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Numerical investigation of the influence of nozzle geometrical parameters on thrust of synthetic jet underwater

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ABSTRACT

The thrust characteristic and efficiency of synthetic jet underwater is easily affected by the geometrical parameters. In this paper, the influence of nozzle geometrical parameters on the thrust of synthetic jet underwater is investigated through numerical method. The geometrical parameters studied include nozzle diameter and nozzle height. The numerical method is validated using the experiment data. A mathematical model of the thrust is established. This model decomposes the thrust into three parts. By adjusting the weights of these parts, the dynamic characteristic of the thrust can be rebuilt. Using this method, the mechanism behind the thrust variation with nozzle geometrical parameters is analyzed. The variation of the thrust with the nozzle diameter is induced by the increase of the acceleration force and the decrease of the pressure force. When the nozzle diameter is small, the thrust is velocity dominated. While when diameter is large, the thrust is acceleration dominated. The thrust variation with nozzle height has two different patterns. The pressure force dominates the first pattern of thrust variation. And the acceleration force contributes more to the second pattern of thrust variation. The results in this paper can be used for the efficiency oriented optimal design of synthetic jet actuator underwater.

1. Introduction

Most underwater robots employ screw propeller for propulsion. When actuated by screw propellers, water is accelerated not only in the axial direction but also in the radial direction. However, only the momentum in the axial direction can generate thrust. So a significant part of energy is dissipated without thrust generation. As a result, the efficiency of screw propellers is low. What is more, the extruded screw propellers can induce significant resistance.

In nature, there exit many marine creatures propelled by jets, such as squid and jellyfish. These creatures ingest the surrounding fluid into a large mantle cavity and then eject the fluid with a high momentum through a nozzle near its tentacles. The high energy shear layer rolls into an array of vortex rings and carries the fluid away from the squid.

The widely used screw propeller is also a type of jet propulsion. The velocity of the jet created by screw propellers merely change. This type of jet is called steady jet. On the other hand, the velocity of the jet created by jellyfish or octopus changes from time to time. This type of jet is called pulsed jet.

Studies about pulsed jet found that compared with the steady jet, pulsed jet possess higher propulsion efficiency [1–6]. Weihs [7], Seikman [8] and Krueger and Gharib [6] have shown that pulsed jet can give rise to a greater average thrust than steady jet of equivalent mass flow rate. Ruiz, Whittlesey and Dabiri [5] found through experiment that pulsed jet has a propulsion efficiency 40% higher than that of steady jet, and the drag-based hydrodynamic efficiency increase more than 70%.

Synthetic jet is essentially pulsed jet. So, synthetic jet also possesses high propulsion efficiency. By the merits of high efficiency, compact structure and minimal effect on the vehicle's drag, synthetic jet underwater is attracting more and more attention and research [9–14]. Krieg and Mohseni [11,12] developed an underwater robot with synthetic jet actuator mounted inside. The experiment with the robot showed the synthetic jet actuator induced the robot rotation of 2.23r/min. It demonstrated the effectiveness of synthetic jet in the steering of underwater robots. Serchi et al. [13] designed a soft robot which replicates the ability of cephalopods to travel in the aquatic environment by means of pulsed jet propulsion. The prototype demonstrated the fitness of vortex enhanced propulsion in designing soft unmanned underwater vehicles. Ruiz et al. [5] investigated the mechanism behind the

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Nomenclature

f_r,a_m	Actuation frequency and vibration amplitude of the piston
L	Height of water column ejected in one period
V_{rad},V_{axi}	Radial and axial velocity distribution of jet velocity
D,h	Diameter and height of the nozzle
d,H	Diameter and height of the cavity
b_1,b_2	Size of the computation domain
L/D	Stroke ratio
Re_{ave},Re_{max}	Average and largest Reynolds number
$\mathbf{T}$	Thrust
p	Pressure
∂V,$\partial V'$	Control volume
$\mathbf{n}$	Normal vector
$\mathbf{a}_{cc}$	Acceleration
$\mathbf{Q}_{\mathrm{m}}$	Mass flow rate
M,M',M''	Mass of fluid accelerated
A	Nozzle plane
f	Pressure force
Φ	Velocity potential
$c(l)$	Decay rate of the axial velocity
k	Coefficient accounting for the velocity distribution
$\mathbf{G}$	Gravity
$\mathbf{F}_{cf}$	Centrifugal force
$\boldsymbol{T_{water}}$,$\boldsymbol{T_{air}}$	Force measured by the force sensor under water and in air
$\boldsymbol{V_p}$,$\boldsymbol{a_p}$	Velocity and acceleration of the piston
Γ	Function describing the thrust dynamic characteristic

thrust enhancement induced by the vertical structures. The experiments demonstrate that propulsive efficiency of synthetic jet is over 50% greater than the performance of the steady jet. Whittlesey and Dabiri [4] utilized a self-propelled vehicle to explore the dependence of propulsive efficiency on the vortex ring characteristics. These experiments demonstrated the importance of vortex ring pinch off in self-propelled vehicles.

Synthetic jet in air is also intensively researched [15–22]. The geometrical parameters have a great effect on its fluidic characteristic. Jain et al. [23] studied effects of cavity and orifice parameters on the characteristics of a synthetic jet actuator through numerical method using Fluent. The geometrical parameters such as cavity height, cavity diameter, orifice height, and orifice diameter as well as cavity shape are investigated. It's found synthetic jets are more affected by changes in the geometric parameters of the orifice than those of the cavity. Studies about the orifice showed that there is an optimum orifice height where the maximum flow can be obtained. This means the performance of the synthetic jet actuator can be enhanced through the optimal design of the orifice parameters. Lv et al. [24] studied effects of actuator parameters and excitation frequencies on the fluidic characteristics of synthetic jet. It was found that when the diaphragm is excited at relative higher frequency, the synthetic jet is affected seriously by the orifice thickness. Besides the orifice thickness, orifice radius also has a big effect on the fluidic characteristic. Small orifice radius restricts the ejection and suction capacity of the synthetic jet actuator. In this case, the mass flux is greatly reduced. To realize the best performance, the geometrical parameters of the orifice should be carefully designed. Zong et al. [25] studied the influence of geometrical parameters on the performance of a plasma synthetic jet actuator. The results showed that orifice with large diameter produces strong perturbation, which means better performance. On the other hand, a small orifice diameter induces a lasting jet with low mass flux. And the orifice with small thickness experience better high frequency performance. Feero et al. [26] studied the influence of cavity shape on synthetic jet performance. Cylindrical, conical and contraction shaped cavities were considered. The results demonstrated that for several operating conditions near Helmholtz resonance of the cavity, noticeable differences were observed in the radial velocity profiles between the three geometries. The cylindrical shape can achieve maximum momentum flux. While, the more complex contraction shape has lower power consumption. These studies only considered the fluidic characteristic of the actuator. The thrust characteristic of the actuator is seldom investigated. This is partly due to the low density of air. Compared with the fluidic parameters such as velocity and pressure, the thrust of the actuator is negligible. The other reason is related to its application.

Synthetic jet in air is mainly used for active flow control. The synthetic jet actuator transfers linear momentum to the surroundings by alternately ingesting and expelling fluid. The high momentum transferred by the jet flow will strongly alternate the pressure distribution in the vicinity of the orifice. Thus the flow field can be controlled. So, studies about synthetic jet in air mainly concern the velocity distribution and mass flux at the nozzle. On the other hand, synthetic jet underwater is mainly used for propulsion. Thrust is the main concern. Like synthetic jet in air, the geometrical parameters will also have a great effect on the thrust and efficiency of synthetic jet underwater. However, the existing studies on synthetic jet underwater only focus on actuator with specified geometrical parameters. The influence of geometrical parameters on the thrust characteristics is seldom studied.

Efficiency is crucial for underwater propulsion. Knowledge about the effect of geometrical parameters on thrust, especially the mechanism behind, can lead to the efficiency oriented optimal design of synthetic jet actuator underwater. The purpose of this paper is to study the effect of nozzle geometrical parameters on the thrust. This study is based on numerical method using the commercial package Fluent. The finding and conclusion in this paper can guide the optimal design of synthetic jet underwater.

The geometrical parameters studied include nozzle diameter and nozzle height. The mechanism behind the influence of nozzle geometrical parameters is analyzed using thrust model established in this paper. The thrust model in this paper decomposes the thrust into three parts. These parts have distinct dynamic characteristics. So, by adjusting the weights of these terms, the dynamic characteristics of the thrust under different nozzle geometrical parameters can be rebuilt. The analysis given in this paper is mainly based on this method. The variation of the thrust with the nozzle diameter is induced by the increase of the acceleration force and the decrease of the pressure force. When the diameter is small, the thrust is velocity dominated. While when diameter is large, the thrust is acceleration dominated. The thrust variation with nozzle height has two different patterns. The pressure force dominates the first pattern of thrust variation. And the acceleration force contributes more to the second pattern of thrust variation.

2. Numerical methods

2.1. Governing equations

The average velocity of the jet flow can be computed as [27]:

$$V = \sqrt{2} f_r L \tag{1}$$

fr stands for the actuation frequency, which is 10 Hz in this paper, L stands for the height of the fluid column ejected by the actuator in one cycle. So the Reynolds number at the nozzle is $Re_{jet} = \rho VD/\mu$. D stands for the diameter of the nozzle. In this study the diameter of the nozzle is varied to study its influence on the thrust