Analysis and Improvement of the Water-jet Propulsion System of a Spherical Underwater Robot

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Abstract—In this paper, we present the static analysis of a water-jet propulsion system. First, some previous researches in this field are introduced. Then, the motivation of static analysis is proposed. Based on that, we analyze the original mechanism that has been completed. After analyzing disadvantages of the mechanical structure of the propulsion system, improvement is carried out. We extend the motion range of water-jet thruster to +60° ~ 90°. Finally, the static analysis is carried out to improve the mechanical structure and compared the results with original design. The comparison result shows that about 50% deformation is declined. The static analysis is very useful to improve the propulsive accuracy of the water-jet propulsion system.

Index Terms—propulsion system, Dynamics modeling, mechanical analysis, structure improvement.

I. INTRODUCTION

Nowadays, the research of Autonomous Underwater Vehicles (AUVs) is a very popular topic in the world. Hundreds of AUVs are developed to satisfy the requirement of market, sea floor exploration, cable deployment, freshwater mapping, anti-submarine warfare, environmental monitoring and so on. Different tasks need different underwater robots. Most of the AUVs are streamline shape due to excellent hydrodynamic characteristics. The streamline body is very suitable for high speed movement because the water resistance is small, besides, a streamline shape can defend the perturbation of water environment. Bluefin Robotics Corporation developed the Bluefin-12 AUV to offshore survey. Streamline shape make the velocity reaching to 2m/s and the Bluefin-12 is very stable to obtain high quality observation data[1]. Besides that the Bluefin-12 adopts a screw thruster as propulsion system and installs it on the stern. Due to structural problems, Bluefin-12 could not adjust attitude flexibly. PETREL, winged hybrid-driven underwater glider designed and developed by Tianjin University [2]. Streamline shape, two wings, four fins and a screw thruster make up the hybrid-driven propulsion system. National Research Council of Canada’s Institute for Ocean Technology (NRC-IOT) and Marport Canada Inc. developed the Marport SQX-500 with twin-pod shape and each of the pod is streamline[3]. Marport SQX-500 contains two vectorial screw thruster. This kind of AUV can be used into many application fields, for instance, intelligence and mine countermeasures and so on. University of Southampton and National Oceanography Centre developed Delphin2 AUV. The propulsion system of Delphin2 AUV contains two vertical and two horizontal tunnel thrusters, and a rear ducted propeller[4]. All of these AUVs adopted screw thrusters as propulsion system. Most of the body shape are streamline or streamline based. The screw thruster usually cause cavitation phenomenon in high speed situation and high noise. Streamline shape can not adjust attitude flexibly.

As we known, traditional AUVs adopt streamline shape and screw thrusters as the propulsion system. In order to adjust the attitude flexibly and reduce the noise of propulsion system, in our laboratory, we developed the spherical underwater robot[5]. Spherical shape and water-jet thrusters are equipped in our underwater robot. We designed and developed three generations of spherical underwater robots[6]. The first generation used metal shell, and water-jet thrusters as propulsion system[7][8]. Similar with the first generation, Harbin Engineering University designed a spherical underwater robot with plastic shell and water-jet thrusters [9][10][11]. The second generation adopted metal spherical frame and water-jet thrusters as propulsion system[12]. But this kind of shape could not resist impact force very well. So the third generation robot was developed[13][14][15].

The deformation of propulsion system will effect the accuracy of the robot movement. This paper will report the static analysis of the propulsion system to analyze the deformation and stress of the propulsion system. And then improve the structure of propulsion system to reduce the deformation.

II. MOTIVATION

The propulsion system is one of the most important subsystem in the development of AUVs, because it provides the basis for the control layers of the entire system. In [16], the author only focused on the modeling of the dynamics of the water-jet thruster, but did not consider of the deflections of water-jet thrusters when the propulsive forces acting on the whole system. Therefore, in this paper, we will focus on...
analyzing the static force feature, and based on the feature, to optimize the structure of water-jet propulsion system.

A. Whole Structure of the Spherical Underwater Robot

The requirements of designing the spherical underwater robot are low noise and high flexibility. In order to achieve these requirements, a spherical underwater robot with three vectored water-jet thrusters were developed. The robot can be divided into 4 parts as shown in Fig.1. The sensor subsystem collects the data and sends them to the control subsystem, after calculation and decision, the control subsystem sends commands to the propulsion subsystem, and then the propulsion subsystem executes the action. The control subsystem and the power supply subsystem are sealed in the waterproof box. The sensor subsystem and the propulsion subsystem are protected by the spherical shell. The conceptual design of the spherical underwater robot is shown in Fig.2.

B. Propulsion System of the Spherical Underwater Robot

In order to achieve 4DOF motion, vectorial propulsion system was designed as shown in Fig.3. Three of water-jet thrusters are circumferentially 2/3 apart from each other and fixed on metal frame. The vectored water-jet thruster can rotate in X-Y plane and X-Z plane. So we can combine the three forces to realize some basic motions, such as heave, surge and yaw. Besides, by applying intelligent control algorithm and utilizing sensor subsystems, hybrid motions can be realized.
C. Importance of Static Analysis

The static analysis is very important to the propulsion system. The deformation of propeller will influence the direction and amount of the propulsive force. Fig.6 shows the relationship between deformation and propulsive force. The thruster is fixed on the robot at point A by a screw.

The length of nozzle
The distance between the action line of gravity center and nozzle
The maximum deformation of nozzle
The offset of acting point of force
The angle caused by deformation

When the water-jet thruster is working, the propulsive force would act on the nozzle and generate deformation. Due to that the deformation is smaller than the length of nozzle, $d_0$ can be approximated to be perpendicular to $x_0$. So, based on the principle of similar triangles, the length of $d_0$ can be get in the equation 1:

$$ \frac{d_1}{x_1} = \frac{d_0}{x_0} $$

so

$$ d_1 = \frac{x_1 d_0}{x_0} $$

$$ \theta = \arctan \frac{d_0}{x_0} $$

According to the measurement, $x_0=80\text{cm}$, $x_1=168\text{cm}$. So $d_1 \approx 2d_0$, $d_1$ will effect the position accuracy of the propulsion system. Angle $\theta$ will cause undesired component force at the direction of Z-axis. Therefore, $d_0$ must be decreased as much as possible. The error of propulsive force is caused by the deformation and $\theta$, these problems will effect the position accuracy of the spherical underwater robot. Worse still, wrong motions of the spherical underwater robot may be caused by the error. Therefore, static analysis of the mechanism structure for evaluation of the value of deformation must be executed.

III. Static Analysis and Improvement of the Mechanism Structure

Static analysis in ANSYS Workbench is commonly used and convenient. Generally, static analysis can be divided into four steps. First, create a geometry that we need, there are two methods to create the geometry, utilizing 3D modeling software or ANSYS geometric module. When the target geometry is simple, geometric module is adopted to create the geometry and when the geometry is complex, 3D modeling software is more convenient. In our research, due to the complexity of the propulsion system, 3D software is employed. Secondly, mesh the geometry, we choose tetrahedron mesh to get more accurate results. Thirdly, setup solver, static analysis need setup of material properties, force and fixed types and so on. Finally, results checking.

A. Static Analysis the Propulsion System

In our research, CATIA is employed to create the model of the propulsion system. Because the thruster can work on different angles, so we analyzed 3 typical cases, $0^\circ$ (horizontal), $75^\circ$ and $+60^\circ$, the detail is shown in Fig.7.

Choosing right material is essential to obtain accurate analysis results. So, we added materials to every part of the propulsion system. The main material be used into the propulsion system is listed in table I.

Where $E$ is modulus of elasticity, $\lambda$ is Poisson’s ratio and $\rho$ is density of materials.

In [16] we can get that the maximum propulsive force is about $2N$, so we added the maximum force to get the maximum deformation. And the propulsion system is assumed to
be fixed on the robot and the robot is motionless. The total deformation results are shown in Fig.8.

Fig. 8 Total deformation of the original propulsion system

Besides the deformation, we also pay attention to the strain and stress of the propulsion system. The results are shown in Fig.9 and Fig.10.

From these figures we can find that the maximum deformation is 0.0022732m, according to equation 2, we can know that \( d_3 \) will reach to 4.5mm.

### B. Improvement of the Propulsion System

Improvement will mainly focus on the frame and support of the propulsion system. The purposes of improvement are to improve the structural rigidity and reduce the structural mass and stress concentration. From Fig.9 and Fig.10 we can see that the maximum stress happened on the joints of frame and horizontal servomotor and the axis of waterproof box. So, we must increase the diameter of the axis and change the material of the frame and support. The triangle holder needs some stiffener to decrease the deformation. And the rectangle waterproof box need to be replaced by cylinder-shaped. Besides that the angle range of water-jet thruster in vertical direction is increased to \(-90^\circ\). The structure of propulsion system is shown in Fig.11.

![Fig. 9 The stress distribution of original propulsion system](image1)

![Fig. 10 The strain of the original propulsion system](image2)

Under the same condition, static analysis was carried out and the results are shown in Fig.12 to Fig.14.

### TABLE II The maximum value of analysis results

<table>
<thead>
<tr>
<th></th>
<th>deformation (mm)</th>
<th>stress (Pa)</th>
<th>strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>original</td>
<td>optimized</td>
<td>original</td>
</tr>
<tr>
<td>90°</td>
<td>1.674</td>
<td>0.810</td>
<td>1.1 \times 10^4</td>
</tr>
<tr>
<td>0°</td>
<td>2.273</td>
<td>1.143</td>
<td>9.0 \times 10^7</td>
</tr>
<tr>
<td>+60°</td>
<td>0.924</td>
<td>0.422</td>
<td>6.2 \times 10^7</td>
</tr>
</tbody>
</table>

From Table II, we can get that the maximum deformation occurred on the situation of 0°. After improvement, the
deformation declined about 50%. The stress and strain was also decreased.

IV. CONCLUSIONS

Based on the design of the propulsion system, the necessity of the static analysis of the water-jet propulsion system was analyzed. And the static analysis through ANSYS workbench was executed. According to analysis results we got main problems of the mechanical structure of the propulsion system, that the joint of frame and horizontal servomotor were not strong enough to support the water-jet thruster and the maximum deformation reached to 2.27mm, it could effect the accuracy of the propulsion system. After that, we carried out some optimization analysis on the mechanical structure, extended the range of water-jet thruster to $-90^\circ$, changed the rectangle waterproof box to cylinder-shaped and the material of support and frame to improve the structure rigidity, and then analyzed the optimal structure as the same condition. Finally, analysis results showed that the deformation reduced to 1.14mm and the strain and stress became more smaller.

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REFERENCES


