Effect of Chord-wise Flexibility to the Power Extracting Efficiency of Tidal Current energy

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***Abstract*—Based on the bionics principle, this paper studies the influence of chord-wise flexibility on the energy extraction efficiency of the oscillating wing in turbulent environment. The energy acquisition performance of flexible oscillating hydrofoils with chord-wise deformation and rigid oscillating hydrofoils are numerically calculated by using computational fluid dynamics software Fluent. The power of hydrofoil with different flexibility coefficient and maximum offset at trailing edge under different conversion frequencies are compared. The differences between the rigid wing and the flexible wing are analysed from the lift coefficient, momentum coefficient, energy extraction efficiency, streamline and hydrofoil surface pressure composite diagram. The results show that the flexible hydrofoil can change the direction of partial streamlines, increase the hydrofoil surface pressure difference and enhance the instantaneous lift force in a single period, thus improving the energy efficiency of the hydrofoil.**

Keywords: oscillating hydrofoil, computational fluid dynamics, power-extraction efficiency, chord-wise flexibility, numerical analysis

I. INTRODUCTION

The ocean covers about 70% of the earth's total area, and contains rich sources of renewable energy. As a typical renewable energy source，the prospect of tidal current energy is becoming more and more attractive. In recent years, compared to the traditional rotating-axis tidal current turbine, a new type of oscillating-wing turbine has been proposed and studied. In 1981, Toronto University, McKinney and DeLaurier pioneered the study of oscillatory wings to extract power from a fluid flow[1]. Subsequently, Young J[2], Platzer M[3], Xiao Q[4] studied various parameters affecting hydrofoil motion and obtained the optimal parameter range. At the Laval university, Kinsey and Dumas used computational fluid dynamics software Fluent to calculate the energy extraction performance of the oscillating hydrofoil[5-7]. A series of experiment has been carried out on the oscillating hydrofoil. With the aid of experimental and simulation work, they verified the feasibility of using oscillating hydrofoils to extract tidal current energy. At Harbin engineering university, Xu and Sun also conducted simulation analysis of the oscillating-wing turbine and experimental verification [8-9]. In summary, using the oscillating wing to obtain the tidal current energy has good prospects.

The above studies on the oscillating hydrofoil tidal energy current concentrate on the rigid wing, and doesn't consider that the hydrofoil may be deformed due to the effect of fluid loading when it is moving in flow field. In nature, the fish's fins and insect wings are all flexible and will produce flexible deformation during flapping. Zhu conducted numerical simulations of flexible wings under different fluid densities[10]. The results show that the flexible wing can improve the propulsion efficiency of the wing. In the high-density fluid environment similar to water, the chord-wise deformation of the wing is the main factor to increase the propulsion efficiency of the wing. Bose assumed that the chordwise deformation of the flexible hydrofoil only occurred in the latter half, and proposed the optimal deformation mode with a chord length of 1 meter, which had a good effect on the hydrofoil propulsion efficiency[11]. Since the principle of the bionic propulsion is similar to the energy extraction, the flexible hydrofoil can be applied to the study of the oscillation hydrofoil tide current energy extraction to improve the energy harvesting efficiency. Siala [12], Liu [13], Wu [14], Tuyen Quang Le [15] carried out some simulation studies on flexible hydrofoil energy extraction and verified the feasibility of flexible foil.

Due to the research on the passive flexible hydrofoil energy extraction is too complex. In this paper, we simplify the method based on previous research, define two key factors:

the flexible coefficient and the trailing edge deformation, optimize Bose's deformation equation, and use the method of defining the deformation mode of the flexible hydrofoil for simulation study. Finally, we verify the rationality of the flexible hydrofoil to improve the efficiency of energy acquisition and study its impact mechanism.

II. PROBLEM DESCRIPTION

In this paper, computations are conducted for a foil by using commercial CFD software ANSYS Fluent. The finite volume method is used to discretize the fluid domain and establish the corresponding algebraic equations on the nodes of the discrete area. Fluid analysis is performed by solving the equations. The gambit software is used to perform hydrofoil geometry modeling, divide fluid domain, and determine boundary conditions. Hydrofoil moves in unsteady flow turbulent fields. The surrounding fluid can be used as a uniform incompressible constant viscosity fluid $\nabla \bullet u = 0$ and there is no heat transfer in the fluid domain. The numerical analysis of hydrofoil energy acquisition performance needs to follow the continuity equation and momentum conservation equation. The differential form of the continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} = 0 \tag{1}$$

ρ---- Inflow fluid density kg/m^3

u_x----Inflow direction speed m/s

v_y----Hydrofoil vertical speed m/s

t----time s

The momentum conservation equation is also called the Navier-Stokes equation. The Navier-Stokes equations in the x and y directions are as follows:

$$\rho\left[\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + v_y \frac{\partial v_y}{\partial y}\right] = \rho f_x - \frac{\partial \rho}{\partial x} + \mu\left(\frac{\partial u_x^2}{\partial x^2} + \frac{\partial u_x^2}{\partial y^2}\right) \tag{2}$$

$$\rho\left[\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + v_y \frac{\partial v_y}{\partial y}\right] = \rho f_y - \frac{\partial \rho}{\partial y} + \mu\left(\frac{\partial v_y^2}{\partial x^2} + \frac{\partial v_y^2}{\partial y^2}\right) \tag{3}$$

f_x---- Hydrofoil horizontal force N

f_y---- Hydrofoil vertical force N

μ---- Dynamic viscosity Pa s

In this paper, a NACA0015 foil is used as a two-dimensional model. The foil chord-length is c=0.22m. In order to simulate the hydrofoil energy acquisition process, in this paper, the oscillating hydrofoil motion in the fluid is considered to be combined with two kinds of motion: heave motion and pitch motion. The specific movement rules are as follows:

$$\begin{cases} h(t) = h_0 sin(2\pi ft + \varphi) \\ \theta(t) = \theta_0 sin(2\pi ft) \end{cases} \tag{4}$$

$h(t)$ and $\theta(t)$ represent the instantaneous position of the hydrofoil during oscillating motion.h_0 and θ_0 are the amplitude of heave and pitch.$\varphi$is the phase difference between the heave and pitch motion. According to the previous studies, the value is 90^0.f is the oscillation frequency of the hydrofoil. The foil pitches at 1/3 chord length from its leading edge. Bose improved hydrofoil propulsion efficiency by studying hydrofoil flexure deformation. Assume that the chord-wise deformation of the hydrofoil only occurs in the second half, the chord-wise deformation equation is as follows:

$$y = 8\delta(x - 0.5)^3 \cos(\omega t + \varphi), x \geq 1/2 \tag{5}$$

Considering that the principle of bionic propulsion is similar to the energy acquisition, the deformation equation is modified to study the mechanism of flexible hydrofoil effect on energy harvesting efficiency. After optimizing the Bose's equation, the new deformation equation can be drawn as follows:

$$\mathrm{y} = \delta_c \frac{x^n}{(c - x_c)^n} sin(2\pi ft) \tag{6}$$

x_c is the starting position of the deformation. In this paper, the hydrofoil deforms from the position of the pitch axis to the trailing edge and the leading edge to the position of the pitch axis is not deformed. So the final deformation equation is as follows:

$$\mathrm{y} = \delta_c \frac{x^n}{(2c/3)^n} sin(2\pi ft), 0 \leq x \leq \frac{2c}{3} \tag{7}$$

δ_c refers to the maximum chord-wise offset at the trailing edge of the flexible hydrofoil. For rigid hydrofoil, δ_c=0. f is the same frequency as the oscillation frequency. c is the chord-length of the foil. n is the flexible coefficient. For rigid hydrofoil, n=1. The hydrofoil control model is shown in Fig.1.

In this paper, the dimensionless reduced frequency f^*, which affects the hydrodynamic performance of the hydrofoil in the fluid, can be defined as (8).

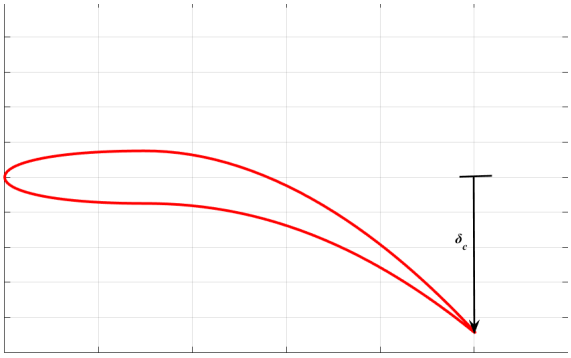


Fig. 1 trailing edge control model

$$f^* = \frac{fc}{u_\infty} \tag{8}$$

The computational domain and mesh is shown in Fig. 2. The fluid area is divided into non-structural meshes. The pitching axis is located at the origin of the coordinates, 35*c* (foil chord) away from the inlet boundary, 40*c* away from the outlet boundary and 35*c* away from the symmetric boundary. A uniform constant velocity in *x* direction is applied as the incoming flow.

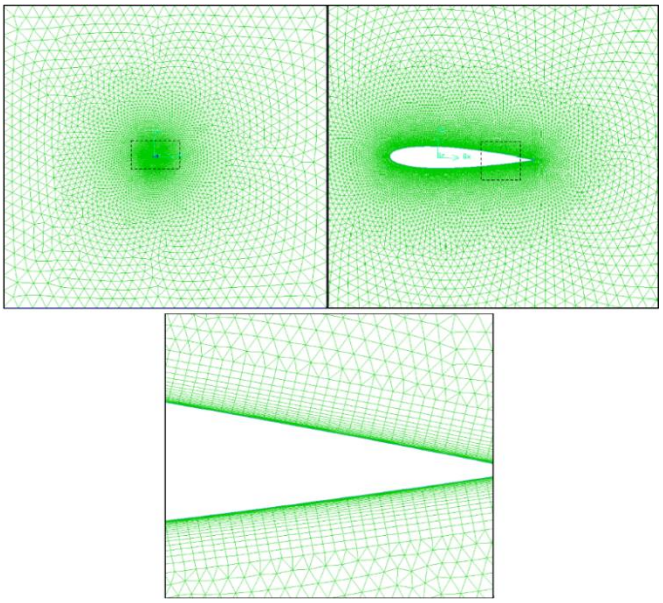


Fig. 2 Computational domain and mesh distribution

III. PARAMETERS OF ENERGY EXTRACTION

Hydrofoil performs heave and pitch motion in the fluid to achieve energy extraction. To quantify the energy output, the instantaneous power *P(t)* is defined as:

$$P(t) = P_y(t) + P_\theta(t) = F_y(t)V_y(t) + M(t)\omega(t) \tag{9}$$

$P_y(t)$ represents the contribution to energy extraction from the heave movement, and $P_\theta(t)$ is the power gained during pitching. $F_y(t)$ is the force component in *y* direction, and *M(t)* is the pitching moment. The average power $\bar{P}$ can be calculated by integrating the instantaneous power *P(t)* in one oscillation cycle as:

$$\bar{P} = \frac{1}{T}\int_t^{t+T} P(t)\,dt \tag{10}$$

T is the oscillation period. In summary, the hydrofoil's instantaneous power coefficient can be defined as:

$$C_P(t) = \frac{P(t)}{0.5\rho U^3 c} = Cp_l(t) + Cp_m(t) = \frac{1}{U_\infty}\left(C_L(t)V_y(t) + cC_M(t)\omega(t)\right) \tag{11}$$

C_l *(t)* represents the instantaneous lift coefficient, and C_m *(t)* is the instantaneous momentum coefficient. They can be defined as:

$$C_l(t) = \frac{F_y(t)}{0.5\rho U_\infty^2 c} \tag{12}$$

$$C_m(t) = \frac{M(t)}{0.5\rho U_\infty^2 c^2} \tag{13}$$

After integrating the power coefficient C_P, the average power coefficient $\bar{C}_P$ can be defined as:

$$\bar{C}_P = \frac{1}{T}\int_t^{t+T} C_P(t)\,dt \tag{14}$$

The total energy extraction P_a from the uniform flow field is defined as:

$$P_a = 0.5\rho U^3 A \tag{15}$$

The efficiency η can reflect the ability of energy extraction, which is determined as follows:

$$\eta = \frac{\bar{P}}{P_a} = \bar{C}_P\frac{c}{A} \tag{16}$$

A is the sweeping height of the flapping foil in two-dimensional oscillatory motion.

IV. VALIDATION

The numerical simulation used in this paper needs to be compared with the results of [6]. The basic parameters of the simulation are set as shown in Table 1.

The non-dimensional oscillating frequency f^*=0.14. Heave and pitch movement can be seen from (4).

Table 1 Validate model parameters

hydrofoil	χ_P	$v(m^2/s)$	$\varphi(rad)$	$U_\infty(m/s)$
NACA0015	1/3c	10^{-6}	0.5π	2
	h_0	Re_c	$C(m)$	$\theta_0(°)$
	c	500000	0.25	75

The non-dimensional oscillating frequency f^*=0.14. Heave and pitch movement can be seen from (4). After five cycles of hydrofoil operation, the result of the sixth cycle is compared with the reference in Fig. 3.

The results of this paper and the [6] are as follows:

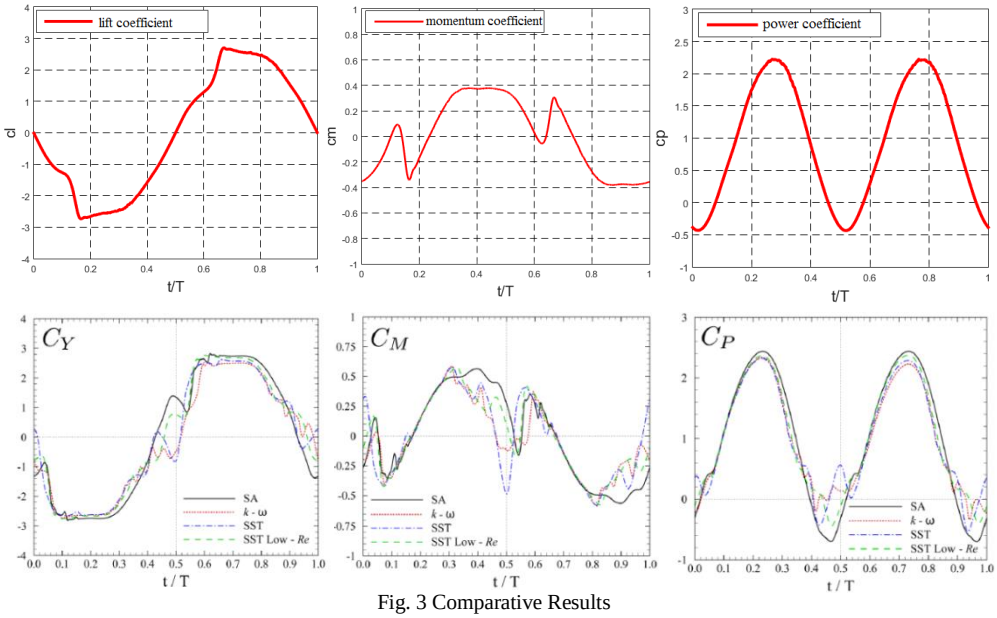


Fig. 3 Comparative Results

Table 2 Numerical simulation results and literature data comparison

Parameter	$\hat{C}m$	$\overline{C_d}$	$\hat{C}_l$
Literature results	0.565	1.757	2.819
Results of this article	0.3821	1.799	2.74
	$\eta\%$	$\overline{C_P}$	
	38.68	0.986	
	36.95	0.942	

Because of the differences in meshing and some parameter settings, the efficiency value of this paper is slightly lower than the reference. But seen from the Table 2 and Fig.3, our results are consistent with the result of [6]. This indicates that the reliability of the results in this paper is high, and this model can be used for the following numerical analysis of oscillatory hydrofoil energy extraction.

V. RESULTS AND DISCUSSIONS

In this section, we present our results about vortex shedding of rigid and flexible hydrofoil and distribution of surface pressure on hydrofoil, and discuss the influence mechanism of flexible hydrofoil on energy extraction efficiency.

A. Hydrofoil Output Efficiency

Fig.4 compares time-mean efficiencies at different flexible coefficient and reduced frequencies. Fig.5 compares time-mean efficiencies at different trailing edge deformation and reduced frequencies.

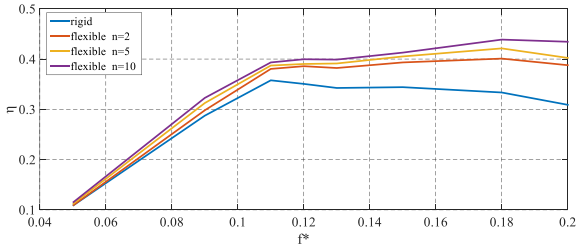


Fig. 4 Flexibility coefficient(n) effect on efficiency

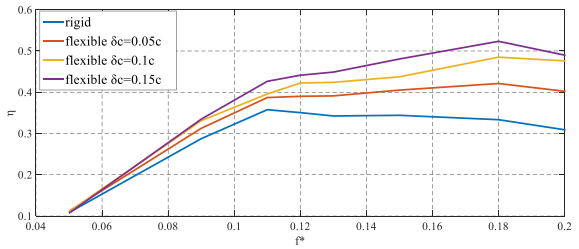
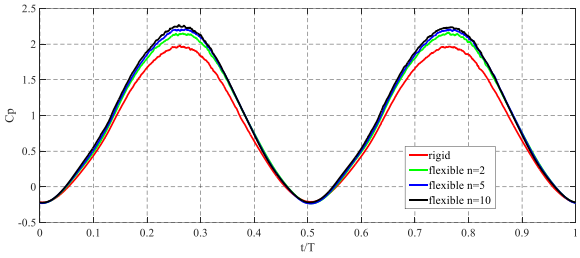


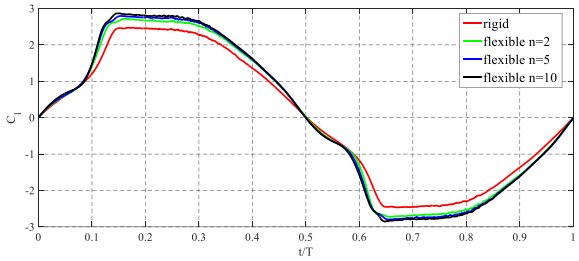
Fig. 5 Trailing edge deformation (δ_c) effect on efficiency

Clearly seen from Fig. 4 and Fig. 5, the energy extraction efficiency of the flexible hydrofoil is obviously higher than the rigid hydrofoil when the conversion frequency is high ($0.1<f^{*}<0.2$). In Fig.4, the efficiency is increased from 0.35 to 0.44 under the influence of the flexibility coefficient. In Fig.5, the efficiency is increased from 0.35 to 0.52 under the influence of the trailing edge deformation (δ_c).This shows that using suitable flexible hydrofoil to improve energy extraction efficiency is feasible.

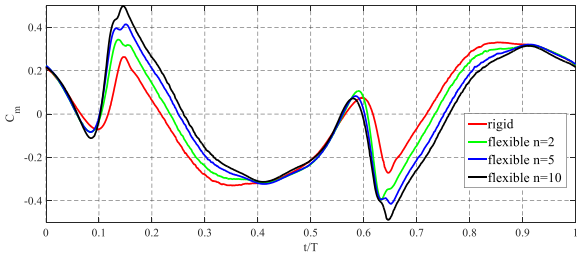
B. Instantaneous C_p, C_l and C_m



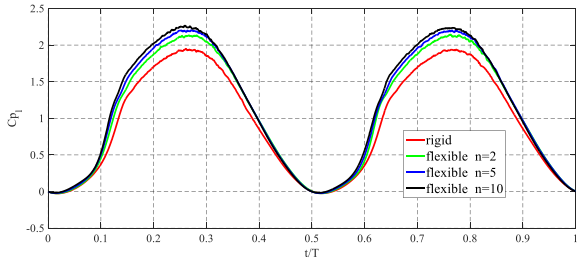
（a）*n* effect on C_P



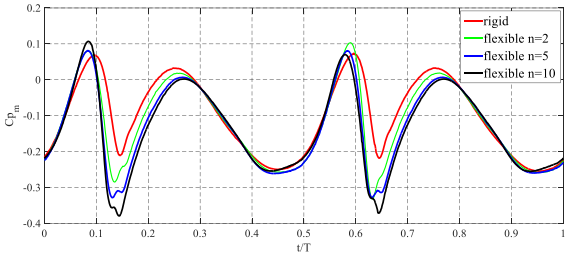
（b）*n* effect on C_l



（c）*n* effect on C_m

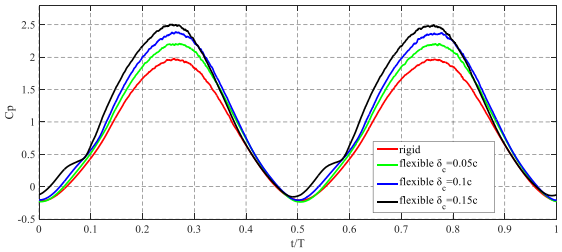


（d）*n* effect on Cp_l

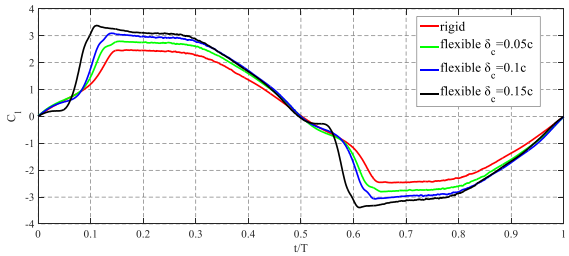


（e）*n* effect on Cp_m

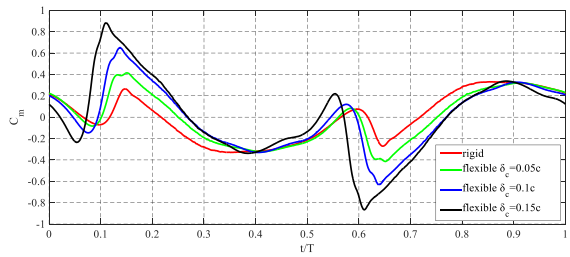
Fig. 6 compares different flexibility coefficient(n) hydrofoil for instantaneous total output power coefficient in (a), lift coefficient in (b), moment coefficient in (c), two power coefficient in (d) and (e).



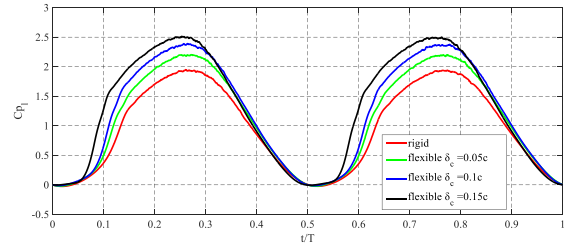
（a）δ_c effect on C_P



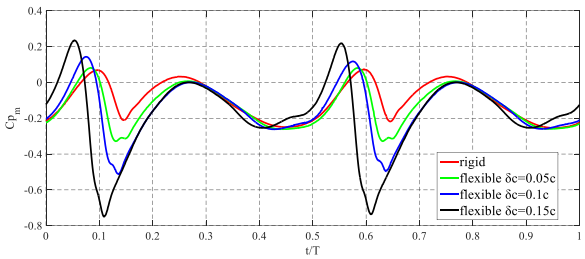
（b）δ_c effect on C_l



（c）δ_c effect on C_m



（d）δ_c effect on Cp_l



（e）δ_c effect on Cp_m

Fig.7 compares different Trailing edge deformation (δ_c) hydrofoil for instantaneous total output power coefficient in (a), lift coefficient in (b), moment coefficient in (c), two power coefficient in (d) and (e).

From Fig. 6 and Fig. 7, both peak C_l, and C_m increase by using the flexible foil. This leads to an increase of positive Cp_l, and a decrease of negative Cp_m. But it is clear that the peak Cp of a flexible foil is higher than a rigid one. As can be seen from the above, the flexible hydrofoil is mainly used to increase energy extraction power by increasing lift.

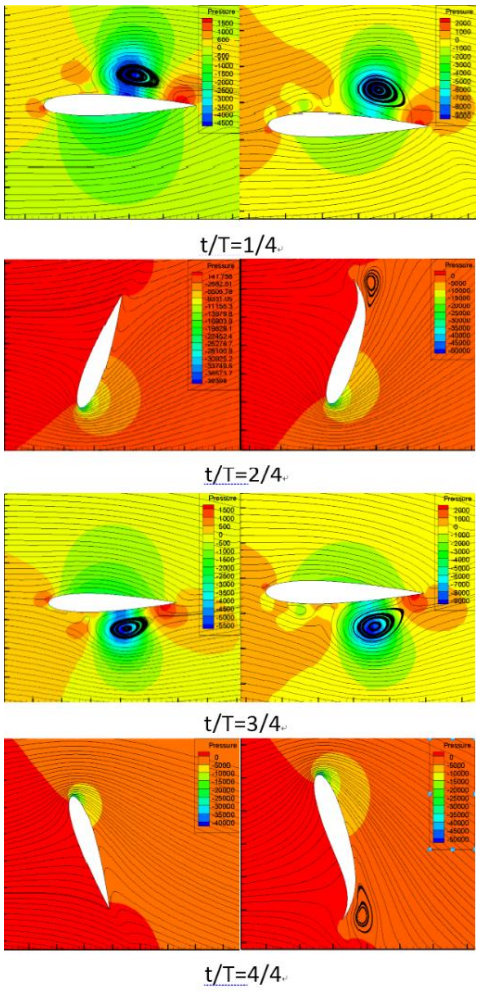


Fig. 8 Hydrofoil surface pressure and streamline

It can be seen from Fig.8 that the flexible hydrofoil changes the direction of partial streamlines. This affects the formation and shedding of vortices, and increases the hydrofoil surface pressure difference. All of above factors result in an increase of the instantaneous lift force for flexible foil. The increase in lift force eventually leads to higher efficiency for the flexible hydrofoil.

VI. CONCLUSIONS

In this paper, the numerical simulation of flexible hydrofoil based on chord-wise deformation is performed. The results show that chord-wise deformation affects the formation and shedding of the leading edge vortex, and increases the hydrofoil surface pressure difference. These factors increase the energy extraction efficiency of the hydrofoil. In summary, we can conclude that compared to a rigid hydrofoil, a flexible hydrofoil can obtain higher extraction energy efficiency, especially at high reduced frequencies.

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