ANSYS FLUENT-based Modeling and Hydrodynamic Analysis for a Spherical Underwater Robot

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Abstract — For an underwater robot, hydrodynamic characteristics are very important. This paper focuses on the research of the hydrodynamic analysis of a spherical underwater robot with three motions, horizontal motion, vertical motion and yaw motion. Firstly, the prototype of related second generation spherical underwater robot (SUR-II) was developed. In order to analyze the hydrodynamic characteristics of the spherical underwater robot exactly, CATIA software was employed to establish the 3D models of the flow field. For the complex structure of the developed underwater robot causing the limitations on meshing and hydrodynamic analysis, we simplified the 3D models properly. Finally, we used ANSYS FLUENT to analyze the three models and compare the simulation results to the theoretical values. It showed that the error was less than 3%. The pressure contours and velocity vectors showed the detail of the flow field when the robot implemented the basic motions.

Index Terms — 3D Model, Spherical Underwater Robot, Hydrodynamic Analysis, Computational Fluid Dynamics (CFD).

I. INTRODUCTION

Thousands of underwater robots have been developed to satisfy the requirement of underwater tasks. The streamline shape is usually used in high speed underwater robots and the special shape is always used in remotely-operated vehicle (ROV) to carry out some real time underwater operations [1]-[3]. For a kind of special shape, spherical shape shows a good performance on water resistance and the spherical underwater robot is easy to realize 0 turning radius no matter in what motion state of the robot. Due to the advantages, some researchers proposed their spherical underwater robots. For example, the University of Manchester and University of Oxford co-developed a kind of µ-AUV [4]. This robot employed 6 propellers as propulsion system and equipped them on the equator of the spherical hull. The development purposes of this micro robot were monitoring the nuclear storage ponds and waste water treatment facilities to prevent leakage. There is another typical spherical underwater robot, ODIN-III, which is developed by University of Hawaii [5]. In our laboratory, a novel spherical underwater robot with vectored water-jet thruster is developed [6]-[13].

Due to the importance of hydrodynamic characteristics, a lot of researchers did study on spherical underwater robots. Leroyer et al. analyzed the DTMB5415 bare hull using a computational fluid mechanics (CFD) method, and proposed two numerical procedures that sped up the Reynolds-averaged Navier–Stokes (RANS) solvers [14]. After compared to a classical simulation the author obtained that, these two method numerical solutions can up to four times faster. Mylonas and Sayer predicted the forces acting on a yacht keel based on the large-eddy simulation (LES) and detached-eddy simulation (DES) solutions [15]. Propulsion systems have also been a main research subject. Wei et al. predicted the propeller- excited acoustic response of a submarine structure using a numerical method [16]. Cheng et al. analyzed the hydrodynamic characteristics of an unconventional propeller with an endplate effect and compared the results to those of a conventional propeller [17]. In my research, the water resistance is difficult to get from experiment, so we want to get the water resistance and other important features according to modeling and hydrodynamic analysis.

The paper is organized as follows. The section II briefly introduced the modelling and meshing of the SUR-II for hydrodynamic analysis. And then in section III, 3 major motion states are analysed by FLUENT. Finally, the conclusions and future work are pointed in section IV.

II. MODELING OF THE FLOW FIELD

A. Prototype of the SUR-II

The prototype of the SUR-II is shown in Fig. 1. We adopted 3 vectored water-jet thrusters as propulsion system. In order to reduce the effect of the propulsion system on the robot flexibility and prevent the propulsion system from the impact force, the propulsion system is assembled inside of the spherical hull. The robot is also a kind of open frame structure. Water is easy to go through the robot, and all of the control parts are contained in the water proof box. This design will reduce the risk of leakage. The waterproof treatment of the servo motors and water-jet thrusters were also done respectively. The structure of SUR-II is too complicated to carry out hydrodynamic analysis because there are two much faces and parts. For example, 12 screws are used for fastening the water proof box and some wires are used to connect the servo motors and water-jet thrusters to the control circuit. Although we can build the 3D model by the software including all of these parts, they will affect the result of hydrodynamic analysis. Worse still, the ANSYS FLUENT
cannot get a result due to the complexity. And the complicate structure will cost a long computational time.

Fig.1 Prototype of the SUR-II

B. Modeling of the SUR-II

The 3D model must be simplified for reducing the computation time and getting more effective result. The simplification standard is to reduce the amount of surfaces and parts. Therefore, some unimportant parts and surfaces will be simplified, including the screws, the wires and the support frame of the servo motors. All the ignored parts are small and complicated. Besides that, we simplify the shape of servo motor to cubical shape and the water-jet thruster to cylindrical shape. Finally, three models for the three basic motions are obtained and shown in Fig.2.

(a) Horizontal motion (b) yaw motion (c) vertical motion

Fig.2 Simplified models for 3 basic motions

C. Modeling of the flow field

For the hydrodynamic analysis, we just care about the influence of the flow field from the robot, so the flow field must be built based on the 3D model of robot. The size of flow field should be big enough to ensure that the wall of flow field cannot affect the results of hydrodynamic analysis. Generally, the size and the shape of flow field are decided by the robot. If the speed of robot is relatively high and have a big effect on the flow field, we should choose a big flow field. In this research, the cylindrical flow field with a radius of 1 m and a length of 4 m. After decided the 3D model and flow field, Boolean operation is carried out between the 3D model and flow field. Then we use the flow field minus the 3D model of robot. Finally, the hydrodynamic analysis object is obtained as shown in Fig.3. We use the same method get three 3D models. Totally, there are three objects should be obtained because three motions must be analysed respectively.

D. Mesh of the flow field

Mesh of the flow field is the most important factor to the hydrodynamic analysis. The amount of mesh decides the performance of hydrodynamic analysis and computational complexity.

Fig. 4 shows the mesh of the flow field. In this research, a total of 1.5 million mesh elements were used. The Fig. 4(b) depicts the detail of the mesh around the robot. This is just an example for horizontal motion. For the complex structure of the robot, the size of element should be very small to get a good hydrodynamic analysis result. Near the wall of robot, three layers are set and mesh density is higher. The mesh is carried out in the ANSYS ICEM. Finally, we output the mesh files as a previous work of hydrodynamic analysis.

III. HYDRODYNAMIC ANALYSIS OF THE SUR-II

Due to the commercial software FLUENT combined into ANSYS, all the analysis works are carried out by using this software. In total, there are 3 meshing files which will be
analysed for the three motions. The steps of CFD are as follows:
1. Import the meshing file to ANASYS FLUENT;
2. Set the condition of flow field;
3. Carry out solution;
4. Get the results.

In the second step, the material and boundary condition should be set. In this research, \(k-\varepsilon\) model is selected to describe the fluid situation, while turbulence occurs when the robot moves at a speed of 0.3 m/s. The maximum speed of robot is about 0.3 m/s \([18, 19]\). There are two methods to describe the kinematic relationship between the fluid and the robot. The first method is dynamic mesh, which set the water to be static and the wall of robot to move. The second method is to assume that the water moves at a speed of 0.3 m/s and the wall of robot is static. Because the second method is very simple and easy to be realized, we choose the second method \([20-22]\).

### A. CFD simulation for horizontal motion and vertical motion

The robot and fluid move relative to each other, so the robot was set as a static wall while the fluid was set as a constant velocity flow. Fig. 5 presented how both the velocity and pressure were affected by the fin that was fixed on the equator of the robot. Thus, the fin cannot be ignored when the robot was moving in vertical direction. But the effect of the holes was not obvious. The velocity of the fluid inside the robot was the same as the velocity of the robot. Therefore, the fluid inside the robot can be assumed as part of the robot and the robot can be assumed as a sphere. However, for horizontal motion (Fig. 6), the fin can be ignored and the holes must be considered, because water flows into the robot through the front holes, and then out of the robot through the back holes, as shown in Fig.6. Thus, the robot cannot be assumed as a closed sphere. In summary, the fins cannot be ignored for vertical motion and the holes cannot be ignored for horizontal motion. Because the robot is set as static and the fluid is moving, the result of Fig 5(a) and Fig 6(a) are relative velocity. The blue colour stands for high speed part. The out boundary is set as pressure output.

### B. Verify the drag coefficient by CFD simulation for horizontal motion and vertical motion

The drag coefficient \(C_d\) is an important hydrodynamic characteristic. It is different in vertical direction and horizontal direction because there are three holes in the horizontal direction. As a sphere object in vertical direction, the \(C_d\) is equal to 0.4. In horizontal direction, we can calculate the \(C_d\) according to (1).

![Velocity Vectors Colored By Velocity Magnitude (m/s)](image)

\[
F_d = \frac{1}{2} C_d (R_e) \rho V^2 A
\]  

Where, 
\(F_d\): water resistance, it is equal to thrust force \(T\); 
\(C_d\): the drag coefficient; 
\(R_e\): the Reynolds number that reflect the flow characteristics; 
\(V\): the relative velocity of spherical underwater robot to the fluid; 
\(A\): the cross-sectional area; 
\(\rho\): the density of the fluid.
propulsion system, as shown in Fig. 7, and a pressure surface was generated around the propulsion system Fig. 7 (b).

\begin{equation}
C_d = \frac{2T}{\rho V^2 A} = 0.61.
\end{equation}

Besides the theoretical calculations, we can also get the drag coefficient from the CFD simulation, which are shown in Fig.7. The drag coefficient for vertical motion converged to a constant $C_d = 0.41$, similar to the value calculated in Section 3. For horizontal motion $C_d = 0.59$, which indicates a 3% error compared to the calculated value. Therefore, the results of the CFD analysis are acceptable.

\textbf{C. Yaw motion}

In addition to vertical and horizontal motion, rotational motion was also simulated. Usually, dynamic mesh and reference motion can be used to simulate the rotation motion, in this paper, because the simulation condition is constant, we selected reference motion to simulate the motion of robot. The velocity and pressure results indicated that the influence which rotational motion exercises on the fluid was negligible. The interaction between the fluid and the robot was caused by the

\begin{equation}
C_d = \frac{2T}{\rho V^2 A} = 0.61.
\end{equation}

\textbf{Conclusions and Future Work}

This paper presented a hydrodynamic analysis for the second generation Spherical Underwater Robot (SUR-II). First of all, the mechanical structure of the SUR-II was presented. Due to the complexity of the SUR-II, it was difficult to get a good simulation result, so we simplified the 3D model of SUR-II. And then the 3D models were meshed by ANSYS ICEM. Finally, the mesh files were imported to ANSYS FLUENT to carry out the CFD simulation. Three main basic motions were analysed, including horizontal motion, vertical motion and yaw motion. The drag coefficient in vertical direction and horizontal direction were obtained and compared to the results of calculation. The simulation results showed that the drag coefficient error is fewer than 3%. The velocity vector and pressure contours clarified the hydrodynamic features and provided important evidence to confirm the assumptions that the robot could be assumed as a sphere in vertical motion.

In the future, we will focus on some hybrid motions to carry out the hydrodynamic analysis.

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Velocity Vectors Colored By Velocity Magnitude (m/s)

(a) Velocity vectors

Contours of Static Pressure (pascal)

(b) Pressure contours

Fig. 7 The results of CFD analysis for yaw motion

REFERENCES


