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Hydrodynamic characteristic of synthetic jet steered underwater vehicle

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ABSTRACT

In this paper, the hydrodynamic characteristic of a synthetic jet steered underwater vehicle is studied. The steering motion studied is the lateral motion and the yaw motion. The lateral motion is induced through the in-phase work of this two actuators and the yaw motion is realized through the out-of-phase work. The vehicle studied is REMUS AUV with synthetic jet actuator mounted inside. The hydrodynamic characteristic of the vehicle under different cruising speed is studied. The driving parameters of the SJ actuator keep invariant in different cases. When the two actuators work in phase, the average steering force is smaller than the thrust of the isolated actuator and keeps nearly invariant under different cruising speed. When the two actuators work out of phase, the average steering moment also keeps invariant with cruising speed. The mathematical model of the additional drag of the vehicle, the thrust of the actuator, the steering force as well as the steering moment is given. The velocity distribution is also given to assistant the analysis in this paper. From the analysis given it can be known the steering method based on SJ is realized through position control other than velocity control.

1. Introduction

The traditional method for the steering of underwater vehicle is using rudders. The rudders are very efficient at cruising speeds. However when speed is low the steering force provided by the rudders is greatly reduced. As a result, the mobility of the underwater vehicle at low speeds is limited. What's more, the protruded rudders can induce significant resistance. This will affect the hydrodynamic efficiency of the vehicle significantly. The other way for underwater steering is using multiple thrusters mounted at different directions.

The other way for underwater maneuvering is thrust vectoring technique. The most common way for thrust vectoring is adding multiple thrusters at different directions. WHOI's ABE, SeaBED and Stanford's OTTER are among AUVs in this category [3,4]. The other way for underwater thrust vectoring is using special designed mechanical system. These mechanical systems can provide the propulsor additional degree of freedom [5–10]. So using only one propulsor, thrust in different directions can be realized. Ba Xin, Luo Xiaohui [5] proposed a vectored water jet propulsor adopting 3RPS parallel mechanism. Emanuele Cavallo and Rinaldo Michelini adopted spherical parallel mechanism to control the thrust in all directions [6]. Michael Nawrot from MIT designed a thrust vectoring tailcone using pivot [7]. And this design is applied in the Bluefin AUV.

Using multiple thrusters or special designed mechanisms will increase the weight and complexity of the propulsion system. It will also induce significant resistance.

There are many marine creatures propelled by jets, such as squid and jellyfish. Inspired by nature, Krueger [11–13], Whittlesey [14,15], Krieg & Mohseni [16–18] proposed a new type of underwater propulsion technique called synthetic jet. The main merit of synthetic jet lies in its high efficiency. Lydia A. Ruiz [15] 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%.

The other attracting properties of synthetic jet actuator include compact structure and small size. As the synthetic jet actuator can be completely mounted inside the vehicle, the added resistance induced by the synthetic jet actuator is negligible.

Michael Krieg and Kamran Mohseni [16,17] developed an underwater robot with synthetic jet actuator mounted inside. The experiment showed the synthetic jet actuator induced the robot rotation of 2.23r/min. The feasibility of synthetic jet in the steering of underwater robots is validated.

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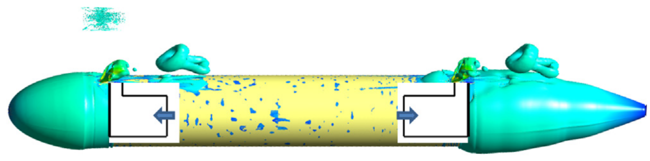
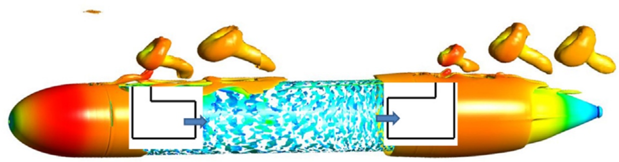


(a)



(b)

Fig. 1. Two actuators (a) work in phase (b) work out of phase.

The thrust characteristic of synthetic jet underwater was previously studied by Krueger [11–13], Whittlesey [14,15], Krieg & Mohseni [16–18]. These studies focused on the near-wake vortex dynamics of stationary propulsors. The dynamics of the vehicle was not considered. Krieg and Mohseni [16,17] designed a synthetic jet actuator and tested the thrust under different stroke ratios and working frequencies. The experimental result agrees well with the prediction of the theoretical model. Krueger & Gharib observed that vortex formation increases the pressure at the exit of the propulsor [13]. This will augment the generated thrust.

According to the author's knowledge, the work of Ruiz, Whittlesey and Dabiri [15] is the only one considering the full dynamic of the vehicle. The authors studied the hydrodynamic efficiency of an underwater vehicle propelled by synthetic jet. The velocity of the vehicle was realized by auxiliary motorized traverse. The maximum cruising velocity studied is 0.6 m/s (nearly 1.2 knot).

Synthetic jet is pulsed jet. When the jet flow is issued into the flow field at high efficiency, the pressure distribution of the vehicle will be affected significantly. As a result, the drag characteristic of the vehicle will be different. On the other hand, the flow field of the vehicle will also affect the vortex formation process of the SJ actuator. As a result, the thrust and efficiency of the actuator will be affected.

In this paper, the hydrodynamic characteristic of the SJ steered underwater vehicle is numerically studied. The vehicle studied is REMUS AUV with the SJ actuator mounted inside the vehicle. The hydrodynamic characteristic of the vehicle under different cruising speed is studied. The driving parameters of the SJ actuator keep invariant under different cruising speeds. The maximum speed of the vehicle studied in this paper is up to 30 knot. In this paper, both the lateral motion and the yaw motion are studied. The variation of the SJ induced axial drag and the lateral drag is analyzed. The thrust of the SJ actuator and the SJ induced total force/moment are also discussed.

2. Mechanism

The steering method studied in this paper is based on double synthetic jet actuator. By adjusting the phase difference between these two actuators, steering force and steering moment can both be generated. The working mechanism of this method is given in Fig. 1.

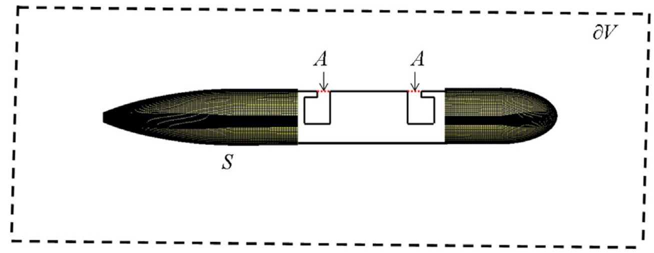


Fig. 2. Control volume.

The nozzle of the actuator points toward the lateral direction. When the two actuators work in phase (eject or inject fluid simultaneously), thrust of these two actuators is in the same direction. On the other hand, their moment is of reverse direction. So the total effect of the double synthetic jet actuator will be lateral force. This will induce the lateral motion of the vehicle. Thus the steering of the vehicle will be realized.

When the two actuators work with reverse phase (one actuator injects fluids while the other one ejects fluid), thrust of these two actuators is of reverse direction. On the other hand, their moment is in the same direction. So the total effect of the double synthetic jet actuator will be yaw moment. This will induce the yaw motion of the vehicle.

3. Mathematical model

3.1. SJ induced added resistance

Synthetic jet is a type of pulsed jet. When the jet flow is ejected into the flow field, the high momentum transferred by the jet will change the pressure distribution of the vehicle drastically. As a result, the drag characteristic of the vehicle will be affected.

So when the vehicle is propelled by synthetic jet, the drag of the vehicle is composed of four main parts which is $\mathbf{F}^p_{vel}$, $\mathbf{F}^p_{jet}$, $\mathbf{F}^f_{vel}$, $\mathbf{F}^f_{jet}$ respectively. $\mathbf{F}^p_{vel}$ and $\mathbf{F}^f_{vel}$ is the pressure force and the friction force when there is no synthetic jet. $\mathbf{F}^p_{jet}$ and $\mathbf{F}^f_{jet}$ is the additional pressure force and additional friction force induced by the synthetic jet flow.

According to the drag theory, $\mathbf{F}^p_{vel}$ and $\mathbf{F}^f_{vel}$ are proportional to the vehicle velocity. So $\mathbf{F}^p_{vel}$ and $\mathbf{F}^f_{vel}$ can be computed directly when velocity is given. While $\mathbf{F}^p_{jet}$ and $\mathbf{F}^f_{jet}$ are pulsed force and can't be modeled directly using the traditional drag theory. In this paper, $\mathbf{F}^p_{jet}$ and $\mathbf{F}^f_{jet}$ are modeled in order to better understand the drag characteristic of synthetic jet steered underwater vehicle.

The control volume studied is depicted in Fig. 2. It is composed of ∂V, S and A. S stands for the vehicle surface, A stands for the exit plane of the synthetic jet actuator and ∂V stands for the boundaries at the far field.

The interaction between the synthetic jet and the background flow is not considered in this paper. So the additional drag is only caused by the synthetic jet. The additional friction force $\mathbf{F}^f_{jet}$ is negligible. So only the pressure force $\mathbf{F}^p_{jet}$ is considered in this paper.

The pressure force of the vehicle can be expressed as:

$$\mathbf{F}^p_{jet} = \int_S p \cdot \mathbf{n} dS \tag{1}$$

The pressure force at the exit plane, A, can be expressed as:

$$F_A = \int_A p \cdot \mathbf{n} dS \tag{2}$$