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Hydrodynamic performance of an autonomous underwater glider with a pair of bioinspired hydro wings–A numerical investigation

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ABSTRACT

A conceptual design of autonomous underwater glider (AUG) is introduced, with a pair of bio-inspired hydro wings undergoing travelling wave motion. Hydrodynamic performance of current AUG is investigated by numerically solving the incompressible viscous Navier–Stokes equations of its surrounding flow coupling with the immersed boundary method to capture the moving boundaries. The force balance along the stream direction is guaranteed by adjusting the kinematic parameters of the travelling wave motion, thus the cruise state of the AUG with a constant velocity can be achieved. The propulsive efficiency under cruise state is therefore directly and well defined. The effects of kinematic parameters on propulsive performance are investigated, and the non-dimensional Strouhal number, as a combination of these kinematic parameters, turns to be a dominant parameter of the propulsive efficiency. There is an optimum range of Strouhal number, in which the AUG achieves its maximum efficiency. The results obtained in current study can provide certain technical supports for the design and development of small submersible vehicle.

1. Introduction

Autonomous underwater glider (AUG) is a novel autonomous underwater vehicle (AUV) without external active propeller. Since Stommel (1989) first put forward the concept of underwater glider, several kinds of AUGs have been built in succession, which are used both in military and civil applications. Compared with the traditional AUV, AUG has several advantages, such as low noise, low energy consumption, long operational range and endurance and great operational flexibility (Davis et al., 2002; Claustre and Beguery, 2014; Chen et al., 2015).

AUG is a buoyancy-driven device, and it periodically changes its net buoyancy by a hydraulic pump to glide upwards and downwards alternately. As AUG dives and ascends, its internal ballast changes its position to control attitude, and its body and wings provide longitudinal hydrodynamic force to drive itself moving forward (Asakawa et al., 2012; Mitchell et al., 2013; Javaid et al., 2014; Zhao et al., 2014; Ye and Qi, 2013). However, apart from aforementioned advantages, some problems concerning AUG should be given due attention. One of the most crucial problems is 'drifting with the current'. For achieving intense data collection, the gliding speed of AUG has to be relatively low, which is only about 0.5 knot (0.25 m/s). Under such a low speed, movement of AUG would be easily influenced by ocean current, and it is not able to be continually maintained following the initially desired route, thus failing to complete specific task. Hence, AUG may encounter a risk of mission failure when operated in a strong-current (Li et al., 2016; Liu et al., 2017). Therefore, additional control strategies are required to make AUG's trajectory as desired, and meanwhile without significant energy consumption. Aiming at this, extensive studies have been reported recently. Niu et al. (2016) proposed a prototype design of hybrid vehicle to improve AUG's gliding speed by using of the additional propeller positioned at the rear part of AUG and the trial result shows that the hybrid underwater glider can achieve the maximum gliding speed of 3 knots. Similarly, Claus & Bachmayer (2016) adopted an energy optimal depth controller design methodology for a long range AUV, presented with applications to a propeller driven hybrid AUG. Jeong et al. (2016) designed a novel underwater glider having a high horizontal speed of the maximum 2.5 knots with the help of a controllable buoyancy engine to regulate the amount of buoyancy drastically. Zhang et al. (2017) utilized supercavitation to reduce drag and increase their underwater speed.

Most of the research mentioned above make effort on utilizing external propeller to increase AUGs' gliding speed. Consequently, the external propeller shall import additional drag which will cause negative impact to its endurance and gliding range. Besides, problems of vibration and noise will destroy AUG's concealment with the

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introduction of propeller. Owing to these, alternative solutions to solve this problem from other perspectives are required. It is worth noting that, in nature, many creatures have acquired extraordinary abilities of locomotion, such as high efficiency, fast manoeuvrability and low noise etc., through natural selection and evolution. This inspires scientists and engineers to explore the nature of their excellent athletic ability. Among them, fish swimming in lake and sea are typical kind of creatures with extraordinary athletic ability (Sfakiotakis et al., 1999). In the past several decades, great endeavours have been devoted in the study on hydrodynamic mechanism of fish swimming (Triantafyllou et al., 2000, 2004) as well as the design of robotic fish (Triantafyllou and Triantafyllou, 1995; Roper et al., 2011, Raj and Thakur, 2016). On the other hand, a complementary design of bioinspired AUG also attracts attentions recently (Fish et al., 2003; Georgiades et al., 2009; Li et al., 2016), which can achieve high efficient propulsion by mimicking fish swimming, and meanwhile fulfil the requirement of enough space for payload and avoid the deformation fuselage like robotic fish. In detail, the bioinspired AUG consists of two major parts, i.e. a 'biomimetic propeller' and a rigid cantered fuselage. With the help of 'biomimetic propeller', e.g. flapping wing or wavy plate, AUG can maintain its initial gliding route, and at the same time, resistance experienced by AUG will not increase significantly causing minimal impact to gliding range and endurance. Instead of using hybrid driven mode, the newly designed bioinspired AUG is supposed to implant a driven-mode of hydrofoil, which also means, under complex underwater environment, AUG would be driven by its 'biomimetic propeller', similar with fish in nature, whereas in rest time, when the environment is relatively stable, the AUG may undergo usual gliding.

In this paper, a conceptual design of bioinspired AUG is introduced, with a pair of bioinspired hydro wings undergoing travelling wave motion. Hydrodynamic performance of current AUG is investigated by numerically solving the incompressible viscous Navier–Stokes equations of surrounding flow. We would like to figure out the effect of hydro wing parameters on the propulsive efficiency of AUG, to achieve an improved understanding of physical mechanisms relevant to the biomimetic locomotion adopted by current AUG. The immersed boundary method is employed to capture the moving boundary of the hydro wings, which has been successfully applied in previous studies on fish-like flapping wing (Shao et al., 2010b; Pan et al., 2016), undulatory foil (Shao et al., 2010a), flexible plate (Pan et al., 2010, 2014), etc. An evaluation process which is first proposed in our previous work (Li et al., 2016) is also applied to investigate the hydrodynamic propulsive efficiency of current AUG in its cruise state. In the following, the physical model of current AUG is presented in Sec. 2, following by the introduction of numerical method in Sec. 3. The simulating results and relevant discussion are given in Sec. 4. Conclusion is drawn in the last section.

2. Physical model

Fig. 1 shows the sketch of current physical model, which is made up with one centred fuselage and two side hydro wings. The total length of

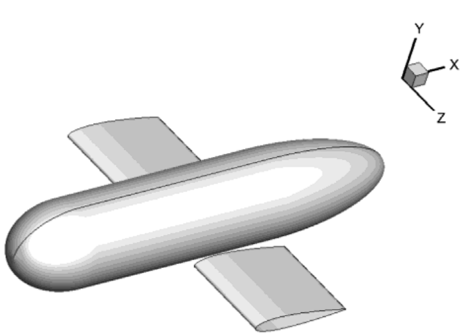

Fig. 1. Sketch of current physical model.

the model (fuselage) is 1.2 m, where the middle part is a cylinder, scaled with 0.25 m in diameter and 0.625 m in length. The front part is a semi-spheroid, with 0.175 m in semi-major axis, and the rear part is also a semi-spheroid, with 0.4 m in semi-major axis. The hydro wings are designed with rectangular wing by using the NACA0015 profile. It has a span length of 0.3 m and a chord length of 0.3m, which is chosen as the characteristic length *C*. In the following, all the variables are non-dimensionised, e.g. length of chamber line, hydrodynamic forces, following the approach presented in Xu and Xu (2017) and Xu et al. (2017).

The bioinspired travelling wave motion of the two hydro wings has been as the propulsion method of current AUG. Each point of the hydro wing surface along its chord length direction makes a transverse oscillation and its lateral displacement can be described by the following sinusoidal function,

$$y(x,\, t) = A(x)\sin\left(\frac{2\pi}{\lambda}x - 2\pi ft\right), \tag{1}$$

$$A(x) = a_0 + a_1{\cdot}x + a_2{\cdot}x^2, \tag{2}$$

where λ is the wave length, f is the frequency, x the distance from a specific point along the chord length of the hydro wing to the leading edge of the hydro wing, and $A(x)$ is a function used to describe the transverse magnitude of the hydro wing and its expression is shown as Eq. (2), where a_0, a_1 and a_2 are all constants. Here, we let $a_0 = -0.02$ and $a_2 = -2a_1$, thus it makes sure the transverse magnitude lies in the maximum depth of the hydro wing's trailing edge. As examples, Fig. 2 shows the camber line deformation of the hydro wing in one period under different parameters. In order to give an intuitive description of the hydro wing's travelling wave motion, Fig. 3 shows the hydro wing deformation in a whole motion period. With the undulation of the hydro wings, thrust force is produced to overcome the drag of ocean current. In our preliminary design of the AUG prototype, the hydro wing surface is made of flexible rubber, while inside the wing, several rigid fin rays are uniformly distributed along the chord length. Each fin ray is connected with a separate electric motor by a crank train. Therefore, the travelling wave of the wing surface is activated with this mechanism. A similar design was adopted by Clark and Smits (2006).

3. Numerical method and validation

The surrounding water around AUG is considered as incompressible and viscous, and the non-dimensional Navier–Stokes equations of fluid motion is employed as

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla P + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{u} + \mathbf{f}, \tag{3}$$

$$\nabla\cdot\mathbf{u} = 0, \tag{4}$$

where **u** is the velocity vector, P the pressure, Re the non-dimensional Reynolds number which can be calculated as Re=U_0C/ν with U_0 and C the characteristic velocity and length scale, and ν the dynamic viscosity, and **f** the additional body force. To discretize the Navier–Stokes equations for numerical solutions, the Crank–Nicolson scheme is used for viscous terms and the Adams–Bashforth scheme is applied for the other terms in Eq. (3). In addition, the finite difference projection method is used to obtain the velocity and pressure fields. For simplification, the Reynolds number in current study is around 200, taking the characteristic velocity to be one, without any additional turbulent model to be applied.

The immersed boundary (IB) method is applied to capture the travelling wave motion of the hydro wings. The additional body force **f** of IB method near the moving boundary is modified according to the 'direct forcing' approach, in which the body force can be derived as

$$f_i^{n+1} = \frac{V^{n+1} - u_i^n}{\Delta t} + RHS_i^n, \tag{5}$$