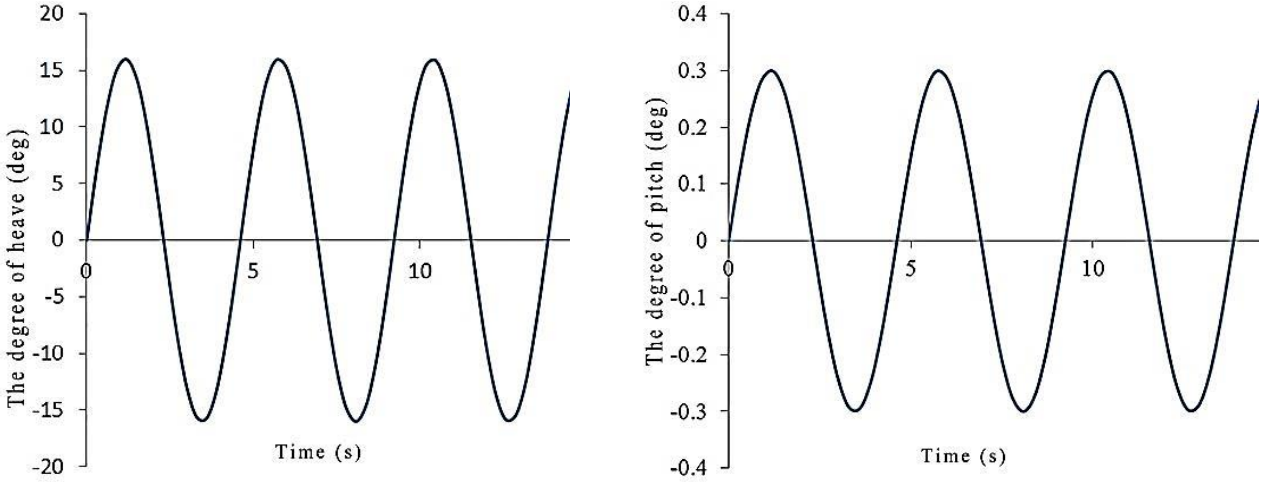

Figure 7. Trajectory of pitch and heave motion

The rolling, pitching and heave motions of the ship are simulated in the irregular facing wave with the encounter angle of 45° and the wave parameters are set as wave height of 2 m and period of 5 s. The P-M random wave spectrum is selected. As shown in Figure 8, the rolling, pitch and heave motions after stable operation are obtained.

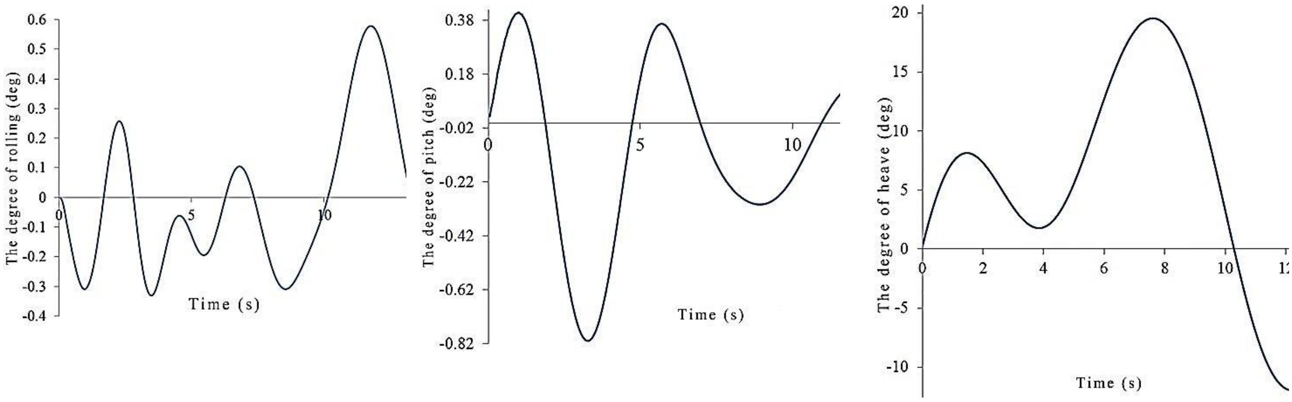

Figure 8. Trajectory of rolling, pitch and heave motions

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