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Research on the Push Efficiency of Fish-like Robot under Water

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Abstract: A high precision dynamical model is very important to calculate the push velocity and push efficient of the fish-like robot and it is also important to control the fish-like to swim. On the basis of the slender body theory, the model of the kinetic parameters of the fish-like robot such as turning angle, phase difference and turning frequency is established. Through the comparision of model simulation and swim experiment of fish-like robot, the efficiency of the fish-like robot is calculated and the fish's high efficiency is explained. All of this is useful to design high efficiency drive mechanism such as fish-like robot

Key words: Efficiency, fish-like robot, slender body theory, momentum theory

INTRODUCTION

Through the study of biomechanics it was discovered that the efficiency of fish swimming mode is the highest in all the marine life (Feng, 2002). More and more researchers from various countries make a lot of exploration on the fishs's swimming mechanism,for example, China,Japan and the United States have produced a wide variety of robotic fish (Wang *et al.*, 2006; Drucker and Lauder, 2002). But it is still a challenge on how to achieve a high efficiency of the real fishes's swimming (Wan *et al.*, 2012; Yeo *et al.*, 2010). Currently, the main theory to analyize the dynamic of fish-like robot includes the theory of planar wave plank and Slender Body's theory. the theory of planar wave plank take the fish tail as a plate and calculates the thrust efficiency of robotic fish with the law of conservation of energy, the law of momentum and the law of wave (Liu *et al.*, 2000). This article obtained the swimming velocity curves of the three-quarters robotic fish, taking a manufactured robotic fish as the experimental model, basing on the slender body theory, establishing the robotic fish's dynamic model of the dynamic characteristics,and being conducted dynamic simulation for this model. Meanwhile, the fish's propulsive efficiency was calculated and predicted, revealed the mystery of the fishes' superior swimming skills, taking the fishes' use of fluid force as their own streamlined instinct, serving for the Marine Engineering. It may be a new idea for the research of large scale autonomous underwater vehicle.

CALCULATION OF PUSH FORCE BASED ON THE THEORY OF SLENDER BODY

According to the studies on fish propulsion theory, researchers from different countries came up with a variety of theories, of which aerodynamics in the slender body theory is a powerful tool to resolve the propulsion problem (Triantafyllou and Triantafyllou, 1995; Shiller *et al.*, 2001). Lighthill had made systermatic research on it. In 1970, Lighthill put the "slender-body theory" of aerodynamics into the study the hydrodynamic analysis of propulsion pattern's fish for the first time (Lighthill, 1969). There are two hypotheses of the theory, one is small swing of every fish's parts according to the length of the fish. The other is that it has a large Reynolds number ($Re = LU/v$) which is generally should be between $10^4 \sim 10^8$. In this premise, the whole fish can be seen as a slender body.

James Lighthill summed up the basic principle about fish swimming when using slender body theory to solve fish motion dynamics problems,which is that momentum in the water near the cross section perpendiculars to its spine, the size of which is equal to the multiplication of mass (mass in per unit length on virtual is m) and the lateral speed relative to the water. However, when taking the balance of momentum into consideration it not only need to take the transfer of momentum through the p plane into account but also the force produced by tail fin's movement in p-plane,which is equals to $1/2\ m\ \omega^2$ (Fig. 1). m is the virtual mass, ω is the swing frequency of fish-like robot. The slender-body theory has several characteristics: Virtual quality is big to lateral direction (perpendicular to plane which is across the spine of the fish body's surface) movement while virtual quality is usually neglected to vertical direction movement. Because of the high Reynolds number, as a matter of fact,the latter's role is limited to the inner of boundary layer, performancing for friction which is generated overcome by the reaction of thrust. In other words, reaction of the fish is determined by the lateral movement. It relates to the following two factors.

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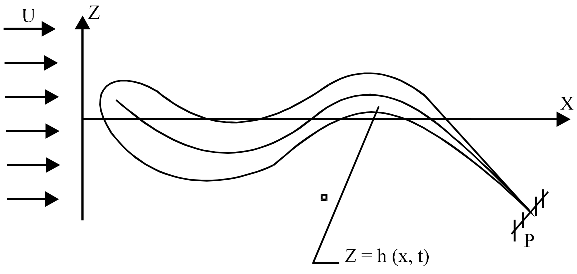

Fig. 1: Fish body’s coordinate system in the fluid

☐ Fish bodies’ rate of change relative to the medium movement velocity.

☐The rate of medium quality and virtual quality interacted with the surface of the fish body.

As is shown in Fig. 1, taking the rectangular coordinate system {x, y, z}, along with the fish center of mass’s movement, x is in the fish direction to move forward, the xy plane is crossing the spine of the fish.

Set swimming depth as unchangable, fish body swings in the z direction and swing equation is:

$$Z = h(x, t) \qquad (1)$$

The swimming velocity is U,wave propagation velocity is $V = \omega/k$.Supposing each fish body section’s lateral velocity relative to the coordinate system is $\omega(x, t)$, the lateral velocity relative to fluid is $\varpi(x, t)$, the equivalent momentum is M, the fish virtual mass per unit length is m (x), so:

$$\omega(x,t) = \frac{\partial h}{\partial t} \qquad (2)$$

$$\varpi(x,t) = \frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x} \qquad (3)$$

$$M = m(x)\varpi(x,t) \qquad (4)$$

According to (2) (3) and (4), when fish is moving, length units passed to the water (unit of length) transverse-momentum is $M = m(x)\times\varpi(x, t)$, unit of length which is passed to the water on the transverse momentum of change rate is DM (partial differential), $D = \partial/\partial t + U\,\partial/\partial x$. Based on momentum theorem and principles of action and reaction, the lateral force R to unit length of fish is:

$$R = -DM = -(U\frac{\partial}{\partial x} + \frac{\partial}{\partial t})(m(x)\varpi(x,t)) \qquad (5)$$

ESTIMATION OF FISH-LIME ROBOT PUSH EFFICIENCY

Thrust calculation: It is firstly required to find out the effective thrust for calculating the fish moving efficiency,so long as getting effective thrust, the effective work required for fish moving forward can be calculated. Based on slender-body theory and using conservation of energy and momentum theorem, the effective thrust to the body can be derived. When the whole body move forward at the speed of ω (x, t) , the power needed can be displayed as follow:

$$E = \int_0^t R\frac{\partial h}{\partial t}dx \qquad (6)$$

Analysis of one-dimensional steady-state kinetic images of fish indicates fish body wave is a transverse wave h (x, t) of which fluctuation increasing shear from first to last, so the wave equation is:

$$\frac{\partial h}{\partial t} + V\frac{\partial h}{\partial x} = 0 \Rightarrow \varpi = \omega\frac{V-U}{V} \qquad (7)$$

According to (5) (6) (7):

$$E = \frac{\partial}{\partial t}\int_0^t (m\varpi\frac{\partial h}{\partial t} - \frac{1}{2}m\varpi^2)dx + U[m\varpi\frac{\partial h}{\partial t}]_{x=t} \qquad (8)$$

The item at the right end and first is the derivative of a simple harmonic quantity on time (obtained by kinematic analysis of fish, z = h (x, t) is a harmonic change amount), therefore,work done by fish to the surrounding medium as per unit time is:

$$\bar{E} = U[m\varpi\frac{\partial h}{\partial t}]_{x=t} = [Um\varpi]_{x=t} \qquad (9)$$

In a stationary reference frame, work made by fish body is composed of three parts: The first is to push forward the body , that is work done by thrust,the second part is kinetic energy produced by the caudal fin margin when it goes into the water which is energy wasted ,the third is the rate of change of the kinetic energy generated by tail fin’s edge around the entire body before controlling rate of change of the kinetic energy in the body:

$$E = UT + U[\frac{1}{2}m\varpi^2]_{x=t} + \frac{\partial}{\partial t}\int_0^t (\frac{1}{2}m\varpi^2)dx \qquad (10)$$

The thrust based on conservation of energy in accordance with (8) and (10) is :

(11)

$$T = [m\varpi(\omega - \frac{1}{2}\varpi)]_{x=t} - \frac{\partial}{\partial t}\int_0^t (m\varpi \frac{\partial h}{\partial x})dx \quad (3)$$

The second is the time derivative of a simple harmonic quantity, actually its value is zero. (7) substituts into (11), the following equation can be obtained:

$$\overline{T} = m(l)\frac{\overline{\omega^2(l)}}{V^2}(V - U) \quad (12)$$

By the equation (12) ,as can be seen, the condition to produce thrust is that V must be bigger than U, where v is decided by the swing frequency ù and the wave number k of the body. However,apart from the connection with the V, U is related to the nature of the fish-like robot's system as a whole, such as appearance, quality and so on.

Calculation of efficiency: From the above analysis and calculation, the effective work can be calculated, W_e = UT . But it is also required to know the total work output for calculating efficiency. One way to strike a total work is by measuring output torque and turning speed of fish-like robot motor.

The efficiency can be displayed as follow:

$$\eta = \frac{\frac{1}{T}\int_0^T F_x \bullet U dt}{\frac{1}{T}\int_0^T M_{\theta_1} \bullet \dot{\theta}_1 \, dt + \frac{1}{T}\int_0^T M_{\theta_2} \bullet \dot{\theta}_2 \, dt} \quad (14)$$

In the above formula, molecular formula is calculated available work based on slender body theory and two-dimensional theory and denominator formula is calculated total work consists of motor output torque and angular velocity. But the efficiency by the estimation method couldn't reflect the actual efficiency driven by the way of the fish swimming mode of fish-like robot, because it contains the mechanical loss. This study estimates the efficiency of fish-like robot by conservation of energy and momentum theorem, avoiding the part's calculation of mechanical efficiency. It could achieve a real assessment of driving efficiency which is implemented by fish body's swing and concluded with propulsive efficiency without mechanical loss efficiency. Assuming it is total power. So the efficiency is the ratio of available work and total work. $\eta = \overline{UT}/\overline{E}$, calculating with equation 8 and 11, the efficiency can be displayed as follow:

$$\eta = \frac{[\overline{\varpi\omega}]_{x=1} - \frac{1}{2}[\overline{\omega^2}]_{x=t}}{[\overline{\varpi\omega}]_{x=t}} \quad (15)$$

Then take (12) into the above equation, the push efficiency can be calculated as follow:

$$\eta = 1 - \frac{1}{2}\frac{V - U}{V} \quad (16)$$

Taking a number of experimental parameters on striking a thrust into above equation, the highest efficiency can up to 51% it is much higher than the efficiency of c urrent autonomous underwater vehicle.

Swimming experiment: In order to improve the validation of the dynamical model of fish-like robot, the swimming experiment was taken on the three section fish-like robot. The dimension of swimming pool is 4×8 m and the depth of swimming pool is 60 cm. The fish-like robot swims at the depth of 10 cm. the swim parameters was same as the simulation parameters, that is $\theta_1 = 15, \theta_2 = 30$, $\omega = 2\pi$, $\varphi = 45°$. θ_1 is the connect angle of first section(head) and second section (body) and θ_2 is the connect angle of second section (body) and third section (tail). Three section fish-like robot swim in the pool from rest to the steady status and the swim image was recorded (Fig. 2). Different parameters experiment was done and According to the swim experiment of fish-like robot with different swim parameters, the push efficient was calculated and the relation curve between push efficient and swim parameters was drawn (Fig. 3).

Fig. 2: Experiment of the robot fish

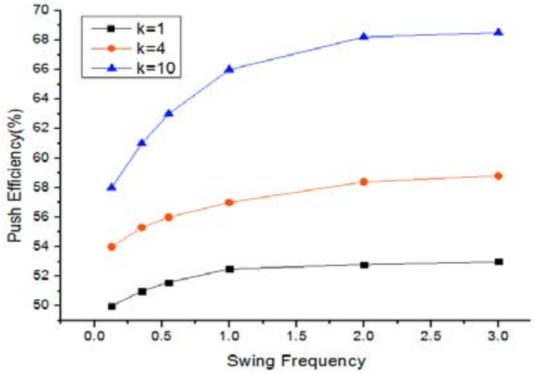

Fig. 3: Propulsive efficiency

CONCLUSION

According to the analysis and experiment of the fish-like robot, the factors that affect the efficiency can be displayed as follows:

- **Estimates of virtual mass:** The virtual mass can be calculated as follow:

$$m=\frac{1}{4}\pi^2 d\beta$$

Among the above formula, d is maximum vertical scale of section (including fins), β is a virtual mass coefficient it depends on the shape of section

- Separation of unsteady fluid
- Determination of drag coefficient
- Dynamical parameters such as swing amplitude, swing frequency, body curves

The first three elements are related to specific experimental conditions and will not be repeated here. The fourth affect factor-dynamical parameters was simulated and calculated and the following conclusion can be obtained:

- ☐ Efficiency has significantly improved with amplitude of swing but slender-body theory exists provided the swing range can not be too big
- ☐ Efficiency increases with frequency but it will not increase any more when increases to a certain size which is almost stable at a value.
- The efficiency increased with the addition of body wave's number k. At the time of mechanism designing of fish-like robot, big k value can be achieved only when the joints number is large, thereby improving the efficiency. But with large joints number, efficiency loss of motor and efficiency loss caused by mechanical friction increases. Therefore there exsits a optimized jounts number to get a highest efficiency of fish-like robot

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