Analysis of the seakeeping performance for Unmanned Underwater vehicle using STAR-CCM+

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Abstract. In this paper, the seakeeping performance of unmanned underwater vehicle (AUV) under the action of transverse waves is calculated and analyzed, based on the commercial CFD software STAR-CCM+. The test data verifies the reliability of the numerical calculation method. The roll and heave response of the vehicle under different working conditions provide a reference for the overall parameter design of the unmanned underwater vehicle.

1. Introduction
The unmanned underwater vehicle is a kind of underwater vehicle which does not need man-on-the-spot operation, and carries out the tasks of underwater operation, long-distance transportation, navigation and positioning, ocean monitoring completely or partially. Due to the influence of the wind and waves, the motion of the vehicle is inevitable when the vehicle is navigating in the waves, which is of great significance to its ability to operate at sea and the safety of the aircraft itself [1]. Therefore, it is necessary to systematically evaluate and evaluate its seakeeping performance at the initial stage of design, so as to provide strong support for the actual design plan to finally meet the requirements of the development mission statement and specifications.

With the rapid improvement of computing performance and the continuous development and improvement of computational mathematical theory, numerical methods have become one of the important methods for researching and solving problems. It is widely used in both theoretical research and engineering practice. In this paper, numerical simulation is used to calculate the roll and heave motion of the UUV under different waves.

2. Mathematical models and numerical methods
In this paper, the time-averaged continuity equation and the Reynolds average Navier-Stokes equation (RANS) in the viscous incompressible flow field are used as the governing equations [2], and the tensor form in the Cartesian coordinate system is:

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right) + S_i$$
In the formula, $\rho$ represents the density of the fluid; $\mu$ represents the dynamic viscosity coefficient; $\mu_i, \mu_j$ represents the time average of the velocity component; $\mu_i', \mu_j'$ represents the pulsation of the velocity component; $P$ represents the time average of the pressure; $\mu_i'\mu_j'$ represents the time average of the velocity pulsation product; $S_i$ represents the generalized source term.

In the calculation, the Realizable $k-\varepsilon$ turbulence model is used, and the corresponding $k$ equation and $\varepsilon$ equation are as follows:

$$
\rho \frac{d}{dt} \left( \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_i}{\sigma_k} \frac{\partial k}{\partial x_i} \right) \right) + G_k + G_b - \rho \varepsilon - Y_M = 0
$$

(3)

$$
\rho \frac{d\varepsilon}{dt} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_i}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + \rho C_i \varepsilon S_k - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1_\varepsilon} \frac{\varepsilon}{k} C_{\varepsilon} G_b
$$

(4)

In the formula, $C_i = \max \left[ 0.43 \frac{\eta}{\eta + 5} \right]$; $\eta = Sk / \varepsilon$; $G_k$ represents the generation of turbulent kinetic energy due to the average velocity gradient; $G_b$ represents the generation of turbulent kinetic energy due to the influence of buoyancy; $Y_M$ represents the effect of compressible turbulent pulsating expansion on the total dissipation rate; $C_2$ and $C_{1_\varepsilon}$ are constants; $\sigma_k$ and $\sigma_\varepsilon$ are respectively Turbulent Prandtl number of its turbulent kinetic energy and dissipation rate.

The VOF (Volume of Fluid) method [3] is used to deal with the free surface. VOF method is a kind of method which can deal with any free surface. Its basic principle is to determine the position and shape of the free surface by calculating the ratio function $F$ of the volume of fluid in the grid unit and the volume of the grid unit itself. The VOF method constructs and tracks the free surface according to the function of the volume occupied by the fluid in the grid unit at each time. A scalar function $f$ is defined for a space region containing two kinds of fluids, liquid and air, $f = 1$ in the liquid space, otherwise 0. In the VOF method, the fluid volume function $F$ is set at the center of the cell, and the fluid velocity is set at the center of the grid cell. The volume of fluid flowing through the specified cell grid is calculated according to the fluid volume function $F$ of the adjacent grid and the fluid velocity on the four sides of the grid cell. The function $F$ satisfies the following equations:

$$
\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0
$$

(5)

For wave simulation, the Pierson-Moskowitz wave spectrum model [4] of STAR-CCM+ software can be used to simulate the influence of sea waves on the motion attitude of the vehicle.

3. Boundary setting and meshing

3.1. Boundary setting

The calculation object in this paper is an unmanned underwater vehicle (UUV) with the shape shown in Fig. 1. According to the model and the corresponding flow conditions, the computational domain is: $4L \times 6L \times 3L$, in which, $L$ is the total length of the vehicle.

During the entire numerical simulation process, it is necessary to specify wave generation conditions, the domain boundary conditions and the object surface conditions. The specific boundary conditions are set as follows: the top boundary surface of the watershed is set to Pressure Outlet, and the bottom boundary surface and the surrounding boundary surface are set to Velocity Inlet, and the surface of the vehicle is set to the wall function.
3.2. Meshing

The quality of the grid directly affects the calculation accuracy of the numerical solution. In the calculation area, cutting volume mesh, prismatic layer mesh and surface reconstruction is used to generate mesh. The body surface of the vehicle is divided by a prismatic layer grid, so as to ensure that the proper boundary layer on the surface, and the calculation area outside the prismatic layer is generated by a cut volume grid. In order to save computing resources and improve the fluid feature resolution of the flow field around the vehicle, on the one hand, we choose to gradually refine the volume from far to near. The grid is sparser away from the vehicle, and the grid is denser closer to the vehicle; on the other hand, the area near the waterline and the tail fin is refined. This greatly reduces the number of grids while ensuring the accuracy of the grid. The grid is divided as shown in Fig. 2, and you can see the grid densification of the surface boundary layer and the vicinity of the tail of the vehicle.
4. Numerical calculation results and analysis

4.1. Comparison of numerical simulation and experimental results

Under the action of the three-stage transverse waves (according to GJB4000-2000, the corresponding wave parameters of three-stage sea conditions are: significant wave height $H=1.25\text{m}$, average period $T=7.5\text{s}$), the comparison of the simulated and experimental values of the roll angle of the unmanned underwater vehicle (UUV) is shown in Fig. 3.

It can be seen that the calculated roll period of the vehicle is basically the same as the experimental value, $t = 5s$; the significant value of roll from the experiment is $\phi_{1/3} = 11.83^\circ$, and the maximum value is $\phi_{\max} = 16.25^\circ$; the significant value of roll from the numerical calculation is $\phi_{1/3} = 12.94^\circ$, and the maximum is $\phi_{\max} = 17.68^\circ$. Compared with the experimental results, the method of seakeeping calculation adopted in this paper is basically credible.

![Figure 3. Comparison of calculated and experimental values of roll.](image)

4.2. Result analysis

(1) Encountered with regular and irregular waves

The wave height and average period of the regular wave are set the same as the irregular wave, where, $H = 1.25\text{m}$, $T = 7.5\text{s}$. The roll angle changes are shown in Fig. 4, when the unmanned underwater vehicle encounters regular waves and irregular waves. From the figure, it can be seen that the roll period of the unmanned underwater vehicle in regular wave is equal to the true period of the regular wave, that is $T_{\phi} = T = 7.5s$, while the roll period in the irregular wave is close to the natural period of the vehicle, that is $T_{\phi} \approx T_0 = 2.6s$, and the amplitude of the roll angle in irregular waves is greater than the amplitude of the roll angle in regular waves.

![Figure 4. Comparison of vehicle roll angles under regular and irregular waves.](image)
(2) Different metacentric heights
Change the metacentric height of the vehicle, \( h=0.15 \text{m}, 0.20 \text{m}, 0.23 \text{m} \). The roll angle and heave of the vehicle with different metacentric heights in irregular wave changes as shown in Fig. 5 and Fig. 6. For quantitative analysis, the Svidrew-Monk definition is used to obtain the motion response amplitudes of the vehicle with different metacentric heights, as shown in Table 1.

![Figure 5](image1.png)
**Figure 5.** The roll of vehicle with different metacentric heights.

![Figure 6](image2.png)
**Figure 6.** The heave of vehicle with different metacentric heights.

**Table 1.** Motion response amplitudes.

|                | \( h=0.15 \text{m} \) | \( h=0.20 \text{m} \) | \( h=0.23 \text{m} \) |
|----------------|------------------|------------------|------------------|
| Roll (degree)  | 21.5             | 22.5             | 25.0             |
| heave (m)      | 0.48             | 0.34             | 0.29             |

It can be seen from the Table 1, as the metacentric height increases, the roll angle of the vehicle also increases, and the heave decreases accordingly.
The attitude change of the vehicle in one cycle is shown in Fig. 7. From the figure, the attitude change of the vehicle can be seen more intuitively.

(a) \( t / T_p = 0 \)

(b) \( t / T_p = 0.25 \)

(c) \( t / T_p = 0.5 \)

(d) \( t / T_p = 0.75 \)

**Figure 7.** The attitude change of the vehicle in one cycle.

5. Conclusion
In this paper, the commercial software STAR-CCM+ is used to simulate the navigation attitude of the unmanned underwater vehicle by selecting the appropriate turbulence model, wave model, and calculation parameters. The calculated roll angle is close to the experimental value, which verifies the accuracy of numerical calculation.

It is found that the rolling period of the vehicle is equal to the regular wave period in the normal transverse regular waves, while the rolling period in the irregular waves is close to the inherent period of the vehicle. When the metacentric height of the vehicle is increased in a certain range, the roll angle of the vehicle will increase and the heave of the vehicle will decrease accordingly.

References
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