Biomimetic Robotic Fish Fins Propulsion Modes Research in Flow Field

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Abstract - Compound propulsion modes adapting to the flow field features is important to improve the robotic fish dynamic control level. Flow velocity and pressure field spread data around the robotic fish are essential condition. The positive propulsion force can be obtained by unsymmetrical flapping of tail and pectoral fins according to the flow field feature. In this paper, taking linked robotic fish as the research object, the flow velocity and pressure field characters are analyzed. Furthermore the suitable propulsion mode and computation method of tail and pectoral fin are proposed. Particularly the best propulsion mode in direct and turning motion is studied and typical control strategy is obtained. The result in this paper will contribute to reveal the mechanism of multiple fins linked propulsion mechanism and postpone the deep breakthrough from the view of compound control, which will provide potential for improving the biomimetic level.

Index Terms - Robotic Fish, Flow Field, Linked Propulsion Mode, Tail Fin, Pectoral Fin.

1. Introduction

Flow is common in the outdoor water area. Natural fishes evolve ten thousands of years and have been adapted to the flow environment. Taking the robotic fish and environmental flow field as whole research object and acquiring the dynamic control mechanism in flow field are important for the practical application of the robotic fish.

Since the fish structure is complex, it is hard to analyze the flow force on robotic fish because it varied with the position on fish body. The development of CFD (Computational Fluid Dynamics) numerical computation method provides the technology possibility to solve this problem. The integration research of robotic fish dynamic performance and flow field has been a hot focus in recent years. Liu(1999)[1] adopted three dimensional(3-D) incompressible Navier-Stokes equation to solve the unsteady hydrodynamic performance of large range flapping, and set up the flow model of tadpole based on this equation. Sandberg (1999)[2] calculated tuna tail and pectoral fin hydrodynamic performance by non structure grid finite element method. Su (2002)[3] analyzed biomimetic tuna rigid and flexible tail fins unsteady hydrodynamic performance by 3-D panel method. Zhang (2008)[4] obtained the robotic fish tail fin vortex street in 3-D water flow by artificial compressibility and non structure mesh method. Though some results about the hydrodynamic performance around robotic fish fin have been obtained, little work has been down about the linked fins compound propulsion. Further research work should be accomplished to improve the control performance.

To better approach natural fish movement coordination ability, the robotic fish structure, propulsion mode and multiple inputs and multiple outputs real-time control become the hot spot of studying. Low(2009)[5] conducted research of the propelling force affected by the fish fin parameters through large quantity of experiments. Flammang(2011)[6] took natural shark as objective to study the 2-D vortex flow and utilizes robotic fish to study the 3-D propelling vortex flow. Experiments show the tail fin stiffness is tightly related with the vortex street. Bi(2012)[7] conducted research of pectoral fin stiffness affection on the propelling force and propelling efficiency. The certain flexibility of the fin posterior segment will improve the propelling force. Wang(2011)[8] conducted robotic cruising dynamic control research based on the Central Pattern Generator(CPG) neuron. Multiple inputs-multiple outputs high biomimetic robotic fish control based on the lateral line sensor can directly control the multiple actuators. However, the result was mainly obtained in the static water, while the natural fish lives in the flow field environment and has the ability to adopt the best swimming mode with coordination of all the associated fins. Therefore, the robotic fish propulsion mode in water flow field with multiple fins is the key research objective of next step. Part of the detail work is the propulsion mode of the linked fins such as the unsymmetrical flapping; multiple fins linked moving mode, the moving performance and propelling efficiency. According to this requirement, Shanghai Ocean University developed several linked moving robotic fish. Fig.1 is the illustration figure of the head, dorsal fin and tail fin linked structured turning robotic fish. Fig.2 is the robotic fish SHOU-II cruising in water.

In this paper, taking the SHOU-II robotic fish as objective, flow velocity and pressure field of different inflow current angle around the fish body is simulated. To keep the fish body balanced in the flow field, unsymmetrical flapping of the tail fin is necessary. The force analysis of the fish body is carried out. Pectoral fin plays the role of balancing the force and torque. Typical working modes of the pectoral fin are studied in different moving situation which provides support for the high efficient complex control.

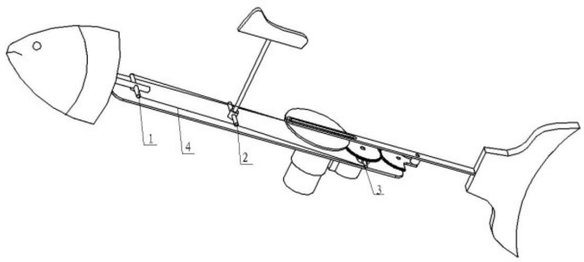

Fig.1. Illustration of head, tail and pectoral fin linked propelling robotic fish structure

Fig.2. Robotic fish SHOU-II cruising in water

2. Velocity And Pressure Flow Field Analysis Around The Robotic Fish

The 2-D z plane is described with the complex number

$$z = x + iy$$

where x denotes the real part and y is the imaginary part.

The even inflow speed denotes with Q, inflow angle is denoted with α, the circular rector is denoted with Γ, the radius is denoted with R along axis ζ, the center ζ_{off} is in complex plane $\zeta_{off} = \xi_{off} + i\eta_{off}$, its complex potential is

$$F(\zeta) = \phi + i\Psi = Qe^{i\alpha}(\zeta - \zeta_{off})$$

$$+ Qe^{i\alpha}R^2/(\zeta - \zeta_{off}) + \frac{i\Gamma}{2\pi} In[(\zeta - \zeta_{off})/R] \qquad (1)$$

where ϕ, Ψ, are the potential function and streamline function.

The transformation to describe the fish body boundary is

$$z = \zeta + \lambda^2/\zeta \qquad (2)$$

where

$$\lambda = \xi_{off} + \sqrt{R^2 - \eta_{off}^2} \qquad (3)$$

Γ is computed by $\Gamma = 4\pi QR\sin(a - \theta_{TE})$. θ_{TE} means the angle between the center-end point line and horizon line.

$$C_p = \frac{P - P_\infty}{\rho Q^2/2} = 1 - \frac{q^2}{Q^2} \qquad (4)$$

where P is the pressure, ρ is the fluid density, $q = \sqrt{u^2 + v^2}$ is the local speed, the local speed $\omega = u - iv$ in z plane. Conjugate multiplication is q^2.

Differentiate z from F

$$\omega = \frac{dF}{dz} = \frac{dF}{d\zeta}\frac{d\zeta}{dz} = \left[Qe^{i\alpha} - Qe^{-i\alpha}R^2/(\zeta - \zeta_{off})^2 + \frac{i\Gamma}{2\pi(\zeta - \zeta_{off})}\right]\frac{d\zeta}{dz} \qquad (5)$$

where
$$\frac{d\zeta}{dz} = \frac{1}{1 - \lambda^2/\zeta^2} \qquad (6)$$

Take $R = 1$, $Q = 1$, inflow angle $\alpha = 8\pi/180$, $\zeta_{off} = 0.093R$, $\eta_{off} = 0.08R$, $-3.5R \le \zeta \le 2.5R$, $-2.5R \le \eta \le 2.5R$. The velocity field produced by the inflow is as Fig.3. The pressure field produced by the inflow is as Fig.4.

There exist high pressure part and low pressure area around the fish body. Particularly the pressure closed to the pectoral fins varied a lot.

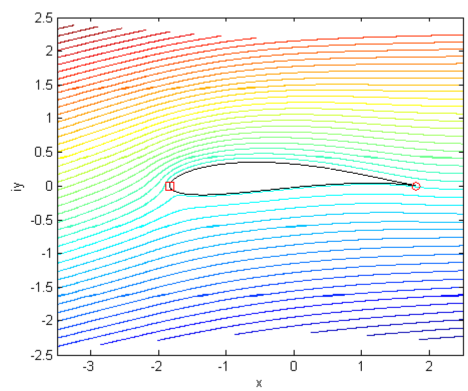

Fig.3. The velocity field spread around the robotic fish under inflow angel $\alpha = 24\pi/180$

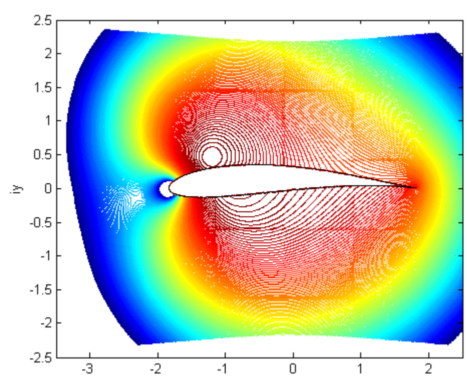

Fig.4. The Pressure field spread around the robotic fish under inflow angel $\alpha = 24\pi/180$

If the inflow angle $\alpha = 24\pi/180$ and other parameters unchanged, the flow velocity field and pressure field are as Fig.5 and Fig.6.

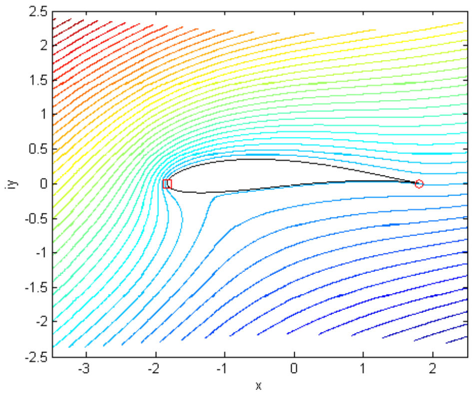

Fig.5. The flow velocity field spread around the robotic fish under inflow angel $\alpha = 24\pi/180$

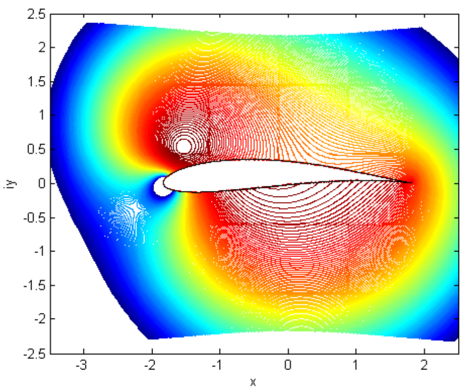

Fig.6. The pressure field spread around the robotic fish under inflow angel $\alpha = 24\pi/180$

Compared Fig.3 and Fig.5, the path lines under different inflow angle lead different streamline feature. Fig.5 show the static streamline area is enlarged outside the left side of the fish body, which means the propelling direction of the tail will vary according to inflow angle to keep the fish body stable in the water. The presser area and depressor area varied with the change of the inflow angle, which means the tail and pectoral fins stiffness should be variable to achieve better propelling force.

3. Typical Propulsion Mode Research and Analysis

The robotic fish in the flow field bears complex forces including dominant propelling force from the unsymmetrical flapping tail, inflow force on fish body and the force from the pectoral fin backward and forward sliding. Among these forces, dynamic analysis of the forces on fish body in the flow field is the base of the propulsion mode research.

A. General Force Analysis on Robotic Fish Body in Flow Field

Seeing Fig.7, the forces on the fish body gravity center from tail involve the propelling force F and torque T. The join force on fish body surface produced by the flow is Q. Since the force arm is short by the robotic fish out surface design, the torque produced by this force is ignored. The join drag force is f, which is in the opposite direction of the fish body moving. The f direction goes across the gravity center, so there is no torque produced from the drag force. If the flow direction is as Fig.7, to keep the cruising state steady, the tail fin should flapping asymmetrically, for example, between AB and AC with AD as the flapping center axis, which produces a propelling force. The force can be divided into positive force F and turning torque T.

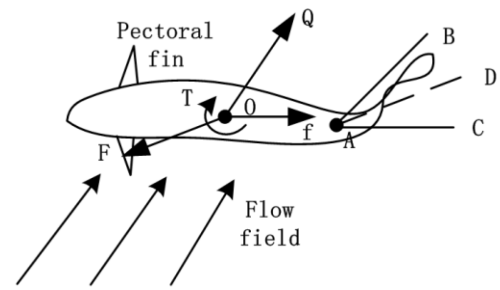

Fig.7. The general force analysis of the robotic fish in flow field

Pectoral fin slides forward and backward which produce torque to balance the torque from tail fin. The pectoral fin also produces force which will help to dynamically maintain the balance of the force and torque. The propelling force F and drag force f is the basement to study the moving mode. The flowing subsection will deduce the calculation equations which can provide the quantities values of the system control.

B. Propelling and Drag Force Computation

From paper 9-10, the even propelling force produced by the flapping fin is:

$$\overline{T} = \left\{ \frac{m}{2} \left[\overline{\left(\frac{\partial w(z,t)}{\partial t} \right)^2} - U^2 \overline{\left(\frac{\partial w(z,t)}{\partial z} \right)^2} \right] \right\}_{z=L} \tag{7}$$

where z denotes the coordinate in the tail length direction and $w(z,t)$ is the tail displacement time function, t is time. L means the length of the tail. $z = L$ denotes the tail end point coordinate. $\overline{(.)}$ means even value, m is the virtual mass at $z = L$ and is denoted as

$$m = \frac{1}{4} \pi S_c^2 \rho_w \beta \tag{8}$$

where S_c is the width at the end of $z = L$, ρ_w is the fluid density, β is parameters closed to 1. Eq. (7) means the even propelling force is only related with the side flapping speed $\partial w / \partial t$ and the slope of the end point $\partial w / \partial z$.

The drag force F_D when fish cruise is:

$$F_D = \frac{C_D \rho_w U^2 S}{2} \tag{9}$$

where S is the wet area of the fish body, C_D is the resistance efficiency.

With $w(z,t)$ as

$$w(z,t)=\frac{1}{2}z^{0.5}a\sin\omega t \qquad (10)$$

where z denotes the dimension along with the tail, a denotes the amplitude of the oscillating, ω is the frequency of the flapping.

With the requirements of Eq.(7) and according to Eq.(10), the partial differential function of $w(z,t)$ is as following,

$$\frac{\partial w}{\partial t}=-\frac{1}{2}z^{0.5}a\omega\cos\omega t$$

$$\frac{\partial w}{\partial z}=\frac{1}{4}z^{-0.5}a\sin\omega t$$

In Eq.(7)-(10) $S_c=0.1m$, $\rho_w=10^6 g/m^3$, $\beta=1$, $S=0.2m^2$, $C_D=0.1$, $z=0.1$, $a=0.1$, $\omega=1.5$. The cruising speed of the robotic fish is

$$U=0.0904m/s$$

In static water, from Eq.(7)(8)(9) and second Newton law, the brief propelling and drag force and hydrodynamic cruising speed can be calculated. However, in the flow field, it will different since the working of flow force on fish body and the sliding force of pectoral fin. More detail force analysis should be done to get suitable apprehension of the hydrodynamic process. The following subsection will analyze these in general.

C. The Force Analysis and Propulsion Mode Research of Robotic Fish in Flow Field

Experiments show it is hard to keep the moving state stable in flow field such as cruising in straight direction. Pectoral fin's flexible posture is important to keep the fish move in straight cruising or turning. The pectoral fins involve two parts, the left one P_l and the right part P_r. The coordination between the two fins as well as the tail fin is crucial to improve the dynamic system performance.

1) The Pectoral Fin Propulsion Mode of Robotic Fish in Straight Cruising

To keep the robotic stable cruising in the flow field, for robotic fish SHOU-II, several propulsion modes are adopted. By the force analysis from Fig.7, the unsymmetrical tail flapping will produce propelling force and the mean direction is along with AD. Since the effect of torque T in the gravity center point, the robotic fish will turn right without other force to balance it. Several modes of the pectoral fin are suitable to achieve this objective. Fig.8 shows a methodology by applying P_r to balance the torque T . The backward sliding of right fin is the main working process which produces forward force to avoid the continuous turning of fish body because of T . The forward sliding of the P_r fin plays less working process in the restore process of the fin. Compared with the method shown in Fig.8, Fig.9 shows another more comprehensive way to attain better effect. With the work of the two pectoral fins backward and forward sliding, there is more space to realize better straight cruising effect.

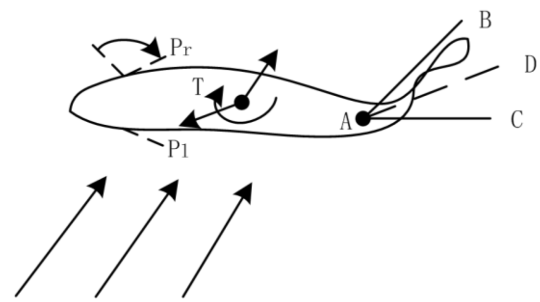

Fig.8. Unsymmetrical propulsion mode-1 in flow field

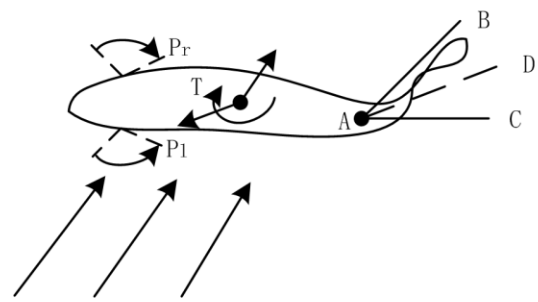

Fig.9. Unsymmetrical propulsion mode-2 in flow field

2) The pectoral Fin Propulsion Mode of Robotic Fish in Turning

For the turning of the robotic fish, smaller turning radius will provide the robotic fish flexibility of moving which is the main objective to achieve. Compared with the straight cruising, the turning torque T is a positive element at this situation and is the main force to turning. Pectoral fin's sliding mode can help to keep the turning process stable and decrease the turning radius, seeing Fig.10 and Fig.11. The left and right fin can work reversed according to the turning requirement which has the potential a achieve turning on the spot.

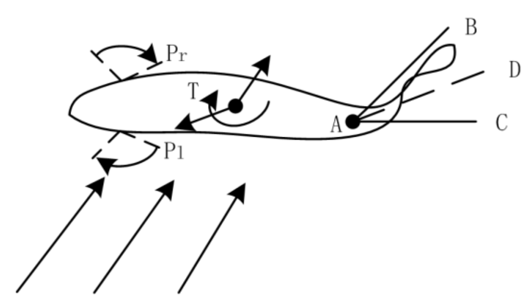

Fig.10 Unsymmetrical propulsion mode-3 in flow field

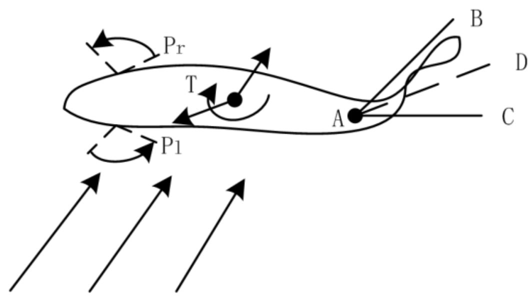

Fig.11 Unsymmetrical propulsion mode-4 in flow field

3) General Propulsion Modes Analysis of Pectoral and Tail fin

The pectoral fin can slide backward or forward. One of the sliding processes plays key role while the other one restores the position after the end of the sliding. Therefore, the different combination of the two pectoral fin's sliding will provide the propelling modes in different flow field which is analyzed as following.

In opposite flow field like showing in Fig.8, to keep the robotic fish straight cruising, right pectoral fin backward sliding and left pectoral fin forward sliding should play the main role with the tail fin flapping center axis AD at the right side of the fish body center line. To achieve small radius turning and if turn left, the control strategy should be same with the control methodology above. If turn right, right pectoral fin forward sliding and left pectoral fin backward sliding should play the main role. In positive flow field, the propulsion should be same with that in the opposite flow field. The differences are the force contributed by the left and right fin will be different.

Based on the lateral sensor to acquire the flow field features, the force Q of fish body produced by the flow can be obtained from the flow velocity and pressure field. Propelling force and drag force can be calculated by Eq.(7) (9). According to the dimension of the robotic fish and the angle between AD and the center line of the fish body in Fig.7, the join force and torque on fish will be acquired. Furthermore the optimized hydrodynamic control can be achieved.

4. Conclusions

The robotic fish with tail and pectoral fin is the smallest system to achieve stable control in flow field. In this paper, flow velocity and pressure field around the robotic fish are computed based on the inflow angle which help to provide rich data for further analysis. The coordination of the tail and pectoral fins helps to achieve better propulsion effect. The force produced by the unsymmetrical flapping of the tail fin is analyzed. Propelling force and drag force equation is deduced. Pectoral fin's optimized propulsion modes are studied to get optimal control effect and high efficiency. Pectoral fins mainly play the role to maintain the robotic fish stable in straight cruising and contribute to absorb the flow momentum to improve the turning performance.

Considering of the pressure field around the fish, to get optimal fin deformation and produce largest force, the tail and pectoral fins should involve adaptable stiffness spread. Natural fish has blood, muscle to automatically change the stiffness. This is an important objective for further research.

Acknowledgments

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