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Propulsive performance and flow field characteristics of a 2-D flexible fin with variations in the location of its pitching axis

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Abstract: The thrust coefficients and propulsive efficiency of a two-dimensional flexible fin with heaving and pitching motion were computed using FLUENT. The effect of different locations of the pitching axis on propulsive performance was examined using three deflexion modes which are respectively, modified Bose mode, cantilever beam with uniformly distributed load and cantilever beam with non-uniformly distributed load. The results show that maximum thrust can be achieved with the pitching axis at the trailing edge, but the highest propulsive efficiency can be achieved with the pitching axis either 1/3 of the chord length from the leading edge in modified Bose mode, or 2/3 of the chord length from the leading edge in cantilever beam mode. At the same time, the effects of the Strouhal number and maximal attack angle on the hydrodynamics performance of the flexible fin were analyzed. Parameter interval of the maximum thrust coefficient and the highest propulsive efficiency were gained. If the Strouhal number is low, high propulsive efficiency can be achieved at low $\alpha_{\max}$, and vice versa.

Keywords: flexible fin; pitching axis; Strouhal number; maximal attack angle; propulsive performance
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1 Introduction

Fish possesses different kinetic and deflexion modes during starting, accelerating and turning, after which the instantaneous morphology will produce distinct effects on the hydrodynamic performance. Consequently, the locomotion of flexible fin and its characteristics of flow field play an important role in the field of bionic propulsion hydromechanics.

Academician Tong Bing gang[1-2] had introduced the development of the observation on swimming biomechanics numerical calculation, including two-dimension numerical computation and analysis of the theoretical model toward model of fast C-start, European eel inverse swimming and S-start of northern pike. Wu[3] and Zhang Cheng et al[4] studied the thrust coefficients, propulsive efficiency and the pattern of wake vortex sheet for a two-dimensional flow around a waving plate by using a two-dimensional waving plate theory. Bose[5] established the chord deflexion equation of two-dimensional flexible fin (Bose mode) and gave the flexibility state corresponding to the highest propulsive efficiency. Su[6], Cheng[7] analyzed the unsteady hydrodynamic characteristic about flexible fin and rigid fin of tuna by using three-dimensional panel method. Zhang et al. and Wang[8] studied the hydrodynamics performance of two-dimensional, three-dimensional rigid and flexible fin in viscous flow field, and investigated the effect of instantaneous angle of attack and flexibility of foil on the performance of propulsion. In addition, Li et al[9] investigated the force characteristics and vortex shedding of the foil in shear flows, analyzed the effect of the oscillating frequency and amplitude on the vortex shedding and force behavior. Deng[10] studied the propulsive performance of fish-like swimming foils by using the immersed-boundary method. Miao[11] investigated the unsteady flow field characteristic of chordwise flexible airfoil by using dynamic mesh technology. A non-conventional method was considered to model the flexibility of the fins of stingray by Zhang[12], and pressure contours with different undulating modes were presented which can be criterion for the design of bio-robotic underwater propulsor.

The references present that the flexible deformation of fins and kinematic parameters have notable influence on their propulsive performance. So this paper studies the effect on hydrodynamic performance of two-dimensional flexible fins concerning the position of the pitching axis, Strouhal number and the maximal attack angle $\alpha_{\max}$ with three deflexion modes by using FLUENT.

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2 Computation model for 2-D flexible fin

2.1 The governing equations and numerical methods

Continuous equation and RANS equation are chosen as the governing equations of two-dimensional flexible fin:

$$\frac{\partial u_i}{\partial x_i} = 0,$$

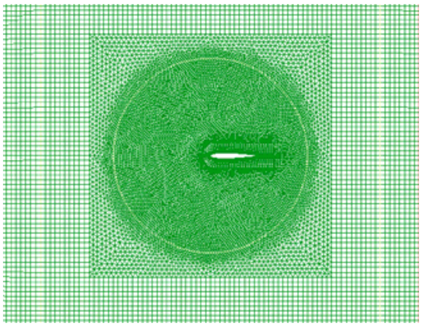
$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[(\gamma + \gamma_t)(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})],$$

where $u_i (i = 1,2)$ is fluid velocity, $x_i (i = 1,2)$ is space coordinate, p is fluid pressure, t denotes time, γ is kinematics viscosity coefficient; $\gamma_t = c_\mu k^2 / \varepsilon$ is turbulent viscosity coefficient which is obtained by solving SST *k–w* turbulence model, *k* denotes turbulent kinetic energy, ε denotes turbulent dissipation rate, c_μ is constant.

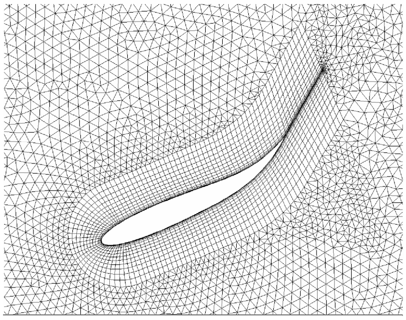
Solve the governing equations based on finite volume methods; QUICK scheme, which has 3rd accurate, is applied in discretion of diffusion and convection terms; PISO type is employed for velocity-pressure coupling. In addition, dynamic meshes are adopted to solve moving motions and deformable simulation of caudal fin.

2.2 Calculated domain and grid generation

Select the calculated domain 10c×22c, where c is chord length of fin. Hybrid mesh system is adopted for grid generation just as shown in Fig.1(a). To ensure the qualities of grid which is close to the fin boundary, refined structured grids are adopted around the fin surface, which also synchronously move and deform, followed with the flexible fin, as shown in Fig.1(b). For boundary condition, the left, upper and lower boundaries are defined as velocity inlet while the right boundary is defined as pressure outlet.



(a) Calculated domain



(b) Diagram of dynamic mesh

Fig.1 Calculated domain and grid generations

2.3 Kinematics and deformable model for 2-D flexible fin

The major parameters describing the locomotion of flexible fin are as follows: chord length *c*; the distance between the pitching axis and leading edge *b*; the heaving amplitude of fin y_0; the pitching angle of fin θ_0 and advance speed *U*.

Assuming the locomotion is simple harmonic motion (SHM). In that case, the heaving location *y*(*t*) and angle of pitch $\theta(t)$ are defined as follows:

$$\begin{cases} y(t) = y_0 \cos(\omega t), \\ \theta(t) = \theta_0 \cos(\omega t + \varphi), \end{cases}$$

where φ is the phase angle between pitching and heaving. As shown in Fig.2(a), the value of φ is 90 degrees. ω is the oscillating round frequency.

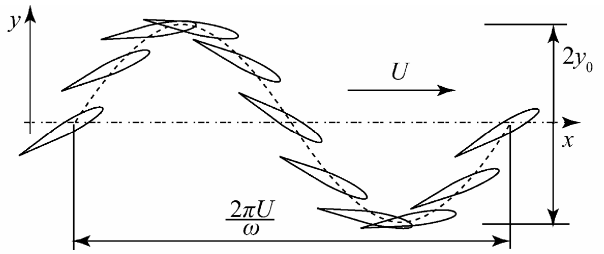
The relative attack angle of oscillating fin has a great effect on the hydrodynamic performance. The attack angle shown in Fig.2(b) is defined as the angle between instantaneous relative flow speed and chordwise direction of fin.

$$\alpha(t) = \theta(t) - \arctan\left(\frac{\dot{y}}{U}\right)$$

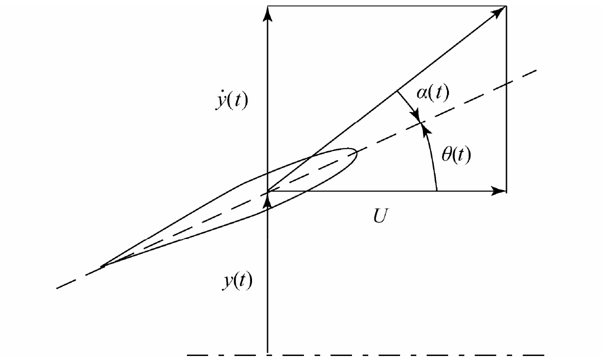
For the fin with SHM, when $\varphi = 90^\circ$, the instantaneous attack angle is

$$\alpha(t) = \arctan\left(\frac{y_0 \omega \sin(\omega t)}{U}\right) - \theta_0 \sin(\omega t)$$

Strouhal number of oscillating fin $St = 2 y_0 f / U$, where *f* is oscillating frequency.



(a) Kinematic sketch of oscillating fin



(b) Relationship between oscillating angle and attack angle

Fig.2 Kinematics model of oscillating fin

Based on Bose[6] model, the deformable models for two-dimensional flexible fin are set up as modified Bose mode[MBM], cantilever beam with uniformly distributed load[CBULM], cantilever beam with no-uniformly distributed load deformation mode [CBNULM] respectively. Equations are as follows:

$$y=\delta_c\left(\frac{x-s}{c-s}\right)^{\varepsilon+3}\cos(\omega t+\varphi),$$

where $0\le s<c$, $x\ge s$ [MBM]

$$y=\frac{1}{4}\delta_C\left(10\frac{(x-s)^2}{(c-s)^2}-10\frac{(x-s)^3}{(c-s)^3}+5\frac{(x-s)^4}{(c-s)^4}-\frac{(x-s)^5}{(c-s)^5}\right)\times\left|\frac{x-s}{c-s}\right|^{\varepsilon}\cos(wt+\varphi)$$

[CBULM]

$$y=\frac{1}{4}\delta_C\left(10\frac{(x-s)^2}{(c-s)^2}-10\frac{(x-s)^3}{(c-s)^3}+5\frac{(x-s)^4}{(c-s)^4}-\frac{(x-s)^5}{(c-s)^5}\right)\times\left|\frac{x-s}{c-s}\right|^{\varepsilon}\cos(wt+\varphi)$$

[CBNULM]

In the above equations, the amplitude of chordwise deformation $\delta_c=\delta\times c$, where δ is chordwise deformation coefficient, and c is chord length. s is the distance between leading edge along the chordwise and deflexion at the beginning, $0\le s<c$, $x\ge s$. ε is flexible power exponent, and when the value of ε is bigger, the deflexion near trailing edge is greater. Fig.3 is a diagram of the flexible oscillating fin.

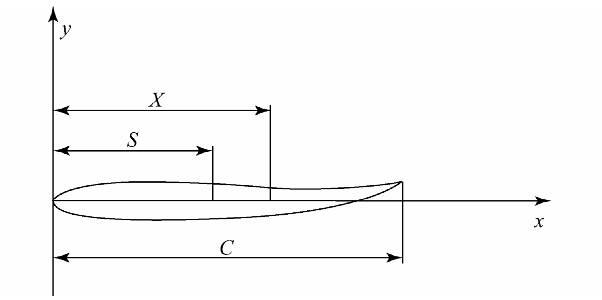


Fig.3 Flexible oscillating fin

2.4 Definition of propulsive parameters of oscillating caudal fin

As shown by Anderson et al[13] and Guglielmini[14], average thrust is defined as $\overline{F_x}=\frac{1}{T}\int_0^T X(t)\,\mathrm{d}t$, where $X(t)$ is instantaneous thrust along the forward direction, T is an oscillating cycle. Average thrust coefficient is defined as $C_t=2\overline{F_x}/\rho U^2 cb$, where c is chord length of fin, s is span length of fin and U is forward velocity. Propulsive efficiency is defined as $\eta=\frac{\overline{F_x}U}{P}$, where $P=\frac{1}{T}(\int_0^T Y(t)\frac{\mathrm{d}y}{\mathrm{d}t}\mathrm{d}t+\int_0^T M(t)\frac{\mathrm{d}\theta}{\mathrm{d}t}\mathrm{d}t)$ is average input power of oscillating fin, $Y(t)$ is instantaneous lift and $M(t)$ is instantaneous momentum.

3 Computational results

3.1 Effects of position of pitching axis on propulsive performance

In order to study the effect of the position of pitching axis on propulsive performance, the hydrodynamic coefficients of a NACA0012 flexible oscillating fin were calculated. The chord length $c=0.1$ m, the maximal attack angle $\alpha_{\max}=20^\circ$, the amplitude of heave $h_0=0.75c$, St=0.3, the forward velocity $U=0.4$ m/s. The flexible deformation modes are respectively modified Bose mode [MBM] ($\varepsilon=0$, $s=1/2c$, $\delta=0.1$), cantilever beam with even load deformation model [CBULM] and cantilever beam with uneven load deformable model[CBNULM] ($\varepsilon=0$, $s=0$, $\delta=0.1$). The distribution of the position of pitching axis exists at the leading edge of the flexible oscillating foil, one third of chord length from the leading edge, two thirds of chord length from the leading edge and the trailing edge, as shown in Fig.4.

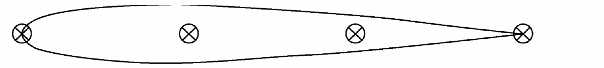


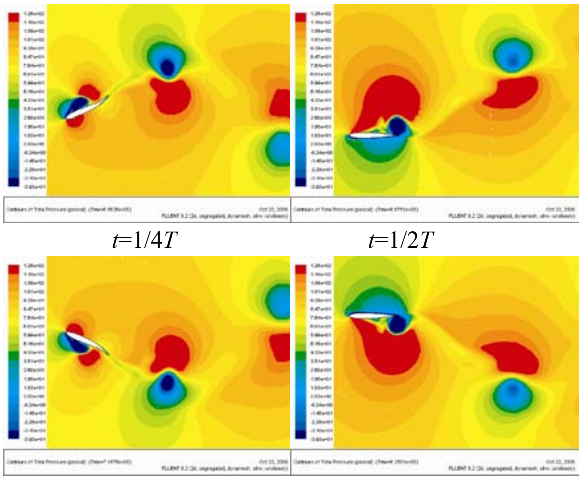
Fig.4 The position of axis of pitch of flexible oscillating foil

Table 1 Hydrodynamic coefficients under different positions of the axis of pitch

Position of pitching axis	Deformable equation	*Ct*	*η*
LE	MBM	0.2621	0.4447
1/3 chordal length from LE		0.2394	0.4994
2/3 chordal length from LE		0.2783	0.4433
TE		0.2729	0.3388
LE	CBULM	0.4210	0.5324
1/3 chordal length from LE		0.3418	0.5797
2/3 chordal length from LE		0.3440	0.5966
TE		0.4270	0.4784
LE	CBNULM	0.4285	0.5350
1/3 chordal length from LE		0.3459	0.5779
2/3 chordal length from LE		0.3433	0.6030
TE		0.4356	0.4851

Table 1 presents the hydrodynamic coefficients for three deformation modes under different positions of the pitching axis. It can be found that the position of the pitching axis greatly affects hydrodynamic coefficient. Take modified Bose mode as an example, while the pitching axis moves from trailing edge to 1/3 chord length from the leading edge, the propulsive efficiency of oscillating fin can be increased by 47.4%, the thrust coefficient decreased by 12.3%. So the propulsive efficiency can be improved by proper selection for pitching axis position. For flexible cantilever beam deformation mode, the highest propulsive efficiency occurs at the pitching axis lying at a place 2/3 chord length away from the leading edge.

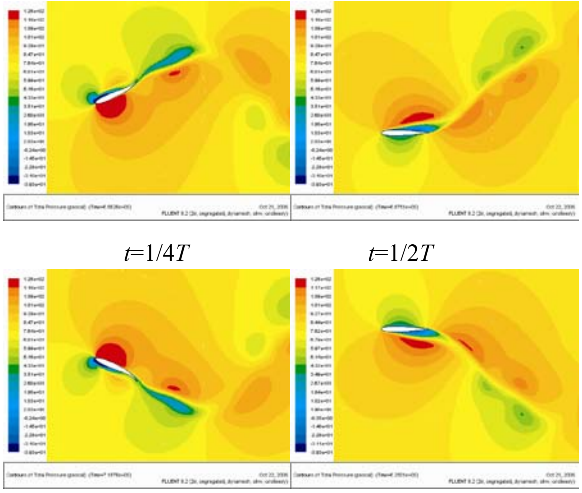
Fig.5 shows the contours of pressure as the pitching axis is located at the trailing edge and 1/3 chord length away from the leading edge under the modified Bose mode. During one quarter of a period, a low-pressure center exists on the upper surface of the leading edge of flexible oscillating fin, and then the center gradually moves backwards and sheds off in the end. That is to say, the lift is positive when the flexible fin oscillates downwards. However, when pitching axis is 1/3 chord length away from the leading edge, the intensity in this center will be much lower than that when pitching axis is at trailing edge. Namely, the drag of oscillating fin is much lower. So, the propulsive efficiency is the highest as the pitching axis locates 1/3 chord length away from the leading edge. However, the intensity of reverse Karman Vortex Street is enhanced greatly as the pitching axis is located at trailing edge. That is to say, the velocity backwards rooted in oscillating fin is faster. So, the thrust of oscillating fin is greater when the pitching axis is located at trailing edge.



t=1/4T t=1/2T

t=3/4T t=T

(a) The pitching axis at trailing edge



t=1/4T t=1/2T

t=3/4T t=T

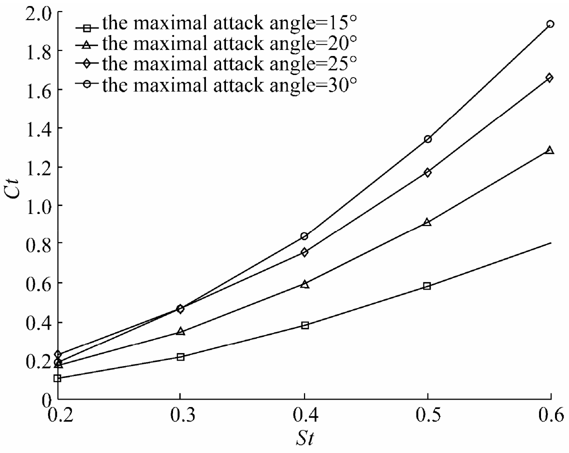
(b) 1/3 chord length from the leading edge

Fig.5 Contours of pressure adopted modified Bose mode

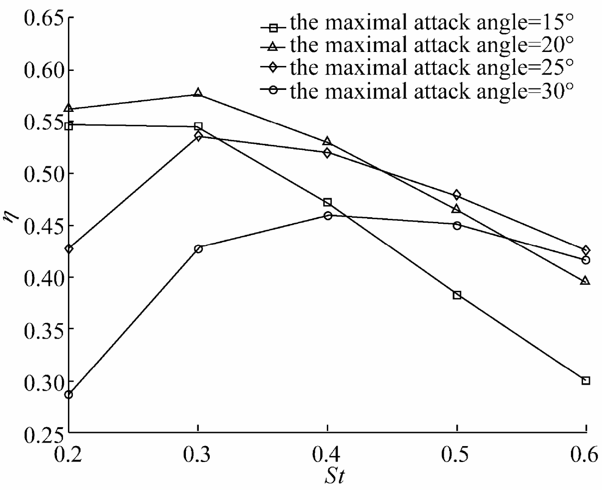
3.2 Effects of Strouhal number on the propulsive performance of flexible fin

To study the effects of Strouhal number on the propulsive performance of flexible fin, the hydrodynamic coefficient of flexible oscillating fin which is introduced of NACA0012 mode is calculated: the chord length $c = 0.1\text{m}$, the amplitude of heave $h_0 = 0.75c$, the velocity of incoming flow $U = 0.4\text{m/s}$. Chordwise deformable equation adopts cantilever beam with uniformly distributed load as the pitching axis is located at 1/3 chord length away from the leading edge, and, $\varepsilon = 0$, $\delta = 0.1$, $s = 0$.

Fig.6 presents the curves of hydrodynamic coefficients of flexible fin as function of the Srouhal number for the different maximal attack angles. It is found that the thrust coefficient is rising with the accretion of Strouhal number, and this trend ascends obviously with the increase of the maximal attack angle. There is a region of Strouhal number which denotes the highest efficiency and gentle change according to the propulsive efficiency of the flexible fin. When the maximum attack angle is 30 degree, and Strouhal number ranges within [0.3, 0.5], the propulsive efficiency is the highest. The span and value of *St* are both little when the maximum attack angle is small. Fig.6 shows the contours of total pressure at four different moments during a running period of the flexible fin. The low-pressure center is just opposite on the surface of oscillating hydrofoil as *St* number is respectively equal to 0.3 and 0.6 when the hydrofoil respectively locates 1/2*T* and *T*. When *St* = 0.3, the force acting on the surface of fin promotes its oscillating locomotion during some intervals in a period. So, the propulsive efficiency is much higher. But from the wake flow field of two foils, it is observed that the wake vortices shedding is more rapid and the total pressure under the width of reverse Karman Vortex Street is higher as $St = 0.6$, which means the velocity of jet is faster, the propulsive coefficient of oscillating fin as $St = 0.6$ is much higher than that is as $St = 0.3$.

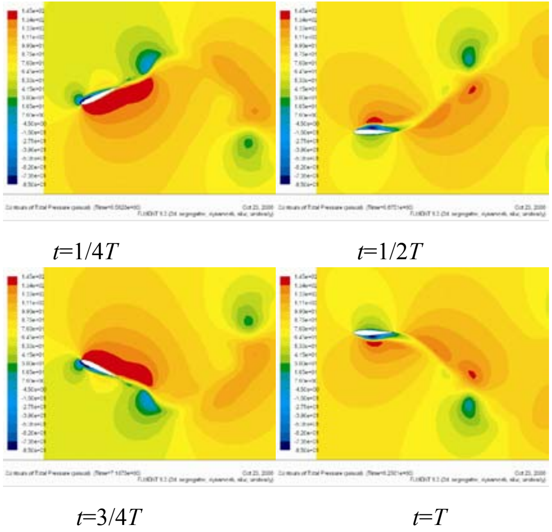


(a) Curves of thrust coefficient



(b) Curves of propulsive efficiency

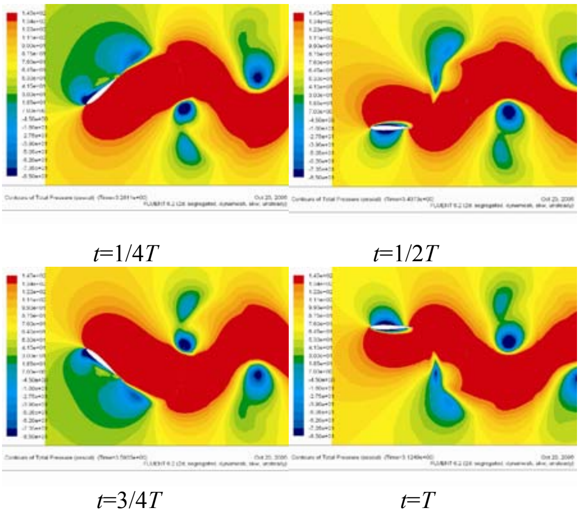
Fig.6 curves of hydrodynamic coefficients as function of the Strouhal number for the different maximal attack angles



t=1/4*T* *t*=1/2*T*

t=3/4*T* *t*=*T*

(a) $\alpha_{\max} = 25^{\circ}$, $St = 0.3$



t=1/4*T* *t*=1/2*T*

t=3/4*T* *t*=*T*

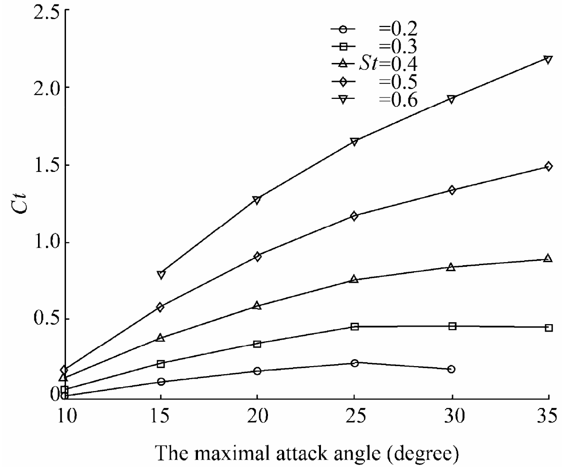
(b) $\alpha_{\max} = 25^{\circ}$, $St = 0.6$

Fig.7 Contours of total pressure during a running period of the flexible fin

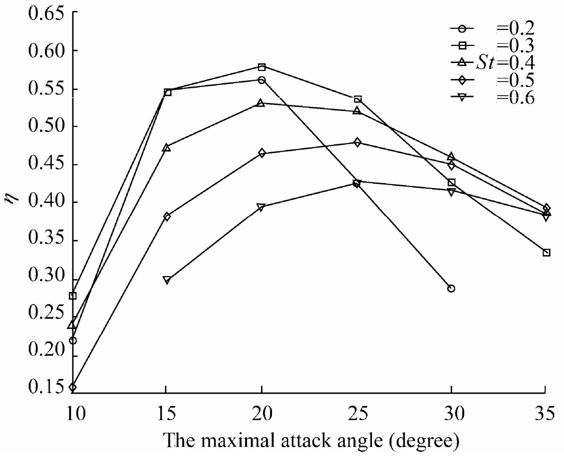
3.3 Effect of maximal attack angle on the propulsive efficiency of flexible oscillating fin

When analyzing the hydrodynamic performance, it is not comprehensive enough to regard the pitching amplitude as the object to study the hydrodynamic performance of oscillating fin solely, and the maximal attack angle $\alpha_{\max}$ for oscillating foil produces much immediate impact. So the hydrodynamic performance under diverse maximal attack angle is calculated in this paper. The heave amplitude $h_0 = 0.75c$, the velocity of incoming flow $U = 0.4$ m/s, chord deformable equation adopts CBULM when the pitching axis locates at 1/3 chord length from the leading edge, among which, $\varepsilon = 0$, $\delta = 0.1$, $s = 0$.

Fig.8 shows the curves of the hydrodynamic coefficients of flexible fin as function of the maximal attack angle $\alpha_{\max}$ for the different *St* numbers. It is observed that the propulsive coefficient is rising with the accretion of maximal attack angle $\alpha_{\max}$, but the trend keeps steady and then decreases slowly as the maximal attack angle reaches a stated peak value which is observably found as $St = 0.2$. For flexible oscillating fin, the greater *St* is, the more enormous the maximum attack angle is corresponding to the peak value of the propulsive coefficient. Thrust is improved at the same time with the range extension of the valid attack angle. An efficient and gently changing space interval for flexible oscillating foil exists, which can be found from the curve of the propulsive efficiency. The bound is $\left[20^\circ - 30^\circ\right]$ as $St = 0.6$, and $\left[15^\circ - 20^\circ\right]$ as $St = 0.2$. That is the highest propulsive efficiency of low *St* appearing at low $\alpha_{\max}$. But the highest propulsive efficiency of high St is lower than that of the low *St*.



(a) Curves of propulsion coefficient



(b) Curve of thrust efficiency

Fig.8 curves of the hydrodynamic coefficients as function of the maximal attack angle $\alpha_{\max}$ number for the different *St* numbers

4 Conclusions

The propulsive performance of two-dimensional flexible oscillating fin by three deformation modes are computed and analyzed in this paper. The effect of some parameters such as positions of pitching axis, *St* number and maximal angle of attack on the hydrodynamic performance is discussed. For the modified Bose mode[MBM], the highest propulsive efficiency can be achieved when pitching axis is 1/3 chord length away from leading edge, and when pitching axis is at trailing edge the most thrust can be gained. In addition, *St* number and maximal angle of attack have great influence on thrust and propulsive efficiency for flexible oscillating fin. The results show that the highest propulsive efficiency of low *St* number occurs when angle of attack is low, and vice versa. The highest propulsive efficiency according to high *St* is lower than that when *St* is low.

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不同纵摇轴位置下的二维柔性鳍推进性能与流场特性研究

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摘　要：利用 FLUENT 软件数值计算了二维柔性鳍作升沉纵摇运动时的推力系数及推进效率，探讨了修正 Bose 变形方程、均匀载荷和非均匀载荷悬臂梁变形方程等三种柔性模式下纵摇轴位置对摆动鳍推进性能的影响，其中纵摇轴在尾缘处能够获得更大的推力，而最高的推进效率分别对应修正 Bose 模式下纵摇轴距首缘 1/3 弦长处和悬臂梁柔性变形模型下纵摇轴距首缘 2/3 弦长处．同时计算分析了斯特劳哈尔数、最大攻角等参数对柔性鳍水动力性能的影响，建立了最大推力系数和最高推进效率所对应的参数区间，其中低 St 数的最高推进效率发生在低 $\alpha_{\max}$，高 St 数的最高推进效率发生在高 $\alpha_{\max}$．

关键词：柔性鳍；纵摇轴；斯特劳哈尔数；最大攻角；推进性能