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Jet Propeller Design and Impeller Modification of Underwater Spherical Robot

Mingqi Fang, Yunxia Yu, Lei Wang, Zhaobing Liu

School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, 430070, China

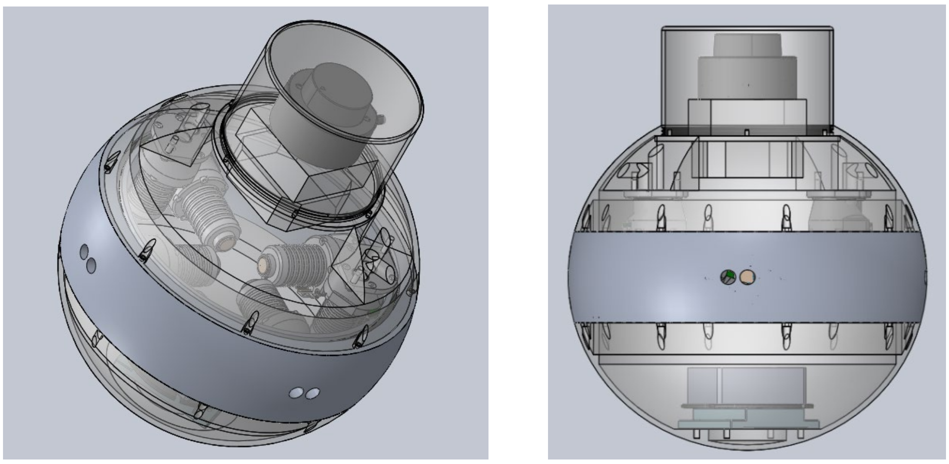
Abstract: *With the increase of deep-sea exploration and development activities, the underwater spherical robot has been widely concerned as a flexible and efficient exploration tool. The propulsion system, as the core component to realize the precise control and efficient movement of the underwater vehicle, has an important impact on improving the performance of the robot. This paper focuses on the design of the jet propeller and the modification of the impeller of the underwater spherical robot, aiming to improve the propulsion efficiency, reduce the noise, and enhance the adaptability and operation ability of the robot in the complex underwater environment by optimizing the design.*

Keywords: *Underwater robot, Jet thruster, Impeller modification, Propulsion efficiency, Noise reduction*

1. Introduction

China's territorial sea has a vast area and abundant Marine resources. Developing Marine resources and exploring the Marine world has become an important strategic direction for China. Underwater robots are important tools for exploring the ocean field, and are of great significance in detecting Marine resources, exploiting combustible ice, monitoring Marine biodiversity, protecting Marine ecology, and underwater military monitoring[1]. Underwater spherical robot has become the focus of underwater robot research because of its unique configuration, convenient maneuverability and flexible motion performance[2]. As the core of the moving parts of the underwater spherical robot, the propeller determines the motion parameters of the underwater spherical robot. Because of the diversity of underwater environment and the complexity of fluid changes, the propeller design of underwater spherical robot is particularly important, which determines the detection performance and safety performance of underwater spherical robot. Therefore, the propeller design of underwater spherical robot is a necessary prerequisite to promote the research of underwater spherical robot.

2. Analysis of propulsion scheme of underwater spherical robot



(a)axonometric drawing *(b) front view*

Figure 1: Three-dimensional model of underwater spherical robot

The underwater environment is complex and changeable, the dark current is surging, and a series of unknown factors such as the seabed reefs and fish schools that may be encountered, underwater robots must adapt to different underwater environments due to the realization of various special operations. This working environment requires the underwater robot to have the following characteristics: good mobility, low noise, simple mechanism, small turning radius, easy to control. At the same time, in order to reduce the blocking effect of water flow, maximize energy consumption, and avoid being stuck on the reef, the surface of the underwater robot is required to be as smooth as possible. In view of the above characteristics, the underwater robot designed in this paper adopts a spherical shell (the diameter of the shell is 190mm) and moves underwater in the form of floating. As shown in Figure 1.

At the same time, the propeller offset layout[3] has the characteristics of zero turning radius and flexible movement. It can realize the advance and retreat, lift and rotation of the underwater robot. As shown in Figure 2.

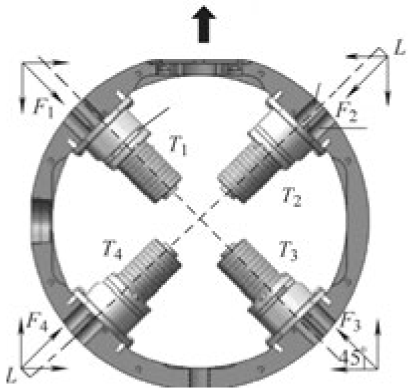


Figure 2: Propeller arrangement and force diagram of underwater spherical robot

The unique structure and small volume of underwater spherical robot, as well as the flexible movement needs of multi-degree of freedom, put forward higher requirements for the propeller design of underwater robot. Considering the safety of underwater spherical robot operation and the flexibility of movement, its propeller is required to have the following characteristics:

(1)Simple and compact structure. The maximum diameter of the underwater robot is 190mm, and the propeller is required to be compact and small.

(2)Easy to assemble. Because the underwater robot works in a complex environment, in order to prevent bumping and sticking with the reef, the propeller must be installed inside the sphere to ensure that the shell is smooth and non-convex. Therefore, the requirements for easy assembly of thrusters are put forward.

(3)Low noise. Because the underwater spherical robot may be used in military, biological detection and other fields, the propeller must have the characteristics of low noise.

(4)Power cleaning. The motion of the underwater spherical robot will generate negative pressure in the underwater area, and the existence of negative pressure will lead to the generation of bubbles. On the one hand, it will affect the environment and cause environmental pollution, and on the other hand, it will also affect the motion of the underwater spherical robot and cause turbulence. Therefore, the propeller design of underwater spherical robot must consider reducing local negative pressure.

At present, there are two main propulsion methods of underwater robots, namely propeller propeller and jet propeller[4]. Considering the working environment and movement characteristics of the underwater spherical robot, the feasibility of the two thrusters is analyzed below.

2.1 Propeller

As the most traditional underwater propulsion method, propeller propeller is widely used in ships, submarines and other scenarios. The principle of its thrust generation is to use the kinetic energy change of the same fluid from the front of the blade to the back of the blade, so that this part of the kinetic energy change into the forward power of the device. The specific formula is as follows:

$$T = \rho A v_1 (v_b - v_a) \tag{1}$$

Where, T represents propeller thrust, N; ρ represents the density of liquid medium, kg/m^3; A represents the projected area of the propeller on the plane of the vertical axis, m^2; v_1 is the fluid velocity through the propeller; v_a represents the velocity of the fluid after passing through the blade, m/s; v_b

represents the velocity of the fluid before it passes through the blade, m/s.

From the analysis of the above formula, it can be seen that in the same medium environment, the factors affecting the propeller thrust include the area of the propeller blade and the flow rate of the fluid. Only for thrusters, the impact of its thrust size are: blade area, speed, blade propeller and so on. Due to the limitation of the maximum size of the underwater spherical robot, the maximum blade size is preliminarily estimated to be no more than 30mm by the formula. Therefore, in order to meet the power needs of the robot, the motor speed and blade lead must be increased, but at the same time, the local negative pressure of the blade will be increased, resulting in cavitation[5], which endangers the operation safety of the spherical robot.

2.2 Jet propeller

The underwater jet thruster uses water as the medium and uses the reverse thrust generated by Newton's third law to drive the robot. The fluid passes through the injector entrance, reaches the pump body, and then shoots out at a certain initial speed through the outlet through the pipeline. During this period, the fluid energy changes, and the thrust generated by the fluid in the opposite direction pushes the robot to move. The basic equations of ideal jet propulsion are thrust equation, energy equation and continuity equation[6] :

$$T = \rho Q\left(v_j - v_0\right) \tag{2}$$

$$\frac{{v_j}^2}{2g} = H + \frac{{v_0}^2}{2g} \tag{3}$$

$$v_0 A_0 = v_j A_j = Q \tag{4}$$

Where: T is the thrust, N; Q is the flow rate, m^3/s; v_j is the outlet fluid velocity, m/s; v_0 is the inlet fluid velocity, m/s; H is the head, m; A_0 is the entrance area, m^2; A_j is the outlet area, m^2; g is the acceleration of the weight, m/s^2.

In the process of water jet, there are energy loss elements such as pipes, nozzles and nozzles, so it is necessary to consider various energy losses and introduce correction coefficients into each equation to get the revised thrust equation, energy equation and continuity equation. As follows:

$$T_e = \eta T = \eta\rho Q\left(v_j - v_0\right) \tag{5}$$

$$\frac{1.03{v_j}^2}{2g} = H + \frac{{v_0}^2}{2g} + K_1\frac{{v_0}^2}{2g} \tag{6}$$

$$v_0 A_0 = v_j A_j = Q \tag{7}$$

Where: T_e is the injection thrust after considering energy loss, N; η is propulsive efficiency; K_1 is the loss coefficient along the path.

The correction coefficient in the above equation should be selected according to the specific application environment, so the propeller design and selection can be carried out according to the work needs of the underwater ball robot.

Propeller composition mainly include pump body, motor, inlet pipe and outlet piping and so on. The structure is relatively simple, there is no extra structure, to meet the needs of smooth surface of the propeller. At the same time, according to the performance comparison between jet propulsion and screw propulsion in Table 1, after analyzing the advantages and disadvantages of these two propulsion methods, it is found that jet propulsion is more suitable for the working requirements and movement characteristics of underwater spherical robots. Therefore, jet propulsion is selected as the propulsion device of underwater spherical robots.

Table 1: Performance comparison between jet propeller and screw propeller

style	propeller	screw type
merit	Low noise; High mobility; Convenient operation, wide usage scenarios.	At high speed, the propulsion efficiency is high.
drawback	The structure is complicated and the design is difficult. At high speed, the propulsive efficiency is low.	Loud noise; Under low speed, transmission efficiency is low.

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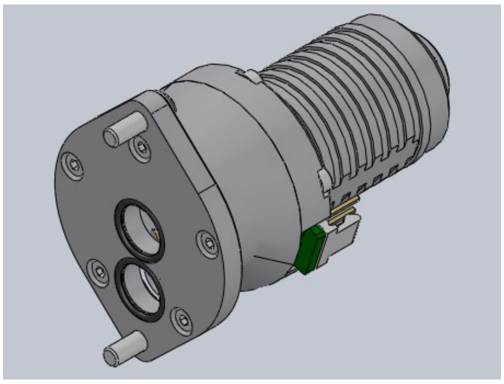
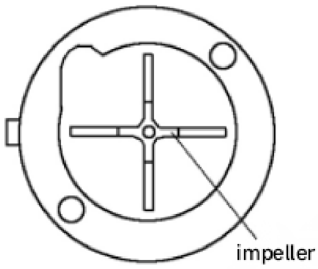
3. Jet propulsion design

According to the jet thruster offset arrangement scheme and the internal structure of the spherical robot, the jet thruster design model is shown in Figure 3. The propeller is mainly composed of a pump body, a motor, an inlet pipe and an outlet pipe. The nut is connected with the body, and the cross impeller is used inside. Based on the design principle of centrifugal pump, the jet is generated to generate thrust.



(a) axonometric drawing



(b) front view

Figure 3: Structure diagram of jet thruster

In order to analyze the stress of the underwater spherical robot, the working environment of the robot is simulated in Fluent according to the fluid dynamics theory. The simulation results are shown in Figure 4, and the running resistance of the robot is further extracted. The calculation results are shown in Table 1.

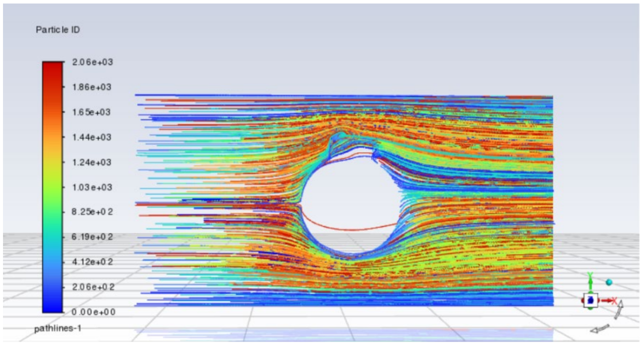


Figure 4: Robot workflow simulation diagram

Table 2: Robot running resistance

kinematic velocity(m/s)	pressure drag(N)	viscous resistance(N)	total resistance
0.15	0.160	0.065	0.225

According to the offset arrangement of the injector, the rated thrust of a single propeller is calculated, and the parameters of the jet propeller are determined according to the design principle of the centrifugal pump. The main parameters of the designed jet propeller are shown in Table 2. The relationship between pressure and flow as well as pressure and power characteristics of the propeller under the condition of 12V are shown in Figure 5 and Table 3.

Table 3: Main parameters of robot

Rated motor speed(r/min)	4800
impeller diameter(mm)	20
inlet diameter(mm)	5
outlet diameter(mm)	5
rated power(W)	20
rated thrust(N)	0.2

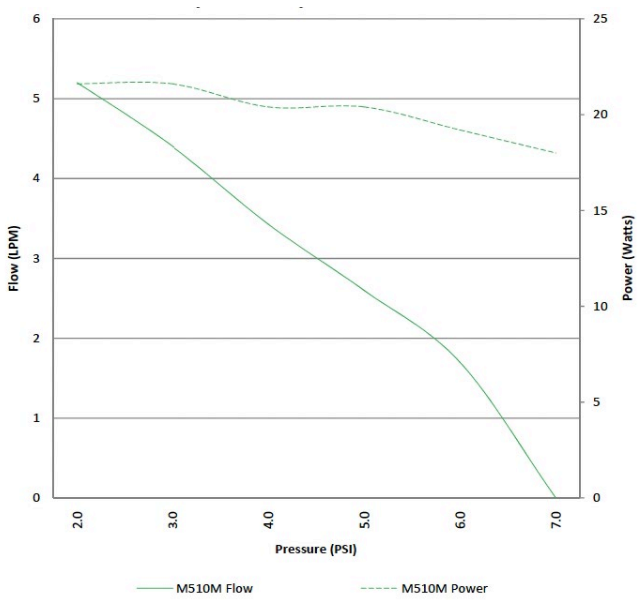


Figure 5: Relation characteristic curve of pressure and flow as well as pressure and power of propeller at 12v

4. Impeller repair design

Considering the working environment of the underwater spherical robot, it is necessary to focus on the analysis of the flow gasification characteristics in the jet pump in order to minimize the precipitation of dissolved gas in the water caused by the operation of the injector. The gasification characteristics inside the pump body are expressed by the cavitation allowance NPSHr. The cavitation allowance is mainly due to the fact that the medium enters the low pressure area in the center of the impeller through the pump inlet. When the ambient pressure is reduced to the vaporization pressure of the current temperature, a large number of bubbles are formed. At this time, the bubbles cannot withstand the high-pressure environment and burst instantly, forming a vacuum, and the surrounding liquid is filled with a high speed, which will have a strong impact on the metal surface and damage the impeller[7]. The smaller the cavitation allowance, the greater the negative pressure inside the propeller, and the easier it is to precipitate bubbles. The calculation formula is as follows:

$$NPSHr = \frac{v_1^2}{2g} + \frac{\lambda \omega_1^2}{2g} \tag{8}$$

Where: v_1 is the absolute velocity before blade inlet, m/s; w_1 is the relative velocity before blade inlet; λ is the blade inlet pressure drop coefficient.

According to the NPSHr expression, the cavitation margin is determined by the environmental parameters and the injector parameters. The environmental parameters are mainly related to external factors such as operating conditions, such as the absolute speed of water flow. The ejector itself parameters include impeller speed, impeller structure and so on. Therefore, in order to ensure the stability of the underwater spherical robot and improve the cavitation allowance, it is necessary to improve the structure of the pump itself. Fluent software was used to conduct finite element simulation analysis of the internal flow field of the jet pump, so as to quantitatively analyze the internal flow field state of the jet thruster under the working state of the underwater spherical robot, in which the local pressure of the impeller was mainly concerned to improve the impeller configuration. The pressure simulation results are shown in Figure 6.

According to the simulation results in FIG. 6, it can be found that the injection pump locally generates significant negative pressure during operation, and the maximum value reaches -84,100Pa. This will destroy the motion balance of the underwater spherical robot and have a great impact on environmental detection. Therefore, in order to reduce the local negative pressure value and increase the cavitation allowance, the impeller is modified. The initial impeller is a cross type, which is simple in structure but poor in hydraulic performance and low in energy conversion efficiency. According to the design principle of the impeller[8], the vortex impeller has excellent hydraulic performance and relatively simple structure,

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which can not only ensure the flow state of the fluid but also take into account the propulsion efficiency. Therefore, a vortex impeller is used instead of a cross impeller. The model is shown in Figure 7.

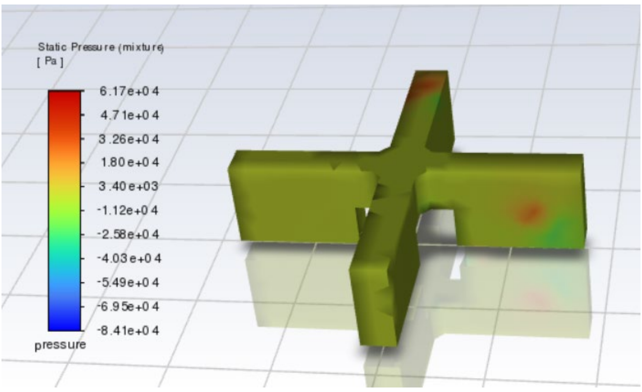

Figure 6: Pressure distribution diagram of jet pump with straight cross impeller

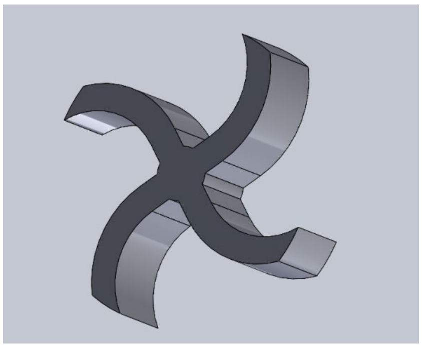

Figure 7: Vortex blade model

After improving the blade configuration, in order to compare the difference in the flow state before and after the improvement, Fluent was used to simulate the injection pump under the same conditions (the same working environment). The simulation results are shown in Figure 8.

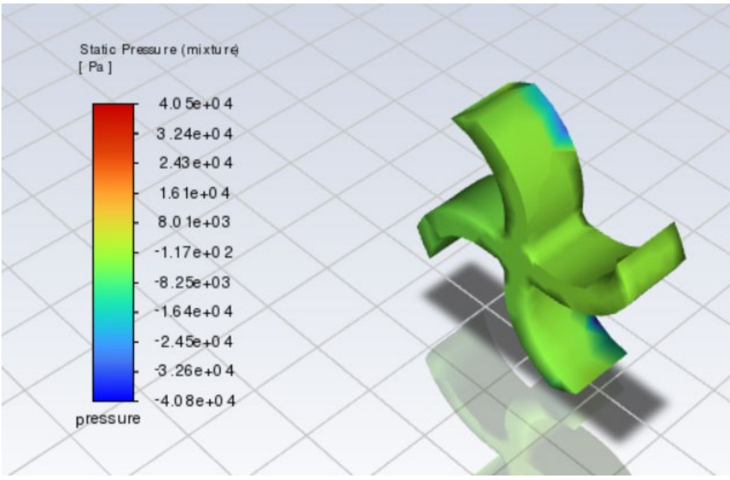

Figure 8: Simulation diagram of local negative pressure after modification

It can be seen from the figure that the maximum local negative pressure value after improvement is -40800pa. Although negative pressure will still be generated after improving the blade profile, the maximum negative pressure value is reduced by 51.48% and the range of local negative pressure is reduced compared with that before improvement. The improvement effect is good.

5. Conclusion

According to the application scenario of the underwater spherical robot, combined with the mechanical structure and motion performance of the underwater robot, the propulsion mode of the

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underwater robot is studied, and the jet propeller design is carried out. In view of the static tightness and safety of the robot operation, in order to study the internal flow state of the jet pump, the fluid simulation of the jet pump is carried out with the Fluent tool. In order to improve the cavitation margin, the blade profile is modified, which greatly reduces the local negative pressure and ensures the safety of the robot operation. Next, we can study the influence of different vortex blades on the power and cavitation margin of the propeller to further improve the performance of the propeller, so as to ensure the safety of underwater operations.

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