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The mechanism of flapping propulsion of an underwater glider*

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Abstract: To develop a bionic maneuverable propulsion system to be applied in a small underwater vehicle, a new conceptual design of the bionic propulsion is applied to the traditional underwater glider. The numerical simulation focuses on the autonomous underwater glider (AUG)'s flapping propulsion at $Re = 200$ by solving the incompressible viscous Navier-Stokes equations coupled with the immersed boundary method. The systematic analysis of the effect of different motion parameters on the propulsive efficiency of the AUG is carried out, including the hydrofoil's heaving amplitude, the pitching amplitude, the phase lag between heaving and pitching and the flapping frequency. The results obtained in this study can provide some physical insights into the propulsive mechanisms in the flapping -based locomotion.

Key words: autonomous underwater glider, flapping propulsion, immersed boundary method

The autonomous underwater glider (AUG) is a new type of underwater vehicles and it is driven by its own buoyancy. Compared with the traditional underwater vehicle, it has the advantages of low noise, low energy consumption, and long range[1].

Despite these advantages, some problems regarding the AUG should be given serious consideration. One of the most crucial problems is the "drift". For collecting intense data, the gliding speed of the AUG has to be relatively low, which is only about 0.5 knot (0.25 m/s). Under such a low speed, the movement of the AUG would be easily influenced by the ocean current, and it is not easy to continually follow the initially determined route.

In order to solve this problem, a conceptual design of the bionic propulsion method is adopted for the design of the AUG. In this paper, the bionic propulsion of a newly designed underwater glider is investigated by numerically solving the incompressible viscous Navier-Stokes equations coupled with the immersed boundary method to reveal the effect of hydrofoil's motion parameters on the propulsive efficiency, including the heaving amplitude, the pitching amplitude, the phase lag between heaving and pitching and the flapping frequency and to have an improved understanding of physical mechanisms of the flapping-based locomotion adopted by swimming animals.

As shown in Fig.1, the computational model is composed of the hull and the hydrofoils. The total length of the model is 1.200 m, where the middle part is a cylinder of 0.250 m in diameter and 0.625 m in length. The front part is a semi-ellipsoid of 0.175 m in semi-major axis, and the rear part is also a semi-ellipsoid of 0.400 m in semi-major axis. The hydrofoil is in the NACA0015 profile with a span length of 0.300 m and a chord length of 0.300 m, which is chosen as the characteristic length C.

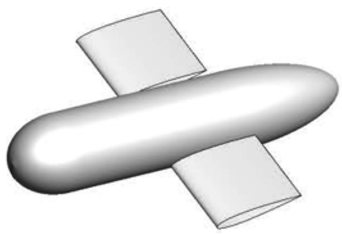

Fig.1 Schematic diagram of the computational model

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The bionic propulsion method is introduced into the design of the AUG, and and the hydrofoil's flapping is used to increase the AUG's advancing speed. The hydrofoil's motion is the combination of the heaving motion along the Y axis and the pitching motion around the Z axis, both directions of motion are sinusoidal, with a phase lag in the same motion cycle. The equations of the heave motion and the pitch motion are, respectively:

$$h(t) = h_0 \sin(2\pi f t) \tag{1}$$

$$\theta(t) = \theta_0 \sin(2\pi f t + \psi_0) \tag{2}$$

where h_0 is the heaving amplitude, θ_0 the pitching amplitude, f the flapping frequency and ψ_0 the phase lag. As a result of the hydrofoil's flapping, the underwater glider can move quickly. The schematic diagram of the movement is shown in Fig.2.

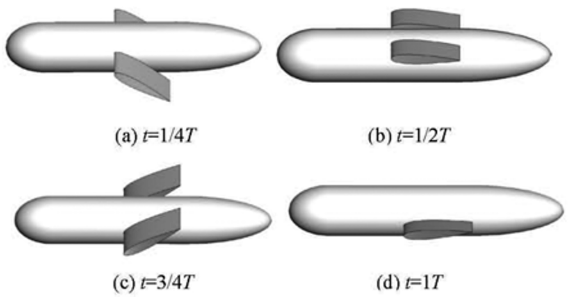

Fig.2 Schematic diagram of the motion process

The surrounding water around the AUG is considered as incompressible and viscous, and the Navier-Stokes equations of fluid motion is employed as[2,3]

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla p + \frac{1}{Re}\nabla^2\boldsymbol{u} + \boldsymbol{f} \tag{3}$$

$$\nabla\cdot\boldsymbol{u} = 0 \tag{4}$$

where $\boldsymbol{u}$ is the velocity vector, p is the pressure, Re is the Reynolds number, which can be calculated as $Re = U_0 L/\nu$ with U_0 and L being the characteristic velocity and length scales, and $\boldsymbol{f}$ is 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 other terms in Eq.(3). In addition, the finite difference projection method is used to obtain the velocity and pressure fields. For simplification, the Reynlods number in the current study is chosen as 200, without any additional turbulent model to be applied.

The immersed boundary (IB) method is applied to capture the flapping motion of the hydrofoil.The additional body force $\boldsymbol{f}$ of the IB method near the moving boundary is modified according to the "direct forcing" approach[2], in which the body force can be derived as

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

where V^{n+1} is the boundary velocity in the next time step, and RHS_i^n represents all other terms in Eq.(3).

It is worth mentioning that unlike other bionic propulsion studies, this paper focuses on the practical application, to maintain a balance between the hull's average resistance and the hydrofoil's average thrust. Thus a glider can maintain a constant moving speed. The formula of balance is defined as

$$\overline{D} = \overline{F} \Rightarrow \frac{1}{T}\int_{t_0}^{t_0+T} D\mathrm{d}t = \frac{1}{T}\int_{t_0}^{t_0+T} F\mathrm{d}t \tag{6}$$

where D represents the drag experienced by the hull, F represents the thrust generated by the hydrofoils, and T is a motion period.

We here present some typical results on the bionic propulsion of the underwater glider. Based on the measurements and the modeling of the animal locomotion, the governing parameters used in this study are chosen as follows: the flapping frequency $f = 0.3\ \mathrm{Hz} - 1.0\ \mathrm{Hz}$, the phase lag between heaving and pitching $\psi_0 = 30^\circ - 110^\circ$, the heaving amplitude $h_0 = 0.05C - 0.5C$, the pitching amplitude $\theta = 30^\circ$ and the moving velocity $V = 0.5\ \mathrm{m/s} - 1.2\ \mathrm{m/s}$.

In order to characterize the propulsive efficiency of the underwater glider, the ratio of the kinetic energy of the body and the input work is usually employed[3,4] and defined as

$$\eta = \frac{\overline{F}U_0}{P} = \frac{\frac{1}{T}\int_0^T F\mathrm{d}t U_0}{\frac{1}{T}\int_0^T P\mathrm{d}t} \tag{7}$$

where T is a movement period, and P the input power, which represents the energy required by the AUG to overcome the fluid force in the unit time and it consists of two parts, which are

$$P = P_1 + P_2 = \overline{D}V + \left[L(t)\frac{\mathrm{d}h}{\mathrm{d}t} + M(t)\frac{\mathrm{d}\theta}{\mathrm{d}t}\right] \tag{8}$$