Research on Multi-mode Swimming Control Modeling of Bionic Underwater Propeller with Double-Tail Fins

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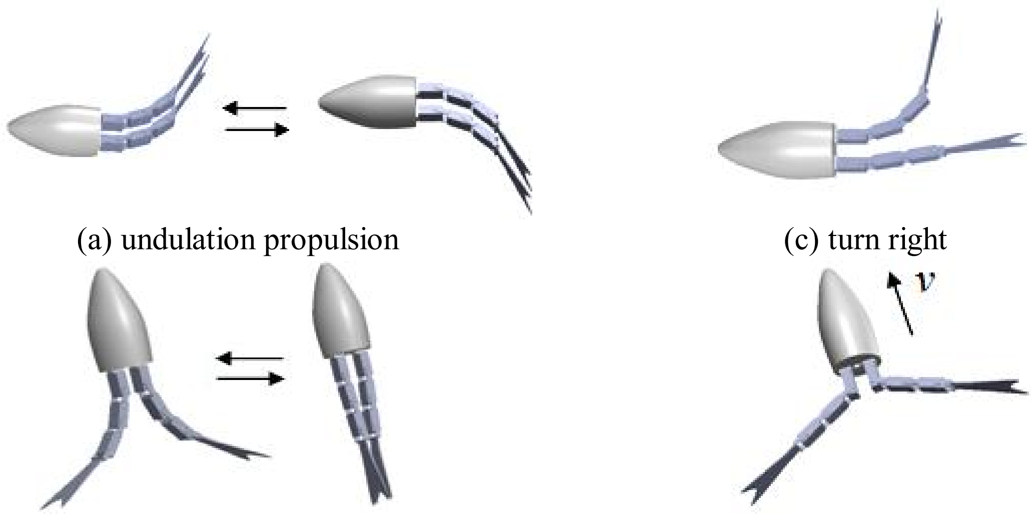
Abstract. A novel type of bionic underwater hybrid propeller is proposed, which combines the undulation propulsion and jet propulsion by the use of the double tail fins cooperative driving, and is capable of achieving a serial of motions: cruise, acceleration, turning and braking. Targeting at approximate smooth tail contours by using rigid tail linkage, a bionic propeller control modeling method is discussed based on digital approximation method, and the control model is established to achieve the undulation propulsion and jet propulsion.

Introduction

Undulation propulsion and jet propulsion are commonly adopted as swimming pattern by the aquatic animal, since the undulation propulsion displays the outstanding performance of high efficiency, high maneuverability and little disturbance[1], while the jet propulsion has the advantage of large instant acceleration and strong environmental suitability[2]. Inspired by nature, a novel type of bionic hybrid propeller is proposed in this paper. By the means of the cooperative control of the double-tail fins, the propeller combines the undulation propulsion of fish with the jet population of jellyfish. The multi-joint control model is established to achieve the undulation propulsion and jet propulsion.

The movement strategy

The bionic propeller is made up of the fish head and two multi-joint tail fins which symmetrical distributed in the fish head. When the two tail fins undulation, the bionic propeller realized the undulation propulsion. It can obtain greater propulsive force and avoid the fluctuation of the single tail fin swing instability problem effectively. When the two tail fins reverse flap, the bionic propeller realized the jet propulsion(see Fig.1).



(a) undulation propulsion (c) turn right

(b) jet propulsion (d) braking

Fig.1 The multi-mode movement strategy of bionic propeller

Coordinate system definitions

In order to describe the movement of bionic propeller, there are five coordinate systems are defined. One is a world coordinate system R^w, as show (x^w, y^w) in Fig.2, where the origin is fixed at the back face center point B of the bionic propeller, and its x-axis is aligned along the swimming direction of propeller. The movement of the whole bionic propeller in R^w is defined as body motion. The next two are local coordinate systems R^{ll} and R^{lr}, as show (x^{ll}, y^{ll}) and (x^{lr}, y^{lr}) in Fig.2, where the origins are fix at the connection point o_l and o_r between the fish head and left/right tail fins, and its x-axis are also aligned along the swimming direction of the propeller. The movement of the left/right tail fins are defined in R^{ll} and R^{lr}. The last two are user coordinate systems R^{ul} and R^{ur}, as show (x^{ul}, y^{ul}) and (x^{ur}, y^{ur}) in Fig.2, where the origins are the same point as R^{ll} and R^{lr}, but its x-axis are aligned along the fish head rather than the swimming direction. The movement of the multi-joint motors are defined in R^{ul} and R^{ur}.

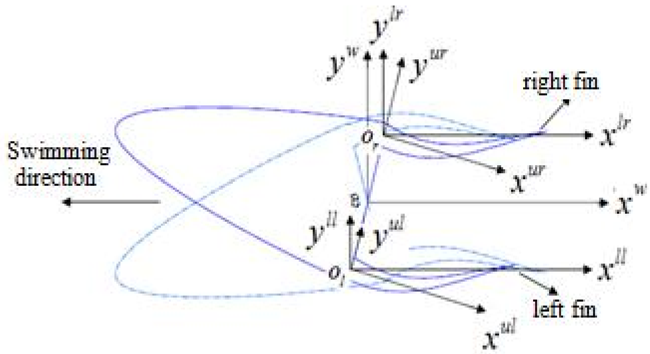


Fig.2 Coordinate system definitions

The control modeling of undulation propulsion

First of all, the center line of the fish head is translated to the positive direction of y^{ll} and negative direction of y^{lr},and the point B is coincide with o_l and o_r. So in the R^{ll} and R^{lr}, the movement of the two tail fins could be described by the travelling wave Eq.(1)[3]. The tail fins wave curve is show in Fig.3(a).

$$\begin{cases} y_l = f_{ll}(x,t) = (c_1 x + c_2 x^2)\sin(kx + wt) \\ y_r = f_{lr}(x,t) = (c_1 x + c_2 x^2)\sin(kx + wt - p) \end{cases} \quad (1)$$

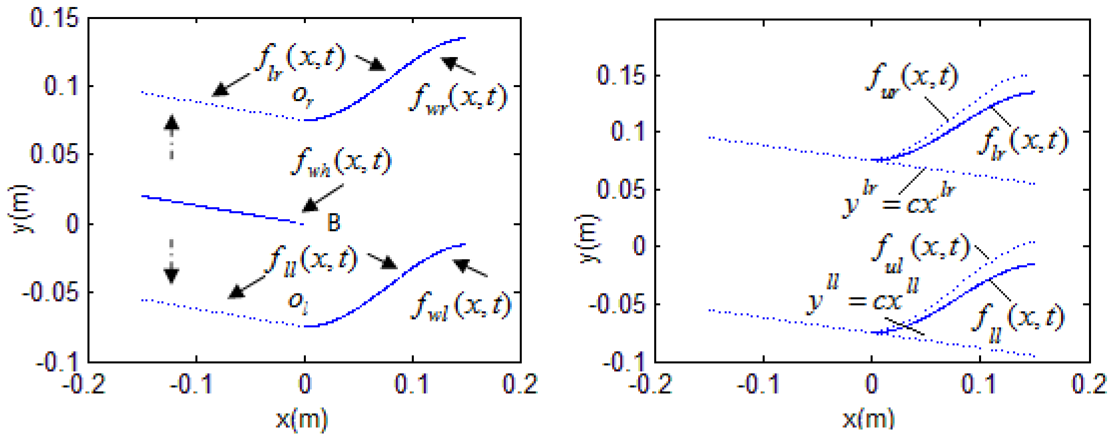
Where y_l / y_r is the lateral displacement of left/right fins; x is the length of the fins; $k = 2p\,l^{-1}$ is the number of fish body wave; l is the length of fish body wave; c_1, c_2 is the coefficient of amplitude envelope; w is the frequency of fish body wave.

In order to restrain the fish head shaking, the Eq.1 is modified and a new Eq.(2) is established in R^{ul} and R^{ur} according to the paper[4]. The modified tail fins wave curve is show in Fig.3(b).

$$\begin{cases} f_{ul}(x,t) = f_{ll}(x,t) - c_l x & x \ge 0 \\ f_{ur}(x,t) = f_{lr}(x,t) - c_r x & x \ge 0 \\ f_{ul}(x,t) = f_{ur}(x,t) = 0 & x < 0 \end{cases} \quad (2)$$

Where $c_l = \left.\frac{\partial f_{ll}(x,t)}{\partial x}\right|_{x=0} = f_{ll}^{'}(x,t)_{|x=0}$, $c_r = \left.\frac{\partial f_{lr}(x,t)}{\partial x}\right|_{x=0} = f_{lr}^{'}(x,t)_{|x=0}$.

The design parameters of the bionic propeller: the bionic propeller overall length $L = 0.35m$, fins length $l = 0.2m$, the two fins distance $H = 0.3m$. The parameters in Eq.1 and Eq.2: $c_1 = 0.4$, $c_2 = -0.1$, $k = 13.1$, $w = -2p$.



(a) The tail fins wave curve (b)The modified tail fins wave curve

Fig.3 The bionic propeller wave curve

In order to reproducing the fish swim patters in our bionic propeller, firstly, the tail motion function should be discretized in to M tail postures $T_{ul}(x,i)(i=0,...,M-1)$ and $T_{ur}(x,i)(i=0,...,M-1)$ over time, and then real fish swimming can be mimicked by approximating each tail posture with rigid linkages between joints.

Fig. 4 shows an example of an approximation of two tail fins posture with six joints(Ⅰ, Ⅱ, Ⅲ, Ⅳ, Ⅴ, Ⅵ). $j_{ij}(i=0...M-1, j=1...6)$ are the slope angles of the linkages. $q_{i,j}(i=0...M-1, j=1...6)$ are the actual control angles, which are angles to turn a joint relative to its anterior linkage. Eq.(3) shows the relationship between j_{ij} and $q_{i,j}$.

$$\begin{cases} q_{i,j}=j_{i,j} & j=1,4 \\ q_{i,j}=j_{i,j}-j_{i,j-1} & j=2,3,5,6 \end{cases} \qquad (3)$$

Considering the physical meaning behind the swimming function, added-mass method is the practical methods to simulate a real fish swimming[5], its principle is to equate the added-mass pushed away by the linkage to that by the real fish. Therefore, two error indexes have to be considered, the magnitude error and direction error, since the added-mass is basically a vector. Direction error is minimized if the magnitude error has been minimized as the" Base" point of the first joint, so only the magnitude error is considered here. As show in Fig.5, a "cross" point C is thereafter defined as the first crossing point between a joint $g_{i,j}(x)$ and tail motion function $f_{i,j}(x)$, and the approximate error can be described as Eq.(4).

$$e_{i,j}(x)=\left|\int_{O\_x_{i,j}}^{E\_x_{i,j}}[g_{i,j}(x)-f_i(x)]\mathrm{d}x\right|,(i=0...M-1, j=1...6) \qquad (4)$$

Where $f_i(x)=\mathrm{T}_{ul}(x,i)$ or $\mathrm{T}_{ur}(x,i)$, $g_{i,j}(x)=\dfrac{E\_y_{i,j}-O\_y_{i,j}}{E\_x_{i,j}-O\_x_{i,j}}(x-O\_x_{i,j})+O\_y_{i,j}$

For a fixed length linkage should meet the following formula:

$$(E\_x_{i,j}-O\_x_{i,j})^2+(E\_y_{i,j}-O\_y_{i,j})^2=l_j^2 \qquad (5)$$

Where l_j is the length of the j-th linkage.

A crossing ratio is introduced as $R_c=\dfrac{O\_x}{C\_x}(R_c\in[0,1])$. For a given R_c, the coordinate of the Cross point can be obtained by solving the following equations.

$$\begin{cases} (x-O\_x_{i,j})^2+(y-O\_y_{i,j})^2=(R_c l_j)^2 \\ y=f_i(x)=\mathrm{T}_{ul}(x,i) \text{ or } \mathrm{T}_{ur}(x,i) \end{cases}, i=0...M-1, j=1...6 \qquad (6)$$

Once we obtain the Cross point, the End point and $g_{i,j}(x)$ can be easily obtained, because of the linear relationships between them (Fig.5). After substituting the End point and Base point into Eq.(4), the approximation error under the gain R_c can be computed. This conditional error is denoted as $(e_{i,j}(x)\,|\,R_c)$.

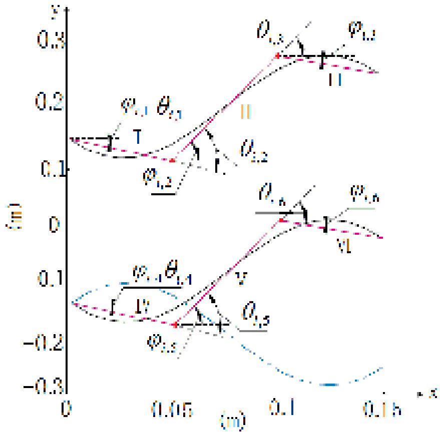


Fig.4 Two tail fins posture approximation result

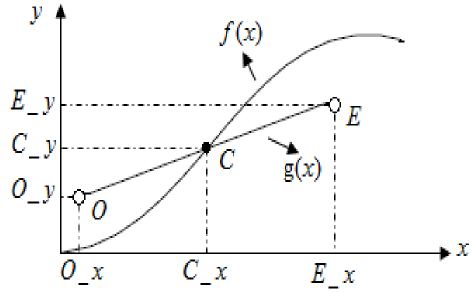


Fig.5 Terms definition for the approximation method

R_c is first discretized into $(R_{c,0}, R_{c,1} \ldots R_{c,n})$ from 0 to 1 with an equal step $1/n$. After substituting them into Eq.(6), one can obtain a series of approximation errors: $(e_{i,j}(x)\,|\,\mathrm{R}_{c,p})(p = 0 \ldots \mathrm{n})$. Thus, the minimal approximate error $e_{i,jmin}$ can be obtained as: $e_{i,jmin} = \min\limits_{p=0\ldots n}(e_{i,j}(x)\,|\,\mathrm{R}_{c,p})$

The corresponding $\{(E\_x, E\_y)\,|\,\mathrm{R}_{c,p}\}$ to $e_{i,jmin}$ is thereafter set as the approximation position for the j-th linkage and i-th tail posture. Further, the gradient $j_{i,j}$ of the linkage can be calculated easily.

When the length of linkages is set as [0.05 0.055 0.095] for three linkage and [0.045 0.045 0.045 0.065] for four linkage to approximate the wave curve, as show in Fig.6, the approximation error is minimized between three linkages and four linkages, but the four linkages fin is more complex than the three linkages fin to control. So the three linkages fin is adopted in this paper. Finally, the joint angle $q_{i,j}$ is calculated using Eq.(3)(see Fig.7)

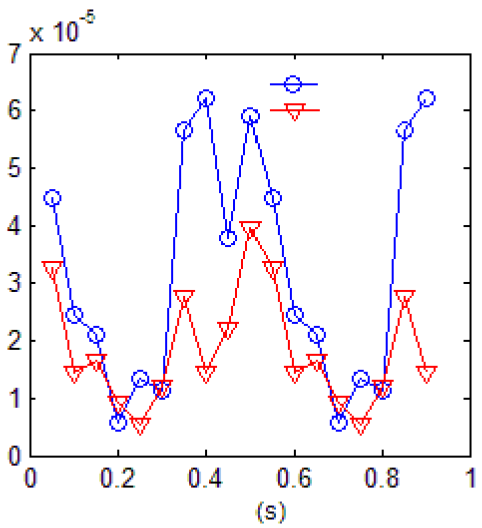


Fig.6 The approximation error

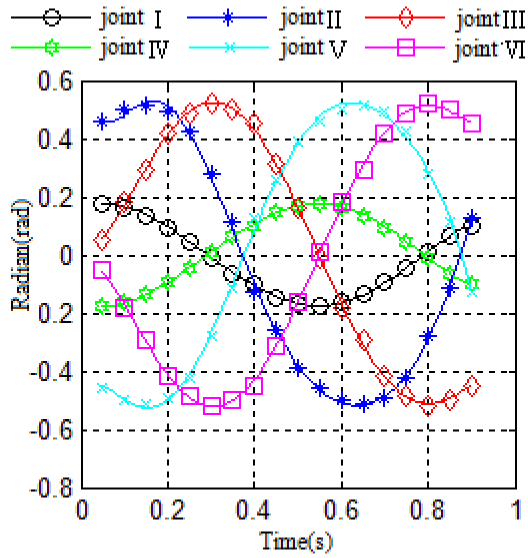


Fig.7 The joint angle of undulation propulsion

The control modeling of jet propulsion

Eq.(7) shows the bionic propeller fins movement function in which the two tail fins with a straight state flapping around the fins root to generate jet propulsion.

$$\begin{cases} y_l = tan(q \sin(w_l t))x - h \\ y_r = tan(q \sin(w_r t))x + h \end{cases} \quad (7)$$

Where y_l, y_r is the lateral displacement of the left/right fins; x is the length of the fins; q is the maximum flapping angle; w_l, w_r is the flapping angular velocity of left/right fins; h is the half distance of the two fins. when $w_l = -w_r$ for reverse flap, a flapping angular velocity is introduced as $w_l = 2p\, rad / s$, then, the joint angle $q_{i,j}$ is calculated using the method as the undulation propulsion above.(see Fig.8)

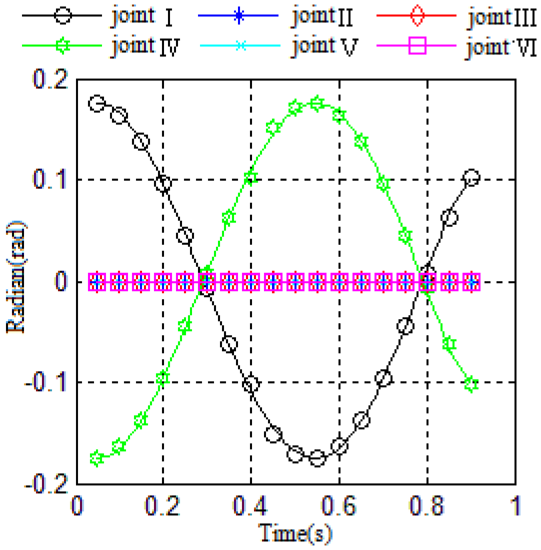


Fig.8 The joint angle of jet propulsion

Summary

Inspired by swimming characteristics of nature aquatic animal, a multi-joint bionic underwater hybrid propeller is proposed, which combines the undulation propulsion and jet propulsion by the use of the double tail fins cooperative driving. The relationship between the linkage number and approximation error is discussed and the control models of undulation propulsion and jet propulsion are established base on digital approximation method.

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