Hydrodynamic Analysis and Structural Optimization of an Underwater Robot

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Abstract. BYSQ-2 is an amphibious spherical exploring robot which can move flexibly in water and on land, it has good water pressure resistance and can perform a rotational motion with a zero degree turn radius. But the actual experiment results show the shortcoming of the robot is the low maximum surge speed. The main objective in this paper is to improve the maximum surge speed and alleviate the heavy pendulum’s oscillation. Firstly, the hydrodynamic coupling under different structural parameters and propeller working states is analyzed by using CFD method, the influence of structure parameters and propeller rotation speed on thrust and water resistance are summarized, based on the optimal structural parameters, the new generation robot with better performance is designed. The simulation and experiment results show the validity of the new design scheme.

1. Introduction

Hydrodynamic characteristics analyses are important for achieving necessary maneuverability, the existed approaches for acquire hydrodynamic characteristics often including scaled or full-scale experiments, empirical formula approximations, system identification and computational dynamic approaches [1, 2]. Experimental method is in high-accuracy but can only obtain limited measure results with expensive cost, empirical formula approximations method requires deeper knowledge and experiences while it is not comprehensive [3]. CFD software such as SHIPMO™, ANSYSCFX™, ANSYS-FLUNT™ and ANSYS-AQWA™ are capable to predict hydrodynamic parameters for a complex-shaped AUV with very low cost and it can supply engineers with accurate information for potential vehicle designs and control algorithms [4-8]. CFD technique is mainly used to analyze the streamline underwater robot, the applications on spherical underwater robot is still relatively few.

2. Mechanical Structure of BYSQ-2 Prototype and Experiment

BYSQ-2 is an amphibious spherical roving robot which can move flexibly in water and on land, it has a fiber glass external hull, the internal structure of BYSQ-2 mainly including a single propeller, the heavy pendulums and a flywheel. The catheter is fixed connected with the spherical shell, the propeller is mounted in the middle of the catheter, the sleeve (or long axis) is mounted the outer wall of the catheter and it can rotate around the catheter, the short axis mechanism and the flywheel rotation axis is fixed to sleeve and perpendicular to the sleeve. The robot regulate its attitude by using the heavy pendulums rotating around the long or short axis.

In addition to the above advantages, the spherical structure has a drawback, that is, the water resistance is larger than the streamlined structure which results the low velocity in moving forward. The
movement resistance of underwater objects includes linear damping term and nonlinear damping term, due to the low speed of the robot, we neglect the linear damping term and the Coriolis forces, based on Newton’s second law:

\[ F = ma \]  

(1)

the surge dynamic equation can be expressed as:

\[ (m + \lambda) \dot{v} = T - F_D \]  

(2)

Where \( m \) denotes the mass of the robot, \( \lambda \) denotes the added mass of water and can be calculated by using radiation/diffraction program MCC and WAMIT, \( T \) represents the Propeller’s thrust, \( v \) is the surge velocity, \( F_D \) is the movement resistance of the robot and can be expressed as:

\[ F_D = \left( 0.632 + \frac{4.8}{\sqrt{Re}} \right)^2 \rho \frac{v^2}{2} A \]  

(3)

Combing the equations (1)-(3), we can obtain:

\[ (m + \lambda) \dot{v} + \left( 0.632 + \frac{4.8}{\sqrt{Re}} \right)^2 \rho \frac{v^2}{2} A - K_p \rho n^2 D_p^4 = 0 \]  

(4)

From equation (4), the maximum velocity can be obtained as:

\[ v_{\text{max}} = \frac{2K_p \rho n^2 D_p^4}{\sqrt{\rho A \left( 0.632 + \frac{4.8}{\sqrt{Re}} \right)}} \]  

(5)

In order to verify the maximum velocity of the theory calculation, the real world experiments have been conducted in the calm swimming pool at BUPT, after the robot reached the maximum velocity, the time period was recorded for the robot moving through 1m distance (see figure 3), The experiment was repeated five times, and the average maximum velocity was calculated based on the experiment results. The experiment recorder is described in table 1.

**Table 1. Test data of maximum velocity.**

| Cycle | 1   | 2   | 3   | 4   | 5   |
|-------|-----|-----|-----|-----|-----|
| Time (s) | 1.53 | 1.54 | 1.52 | 1.54 | 1.53 |
| Test results (m/s) | 0.655 | 0.654 | 0.656 | 0.644 | 0.655 |
| Computational result (m/s) | | | | | 0.681 |
3. Resistance and Thrust Analysis under Different Structural Parameters

The resistance of shell and the thrust of the propeller are the main factors which can affect the robot’s surge velocity. Moreover, the propeller is mounted in the middle of the catheter, the propulsion ability is closely related to structural parameters of the spherical shell in addition to the structure of itself and the propeller’s rotational speed, hence the structural parameters, resistance and the propeller’s thrust couple and interact with each other. In previous work, we had assumed that the robot was an absolute spherical, so the hydrodynamic characteristics were the same for all DOFs. But the planar mechanic machine (PMM) test showed the add mass in surge direction and sway direction was obviously different. To ensure the accuracy of the model and to simplify the analysis of the coupling hydrodynamic coefficients, the sphere-pipe model is established, the bolts were ignored to reduce the complexity of the mesh and enhance the mesh quality. The BYSQ-2 was modelled in a cube flow field with 2 m side length, the mesh density was increased around the robot and three boundary layers were used to obtain satisfactory results and reduce the amount of time required.

We carry out the simulations Under the conditions of \( v=1 \text{m/s} \), \( d = 0.14 \text{m} \), \( n= 600 \text{rpm} \) and shell diameter \( D \) changes from 0.14 m to 0.5 m, the simulation results are shown as in figure 1.

![Pressure change under different spherical shell diameter](image)

**Figure 1.** Influence of different spherical spherical diameter.

From figure 1, it can be seen the pressure in the front is increasing with \( D \) increasing and it can be seen that with the propeller’s diameter \( D \) increasing, the move forward resistance is increased obviously, while the propeller’s thrust change little in the process, so, minimizing the size of the spherical shell is another method to improve the robot’s velocity.

Figure 1 shows that the thrust of the propeller substantially contains unchanged, so if the propeller’s rotation speed \( n \) keeps constant, the thrust of the propeller is not affected by the changing of the shell diameter and the catheter diameter, the move forward resistance of the robot can be reduced by increasing the catheter diameter \( d \) and decreasing the shell diameter \( D \). However, the catheter diameter can’t be too large, and the sphere shell diameter \( D \) of the robot can’t also be too small, because the sleeve is mounted the outer wall of the catheter and it need to rotate around the catheter and the heavy pendulum and the control circuit occupy the internal space of the robot. Therefore, the optimal parameters are chosen 0.14 and 0.35 for the catheter diameter \( d \) and the shell diameter \( D \), respectively. In order to verify the performance of the optimal parameters, the simulation is carried out under the conditions of \( v=1 \text{m/s} \), and propeller’s rotation speed \( n \) change from 0 to 2000 rpm, the simulation results of the optimal parameters are shown in figure 2.
Figure 2. Influence of different propeller rotation speed.

As can be seen from figure 2, when the propeller’s rotation speed increasing, the water pressure in front of the robot keeps almost no change, but gradually becomes smaller in the rear of the robot, the water pressure also gradually becomes smaller in the front of propeller.

In order to further clarify the hydrodynamic coupling under different structural parameters and propeller working states, we have already conducted a lot of simulation analysis, the results can be seen in figure 3.

(a)                                             (b)
Figure 3. Hydrodynamic Analysis of different key parameters.

Figure 3 Analysis the key parameters which can affect the resistance and propeller’s force including the catheter diameter \(d\), the spherical shell diameter \(D\) and propeller rotation speed \(n\) in detailed. From figure 3, it can be seen that the propeller’s rotation speed is the main factor which influence the propeller’s thrust; From figure 3, the move forward resistance of the robot is affected by all of the key parameters, simultaneous it is affected by the propeller rotation speed \(n\); the real world experiments have been conducted in the same conditions as in section 2, from the experimental data, we calculated that the robot’s maximum speed is 1.2 m/s.

4. Conclusion

To solve the problem of low maximum moving velocity, the coupling hydrodynamic characteristic under different key parameters is analyzed. Through simulation and experiment, we found that it is effective for improving the maximum moving velocity by increasing the catheter diameter and decreasing the spherical shell diameter, with the propeller rotation speed increasing, water resistance, the propeller’s thrust, torque and output power increase apparently. According to the above analysis, combined with the internal structure of the robot, we determine the optimal structure parameters and develop a new generation underwater spherical roving robot. The real world experiment show the new generation robot’s maximum speed is about 1.2 m/s.

References
[1] Vervoort J H A M 2009 Modeling and Control of an Unmanned Underwater Vehicle.
[2] Coe R G 2013 Improved Underwater Vehicle Control and Maneuvering Analysis with Computational Fluid Dynamics Simulations, Virginia Tech.
[3] Zhang H, Xu Y R and Cai H P 2010 J. Marine. Sci. Appl. Using CFD Software to Calculate Hydrodynamic Coefficients, 9 149-55.
[4] Yang R, Clement B, Mansour A, et al. 2015 J. Intel. Robot. Syst. Modeling of a Complex-Shaped Underwater Vehicle for Robust Control Scheme, 80(3-4) 491-506.
[5] Ferziger J H and Peric M 1996 Computational method for fluid dynamics, Springer, Berlin, 28-50.
[6] Sarkar T, Sayer P G and Fraser S M 1997 Int. J. Numerical Methods Fluids A study of autonomous underwater vehicle hull forms using computational fluid dynamics, 25(11) 1301-13.
[7] Tyagi A and Sen D 2006 Ocean Eng. Calculation of transverse hydrodynamic coefficients using computational fluid dynamic approach, 33(5) 798-809.

[8] Wilson R, Paterson E and Stern F 2006 Unsteady RANS CFD method for naval combatant in waves, Proceedings of the 22nd ONR Symposium on Naval Hydrodynamics, Washington DC, National Academy Press, 532-49.