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Numerical Simulation of Wake Flow Field in Pitch Motion of Underwater Vehicle

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Abstract—The frequent pitching motion of underwater vehicle during the mission will produce a more complex hydrodynamic wake, which is important for the detection and tracking of underwater vehicles. In this paper, a numerical method is presented to simulate the wake field during the pitching motion of an underwater vehicle by combining the dynamic overset grid method. The evolution law of the wake field is analyzed based on the DARPA SUBOFF simplified model. The effects of underwater vehicle speed on the velocity and turbulent kinetic energy of the wake field and the effects of the longitudinal inclination of the underwater vehicle on the extent of the wake field are discussed.It is found that the wake velocity is positively correlated with the sailing speed of the underwater vehicle, the turbulent kinetic energy of the wake field is directly proportional to the 1.75 power of the sailing speed of the underwater vehicle, and the range of wake field is positively correlated with the pitch angle of underwater vehicle. The larger the pitch angle is, the larger the intensity and size of vortex formed in the flow field are, and the farther the vortex can propagate to the rear of underwater vehicle wake.

1. Introduction

Submarines are stealthily maneuverable and powerful underwater vehicles used for maritime strategy and national security. In its operation, especially in the execution of the mission, the submarine will frequently carry out maneuvering motion such as rising, diving and so on. In the course of the submarine's pitching maneuvering, complex flow separation occurs in the submarine's hull, which leads to strong eddy currents being discharged into the wake and many flow phenomena with rich characteristics.

The hydrodynamic wake left in seawater during submarine pitching motion can be maintained for a long time, and the position and movement of submarine can be determined according to the shape characteristics and velocity changes of the wake, so as to track and detect the submarine. At present, hydrodynamic wake has become a important research target of submarine indirect detection [1-2]. In 1999, a study by the University of Arizona found that for a submarine with a diameter of 10m and a length of 100m, when it accelerates by 10% or turns 5°, its tail eddy current attenuation period can reach 6 days, the horizontal scale can reach 2km and the vertical scale can reach 80m[3]. In 2000, a study by Arizona State University showed [4] that when a submarine in a stratified fluid accelerates, decelerates or changes course, it will transfer enormous energy to the surrounding fluid, resulting in the creation of unusual vortices. In 2015, Ashok[5-6] carried out wind tunnel experiments on a 1:120 DARPA SUBOFF naked boat with no appendage installed in a low-speed wind tunnel with a flow Reynolds number of 2.4×106 by using PIV and hot line technology to study and analyze the wake at different pitch angles, revealing that when the submarine is in pitch motion, a pair of asymmetrical vortices will appear in the wake. These vortexes have become research targets based on eddy current detection in non-acoustic detection [7]. The early information of submarine pitching flow field mainly comes from experiment, but the experiment is not only long period but also very high cost. With the upgrading of computer technology and the rapid development of computational fluid dynamics, the numerical simulation of submarine flow field has been rapidly developed.

In this paper, a numerical simulation of the wake and large eddy generated during the pitching motion of the submarine is carried out by using the overset grid technology and parallel computing.The influence of underwater vehicle speed on flow field velocity and turbulent kinetic energy and the influence of underwater vehicle trim angle on flow field range were explored.It provides a theoretical basis for the future underwater vehicle detection based on vortex wake.

2. Pitching motion and governing equations

2.1. Underwater vehicle pitching motion coordinate system

Underwater vehicle pitching motion is a maneuvering motion occurring in two degrees of freedom in vertical plane. Different translational velocity and angular velocity may be obtained by observing submarine pitching maneuvering motion from different reference frames. To ensure that the result has practical physical significance, the reference frame is given first,as shown in Fig.1. The barycentric coordinate of the initial position of the submarine, O-MN, is taken as inertial reference coordinates, which are referred to as inertial system. Inertial system is stationary relative to the earth, and point O represents the origin of inertial system. The submarine's connected coordinate system is G-XY, referred to the moving system, where point G is the origin of the moving system and the submarine's centroid. At the initial moment, inertial and dynamic systems overlap. The submarine's pitching motion can be divided into the translation of the submarine's centroid point G relative to point O and the rotation of any point S on the submarine around point G.

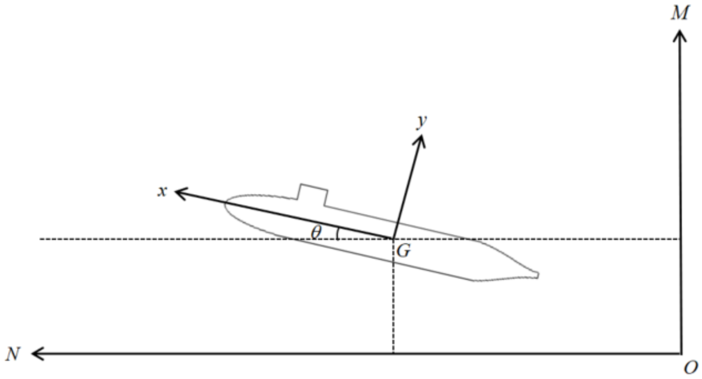

Fig.1 Underwater vehicle pitching motion coordinate system

When elevator is operated to a fixed rudder angle during a fixed depth voyage, the submarine will enter a steady straight pitch motion. If elevator is moved back to its original position, the submarine will make a steady depth voyage at a new depth. The pitch maneuver of the submarine, in the case of elevator, can be operated by a single rudder, and in the case of fast diving and buoyancy, can be operated by a relative rudder. In addition, the minimum depth change $\Delta H_{\min}$ suitable for a given command trim angle θ should match the ship speed.

2.2. Basic theory of turbulence

The solution idea of computational fluid dynamics technology is to discret the governing equations of flow field in space and time, approximate them by means of gradual iteration, replace the original continuous physical field with physical quantities on discrete nodes, and connect different nodes by interpolation. According to the different simplified forms of governing equations, the numerical simulation methods of viscous flow mainly include direct numerical simulation , large eddy simulation and Reynolds average method.

The flow control equation for incompressible viscous flow using tensor index symbol can be expressed as follows:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\rho\frac{\partial u_i}{\partial t}+\rho u_j\frac{\partial u_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right)+S_i \tag{2}$$

Where, u_i , u_j are the components of velocity in i and j direction respectively; x_i , x_j are the components of displacement in i and j direction respectively; ρ is fluid density; μ is the dynamic viscosity coefficient; p is the static pressure; S_i is the component of the volume force on.

The above equations are transient governing equations of turbulence, and the calculation of them is very powerful. So far, they are only limited to some simple flows with low Reynolds number. Reynolds average method and Standard $k-\omega$ turbulence model are used in the numerical simulation of submarine pitch wake.

3. Meshing and numerical simulation

The numerical simulation of submarine pitching motion flow field model is carried out by using computational fluid dynamics technology. The calculation process can be roughly divided into geometric modeling, meshing, material property setting, boundary condition and initial condition setting, solver algorithm selection and iterative calculation, display and output calculation results and so on.

3.1. Grid Division

The DARPA SUBOFF model is simplified and used as a simulation object to establish the appropriate fluid domain and construct the geometric model.

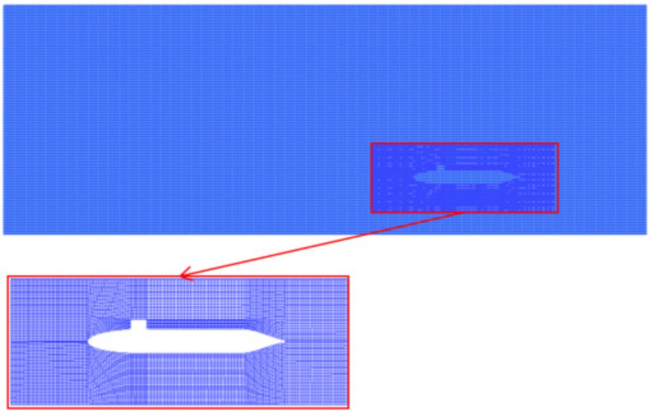

Fig.2 The overset grid of submarine pitching motion

The overset grid method is used in submarine pitch motion simulation,which is presented in Fig.2. The overset grid of submarine pitch motion is composed of the background grid and the surrounding grid of submarine. The two grid regions overlap in space, but do not have a connected relationship and exist independently of each other. Before calculation, holes are dug in the grid and interpolation points are matched to establish the connection relation. In the numerical discretization process, the overset grid is processed into cavity elements, discrete elements and interpolation elements. The fluid control equations are solved on the background grid and the submarine surrounding grid respectively. The interpolation elements constitute the internal boundary condition and are used to transfer data, and finally the flow field information is obtained in the whole computational domain.

3.2. Simulation Results

The evolution of wake field in submarine pitching motion is shown in Fig.3. The simulation results are described in detail below, and the formation reasons are briefly analyzed.

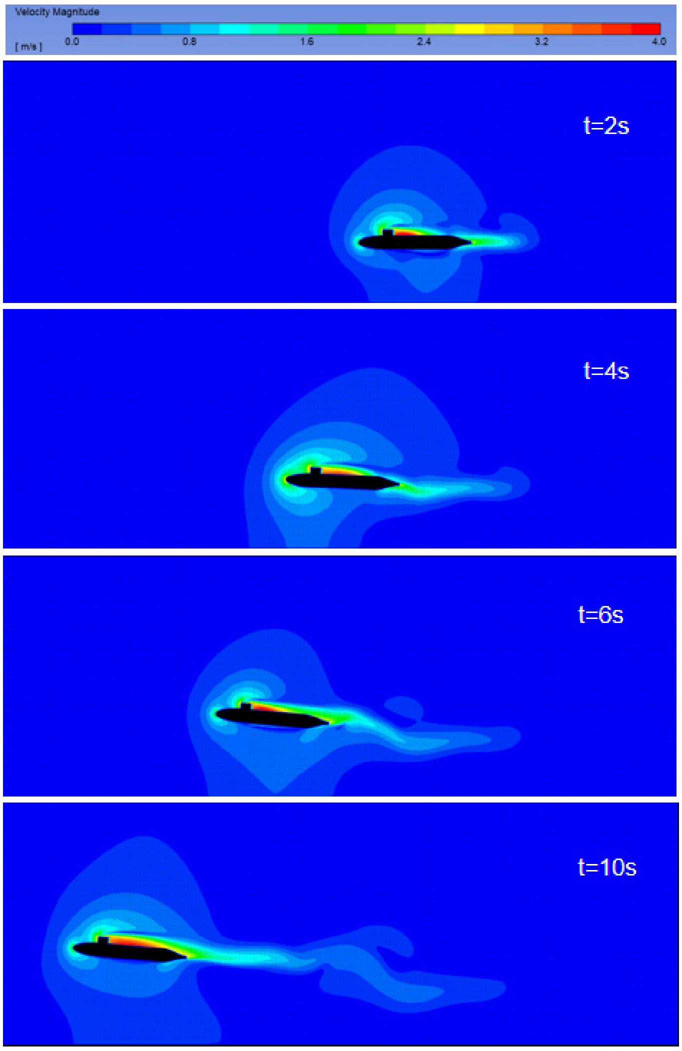

Fig.3 Evolution of wake field in submarine pitching motion

When the submarine is moving in a fixed depth straight line(t=2s in Fig.3), a large range of flow field is formed above the observation platform and behind the stern, and the maximum velocity is located behind the observation platform. When the submarine begins to turn the rudder to carry out pitching motion(t=4s in Fig.3), a wide range of flow field is generated in the front of the submarine. This is because the submarine's pitching motion transfers huge energy to the forward flow, and the wake flow field begins to deform and bend. In the steady linear pitching process(t=6s and t=10s in

Fig.3), the forward flow field begins to transfer backward, resulting in the formation of large range of flow field in the tail, and the deformation and bending part of the wake flow field becomes more obvious and the shedding vortex appear.

4. Comparative analysis of flow field

According to relevant data, the speed of the submarine in the cruising state is about 3m/s, and the speed of the submarine in high speed is generally about 10-15m/s. For the pitch maneuver of the submarine, the single rudder can be operated, and the relative rudder can be operated in the time of fast diving and floating. The general depth maneuver command has a longitudinal angle of 3°-5°, and a fast maneuver of 5°-7°, or greater than 7°. In order to explore the influence of submarine sailing speed and pitch angle on wake field, three different calculation conditions,as shown in Tab.1, are set for numerical simulation.

Tab.1 Three different calculation conditions

condition	I	II	III
speed（m/s）	3	6	3
pitch angle（°）	5	5	10

4.1. Influence of speed on flow rate

The figure on the left in Fig.4 shows the vertical plane velocity cloud diagram of working conditions I and II when the pitching motion reaches T =10s. The figure on the right in Fig.4 shows the velocity change curve of the wake survey line in the far flow field.

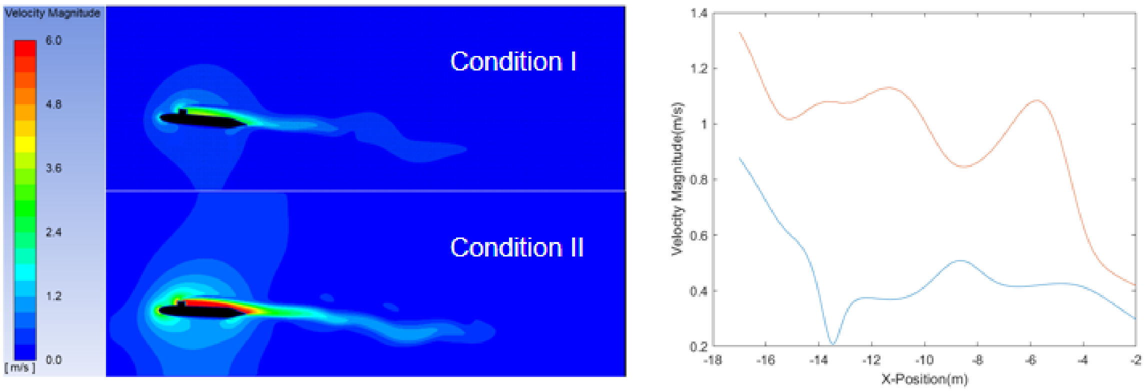

Fig.4 Influence of speed on flow rate

A representative survey line in the wake region is selected and its velocity change with position was plotted. The average velocity of the survey line in condition I and condition II was 0.45m/s and 0.95m/s respectively. Thus, when the ship speed is twice, the velocity of the surrounding flow field is also about twice; The range of near flow field around the submarine increases, but the range of far flow field does not change obviously.

4.2. Influence of speed on turbulent kinetic energy

The figure on the left in Fig.5 shows the vertical plane turbulent kinetic energy cloud diagram when the pitching motion of condition I and condition II reaches T =10s. The figure on the right in Fig.5 shows the change curve of turbulent kinetic energy on the wake survey line in the far flow field.

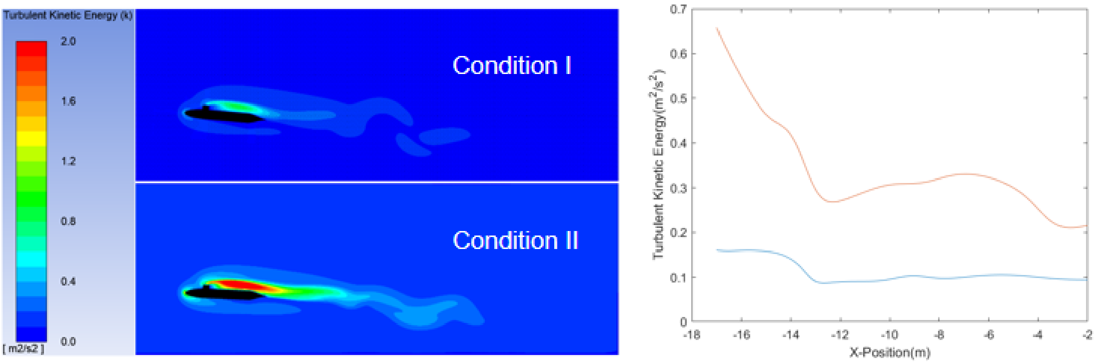

Fig.5 Influence of speed on turbulent kinetic energy

A typical survey line in the wake region was selected, and the variation of its turbulence kinetic energy with position was plotted. The average turbulence kinetic energy of the survey line in condition I was $0.11 m^2/s^2$, and that in condition II was $0.34 m^2/s^2$. Thus, when the ship speed is doubled, the turbulent kinetic energy of the surrounding flow field is about 3.09 times. The range of turbulence kinetic energy in the near flow field around the submarine does not change obviously, but the range of turbulence kinetic energy in the far flow field increases obviously.

In engineering practice, turbulence intensity I is commonly used to estimate turbulence kinetic energy k , and the formula is as follows:

$$I = 0.16 \times \mathrm{Re}^{-\frac{1}{8}} \tag{3}$$

$$k = \frac{3}{2}(v \cdot I)^2 \tag{4}$$

$$\mathrm{Re} = \frac{\rho v d}{\eta} \tag{5}$$

Where, Re is Reynolds number, ρ is the density of the medium, v is the average velocity, d is the characteristic length and η is the viscosity coefficient of the medium.

Therefore, $k \propto v^{1.75}$,when the flow velocity increases to twice, the turbulent kinetic energy should increase to 3.36 times theoretically. Therefore, considering the effect of discrete error and truncation error in numerical simulation, the simulation results are basically consistent with the theory.

4.3. Influence of pitch angle on flow field range

The figure on the left in Fig.6 shows the vertical plane velocity cloud diagram when the pitching motion of condition I and condition III reaches T =10s. The figure on the right in Fig.6 shows the velocity change curve on the wake survey line in the far flow field.

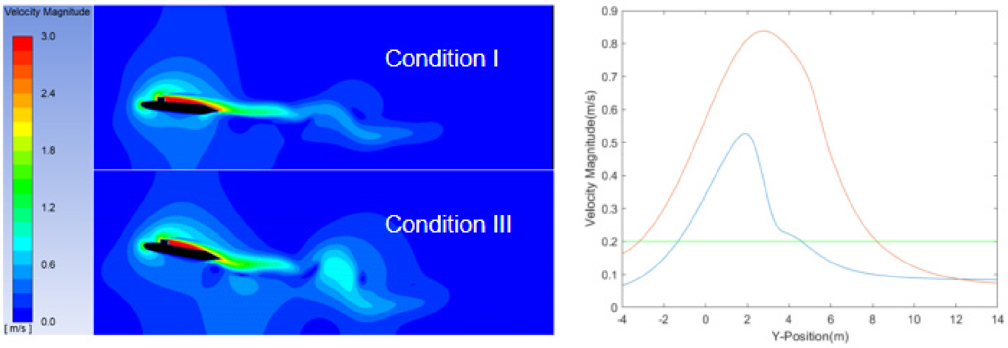

Fig.6 Influence of pitch angle on flow field range

The measuring line parallel to the vertical axis in the center of the shedding vortex of the wake flow is selected to draw the velocity change curve with position on the measuring line, and the range of the flow field with the velocity of 0.2m/s was compared. The longitudinal range of working condition I is 5.8m, and that of condition III is 11.3m. It can be seen that when the pitch angle is doubled, shedding vortex is formed obviously in the far flow field, and the range of the far flow field is significantly increased, which is about twice as large as before.

5. Conclusion

The underwater vehicle pitch motion wake field is simulated and analyzed, and its evolution law is introduced. The effect of underwater vehicle speed and pitch angle on wake field is investigated by setting three different calculation conditions.

(1)When the underwater vehicle changes from uniform linear motion to pitch motion, a wide range of eddy current field will be generated in the tail of the underwater vehicle. The intensity and range of turbulent kinetic energy generated in the pitch motion of the underwater vehicle will be larger than that in the straight motion.

(2)The velocity of wake field is positively correlated with the underwater vehicle's sailing speed, and the turbulent kinetic energy of wake field is proportional to the 1.75 power of underwater vehicle's sailing speed.

(3)The range of wake field is positively correlated with the pitch angle of underwater vehicle. The larger the pitch angle is, the larger the intensity and size of vortex formed in the flow field are, and the farther the vortex can propagate to the rear of underwater vehicle wake.

Therefore, this vortex can become the research target based on eddy current detection in non-acoustic detection. Compared with acoustic guidance, eddy current guided exploration and submersible technology has the advantages of long detection distance, strong anti-interference ability, not easy to deceive and induce.

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