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Hydrodynamic Analysis of Water-jet Thrusters for the Spherical Underwater Robot (SUR III)

Hongbiao Yang[*1, 2], Xiufen Ye[*1], Shuxiang Guo[*3, *4], Shuoxin Gu[2] and Shangze Chen[1, 2]

[*1] *College of Automation*
Harbin Engineering University
Nangang District, Harbin, Heilongjiang Province, 150001, China

[2] *Graduate School of Engineering, Kagawa University,*
Takamatsu, Kagawa 761-0396, Japan

yanghongbiaowork@gmail.com

[*3] *Key Laboratory of Convergence Medical Engineering and System and Healthcare Technology*
the Ministry of Industry Information Technology
School of Life Science
Beijing Institute of Technology
Haidian District, Beijing 100081, China
[*4] *Department of Intelligent Mechanical Systems Engineering*
Kagawa University
Takamatsu, Kagawa 761-0396, Japan

guo@eng.kagawa-u.ac.jp

Abstract **– For the propulsion system of an underwater robot, the nozzle of the water-jet thruster plays an important role in converting energy to generate the reaction thrust. In order to achieve a higher reaction thrust, hydrodynamic analysis of the water-jet thruster is introduced in this paper. First, the prototypes of the third-generation Spherical Underwater Robot (SUR-III) and the water-jet thruster are given. Then the design principle of conical nozzle is described in detail. The shape of nozzle is changed from the traditional cylindrical one to conical one. The control angle is used to change the reaction thrust of the water flow in the outlet of nozzle. Before making the hydrodynamic analysis, we use Solidworks2011 to establish 3D models of conical nozzles with different control angles. Some unimportant parts causing limitations are ignored to simplify the analysis. Finally, ANASYS CFX is employed to make the hydrodynamic analysis. Comparing the simulation results with theoretical values, the velocity error is less than 6.64%. The simulation results show that the increase of control angle of conical nozzles can increase the reaction thrust of water-jet thruster. Meanwhile, the reaction thrust of conical nozzle with 20° control angle is more than two times as big as that of cylindrical nozzle.**

Index Terms – Spherical Underwater Robot, Water-jet Thruster, Conical Nozzle, Hydrodynamic Analysis, ANASYS CFX

I. Introduction

With the development of economy and science technology, various kinds of underwater robots have been developed to meet the requirements of different tasks over the past several decades. Usually, the underwater robots are divided into two categories: Remote Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROVs are working robots that can sneak into the water to complete some certain operations under people's control [1]. But facing a complex environment, ROVs can't make the initiative corresponds. While AUVs have unique advantages in submarine resource exploration, underwater equipment maintenance, target detection or rescue missions, whether in civil field, commercial field, educational and scientific field or military field [2][3]. The underwater robots have been developed, using an assortment of shapes, sizes, weights, and propulsion systems. Spherical underwater robots are the most special ones, because they can make an outstanding performance on water-resistance, resulting in easily implementing a rotational motion with a 0º turn radius.

Combining the advantages with task requirement, many researchers have realized their own spherical robots. Researchers at Harbin Engineering University developed a spherical underwater robot which adopted three water-jet thrusters as its propulsion system [4][5]. This design has some advantages: Low vibration noise and high promotion efficiency. In our laboratory, Reference [6] first proposed the concept of vectored water-jet propulsion, which can be adopted in the spherical underwater robots. And on the basis of this idea, a novel spherical underwater robot had been realized and analyzed [7]-[9]. And other researchers in our laboratory continued to make improvements [10]-[21]. However, there are some common shortcomings in their methods. In other words, the speed is not fast enough under same conditions, as well as the reaction thrust. This paper focuses on the improvement of water-jet thrusters in order to increase the speed and driving force of propulsion system.

Hydrodynamics studies the movement of the liquids and their interaction with the boundaries. Usually, according to the hydrodynamic analysis, we can get the liquid resistance and other valuable characteristics. Through Computational Fluid Dynamics (CFD), Reference [22] proved that blade tip loading can be reduced in order to restrain the cavitation of sheet and tip vortex, resulting in low noise and better protection from surface erosion. Reference [23] made a comparison between Kappel propellers with conventional propellers, hydrodynamic analysis emphasizes the superior performance of Kappel propellers with end-plate effects. Reference [24] made a computational numerical analysis of different nozzles, mainly including cos, exponent, cylindrical and conical ones. The effects of geometric and dynamic parameters of different nozzles on the outlet velocity and pressure map are analyzed

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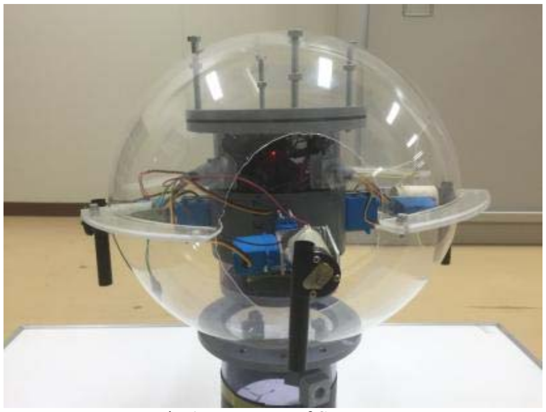

Fig.1 Prototype of SUR-III.

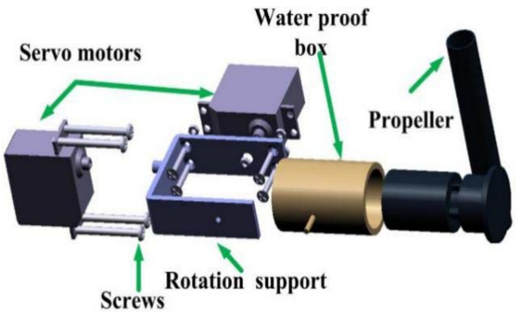

Fig.2 Assembly model of the water-jet thruster system.

in detail. The study result privates us a good theoretical basis for the research of nozzles in the water-jet propulsion system for underwater robots. In our laboratory, Reference [25][26] analyzed the hydrodynamic characteristics of the second-generation Spherical Underwater Robot with ANASYS FLUENT software and verified the drag coefficients for horizontal and vertical motions. Hydrodynamic analysis showed that simulation results were very close to the theoretical values. More relative information can be found in References [27]-[29].

The structure of this paper is organized as follows. In the section I, the background and purpose of the study are introduced. In the Section II, the 3D model of conical nozzles in water-jet thruster and the design principle of conical nozzle are presented. ANSYS CFX-based hydrodynamic analysis of conical nozzles are shown in the Section III. Finally, the conclusion and future work are given in the Section IV.

II. MODELING OF CONICAL NOZZLE OF WATER-JET THRUSTER

A. The Prototype of SUR-III and Water-jet Thruster

In our laboratory, the second-generation Spherical Underwater Robot(SUR-II) takes three vectored water-jet thrusters as its propulsion system, resulting in 3 DOF motions [30][31]. However, the energy consumption of SUR-Ⅱ is high and the max velocity just can up to 0.3m/s. So the third-generation Spherical Underwater Robot (SUR-Ⅲ) is developed with four water-jet thrusters, as shown in Fig.1. SUR-Ⅲ is made up of two hemispheres, fours water-jet thrusters, waterproof box and the control center. The angle between each thruster is 90 degrees. One water-jet thruster system consists of a motor, two servos, a water proof box, the rotation support and a nozzle, as shown in Fig.2.

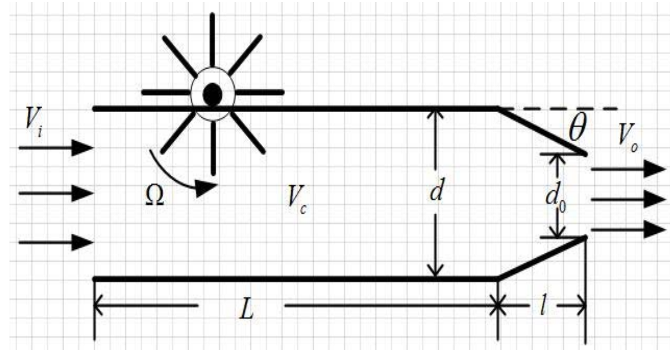

Fig.3 Sketch of the conical nozzle.

B. Design Principle of Conical Nozzle

In order to achieve a higher velocity and reaction thrust of the propulsion system, the design principle of the conical nozzle is given in this section. For the convenience to illustration and calculation, we make some assumptions as follows:

1) Assume that the liquid flow can't be compressed, so the density is same for all units, ρ represents the density of liquid flow.

2) Ignore the thickness of nozzle and simply analyze the effect of its inner wall instead.

As shown in Fig.3, the sketch of the simple thruster is given. From this Fig, we try to change the structure of nozzle from cylindrical shape to conical one. θ is the control angle.

Case 1: $\theta = 0$.

At this time, the nozzle is cylindrical. According to the equation of continuity, the following equation can be obtained [32]:

$$\rho A_c V_c = \rho A_o V_o \tag{1}$$

where V_o represents the outlet velocity of nozzle and V_c represents the velocity after the water flows through the blade. A_c and A_o represent the flow cross-sectional area at the centre and outlet of the nozzle, respectively. Under this circumstance, the nozzle is cylindrical, so we can get:

$$A_c = A_o, V_c = V_o \tag{2}$$

Case 2: $\theta > 0$.

At this time, the nozzle is conical. In order to achieve a higher velocity of the propulsion system, we make a novel improvement and design of the nozzle. According to "(1)", we can see if the flow cross-sectional area at the outlet port of nozzle can be reduced, a higher velocity could be achieved. Sacrificing a part of the export volume, we can obtain a greater reverse driving force. Now, equation (1) can be transformed into the following equations:

$$\frac{V_o}{V_c} = \frac{A_c}{A_o} = \frac{d^2}{d_0^2} \tag{3}$$

$$d_0 = d - \frac{2l}{\cot\theta} \tag{4}$$

where d_0 represents the diameter of the outlet and θ is the angle between inner wall and inclined surface, we call it control angle. l is the horizontal distance we choose to start changing the position of the structure.