

NUMERICAL STUDY INTO THE EFFECTS OF EFFECTIVE ANGLE OF ATTACK MOTIONS ON ENERGY EXTRACTION PERFORMANCE OF PARALLEL FOILS

by

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The effects of different effective angle of attack motions on flapping foil are considered. Energy extraction characteristics of parallel foils with combined plunging and pitching motions at multiple working conditions are systematically analyzed. The energy extraction processes of dual foil at different effective angle of attack motions and reduced frequencies are simulated, respectively. In the range of parameters discussed in this paper, the increase of K_e improves the energy extraction performance of foil effectively. Every effective angle of attack motion has a frequency which can obtain the optimal extraction performance. The optimal energy extraction working condition is $K_e = 2$ and $k = 0.8$, where the extraction efficiency of dual foil achieves 25.8%. The synchronicity of the aerodynamic lift and the plunging motion is increased with increase in K_e . This paper provides a significant reference to the further study and popularization in engineering practice of parallel foils energy extraction.

Key words: *parallel dual foil, energy extraction performance, oscillation motion, effective angle of attack, evolution of vorticity field*

Introduction

As a new energy extraction device proposed in recent years, the flapping foil can use the wind energy, the ocean energy, and other green energy to output power. Because of the structural particularity of flapping foil, they are able to be arranged at the complex terrain, such as the narrow waters, the shoal patch and so on. The available resources could be fully used by the flapping foil, and the global energy crisis and environmental pollution will be relieved. Therefore, the energy extraction mechanism, the aerodynamic characteristics, and the evolution of the flow field during the foil oscillation become the focus of current research. Use flapping foils in a reasonable and efficient way is the basics of the engineering application.

The concept that using the flapping foil to extract energy was firstly proposed by McKinney *et al.* [1]. They experimentally validated that the foil with combined plunging and pitching motions can extract the wind energy. Jones *et al.* [2] proved the correctness of the experiment data from McKinney *et al.* [1] by unsteady incompressible surface panel method. Considered the effects of the motion parameters, air-foil shapes and free stream velocity, some re-

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searchers [3-5] analyzed the extraction characteristics of foil with combined pitching and plunging motions by experiments and simulations. The main factors and evolution law of energy extraction performance are obtained. Sitorus *et al.* [6] designed and established the foil energy extraction experiment table firstly. Then they simulated oscillation processes in the experimental working conditions by 2-D numerical model. The results of experiments and simulations agree very well. The extraction efficiency can increase to 23.05%.

To further investigate the energy extraction mechanism of foils, researchers at home and abroad studied the influence of non-sinusoidal motions on extraction characteristics. Ashraf *et al.* [7] simulated the oscillation processes with sinusoidal motions and non-sinusoidal motions, which adopted the 2-D Navier-Stokes equations. It shows that the non-sinusoidal motions influence the vortex structures around the foil and the output power obviously. Platzer *et al.* [8-10] summarized the potential application directions and research status of the flapping foil, and proposed a foil device which extracting energy by non-sinusoidal combined motions. The power coefficient and efficiency in sinusoidal motions and non-sinusoidal motions were systematically analyzed. The evolution of the flow field in the oscillation process is observed. Xiao *et al.* [11, 12] discussed the extraction performance of various similar trapezoid non-sinusoidal motions by numerical method. It is found that the energy extraction rate and efficiency can be improved clearly by non-sinusoidal motions in a certain range of Strouhal number. The extraction efficiency in non-sinusoidal motion is improved by 50% than that of sinusoidal motion.

Applying the oscillating foil in engineering, the multi-foil arrangement which outputs power simultaneously is always adopted to increase the efficiency. To study the tandem structure with double row foil arrangement, Lindsey [13] and Jones [14] discussed the effects of the foil thickness and the effective angle of attack by simulation and experiment. It can be observed the thinner thickness and the higher effective angle of attack can bring the better extraction performance in high frequency and low amplitude. Some researchers [15-18] discussed the dual foil arrangement numerically and experimentally. They proved the extraction performance of dual foil is better than that of the single foil obviously. Because of the choking action from the up stream foil to the down stream foil, the energy extraction rate will effectively increase by controlling two foils motion reasonably. Karbasian *et al.* [19] developed a program to evaluate the energy extraction performance in different tandem foils arrangement. The extraction processes of multi-foil staggered structure were simulated by the program. It is observed that the multi-row tandem foils enlarge the output power clearly, but the increase is slight when the number of foils reaches the critical value. Karakas *et al.* [20] investigated the extraction performance and evolution of the flow field in different wall arrangement numerically and experimentally. The optimum extraction performance with the free stream and controlled stream was discussed. The results show the wall effect improves the efficiency when the motion is sinusoidal or approximately sinusoidal, and the wall effect limits the energy extraction when the motion is approximately square wave.

At present, research on tandem foils has begun to take shape. But the research on parallel foils is very limited. Investigating the effects of motion parameters and oscillation motions on output power at multi-foil arrangement has significant value on the engineering applications of foil device. In this paper, parallel dual foils with combined plunging and pitching motions are adopted as the object. Considering the effects of oscillation motions, the energy extraction processes of parallel dual foils with different effective angle of attack motions in various working conditions are simulated. The optimum frequencies in different motions and the influence of the effective angle of attack motion parameter on extraction performance are obtained. Furthermore, the effects of different motions on energy extraction rate and aerodynamic lift of the

plunging motion and pitching motion are studied. The evolution law of the vorticity in the flow field is observed.

Numerical method

Calculation model

The calculation model and parameters are shown in fig. 1. Two NACA0012 foils are arranged in parallel. The chord length c is 1 m, the minimum spacing between two pitching axes is called δ which is 1.2 m, and the phase difference between two foils motions is 180° . Based on the experimental validation of Wernert *et al.* [21], the non-uniformity of 2-D flow around the middle section of air-foil is less than 4%. So the 2-D model of middle section can meet the accuracy requirements. Therefore, the 2-D model is adopted in this paper.

Solver and dynamic mesh technique

In this paper, the commercial software FLUENT 16.0 is adopted to solve the unsteady incompressible viscous flow field at low Reynolds number. To discretize the transient term, the second-order-accurate backward implicit scheme is used. And the second order upwind type is adopted to discretize the spatial term. The moving trail of foil is controlled by the user defined function, which is compiled by the C language programming. Using the dynamic mesh technology guarantees the mesh quality during the pitching motion and plunging motion.

The numerical research at $Re = 2 \cdot 10^4$ and $H_0 = 0.175$ was studied by Heathcote *et al.* [22]. The results show that the thrust coefficient and efficiency calculated by laminar model agrees very well with the experimental data at the reduced frequency from 0 to 12.5. Ol *et al.* [23] analyzed the flow field structure at different Reynolds numbers and frequencies. The situation about different plunging and pitching motion frequencies was discussed. It shows that the Reynolds number has the slightest influence on the flow field structure and aerodynamic characteristics. Therefore, the laminar model is selected to simulate the energy extraction characteristics of parallel dual foil which flapping as combined plunging and pitching motions in this paper.

The calculation domain and boundary conditions of parallel foils are shown in fig. 2. The calculation domain includes the inner zone and the outer zone. The inner zone is a square whose side length is $10c$. The dynamic mesh technique adopted can realize the mesh movement during the flapping process. Bos *et al.* [24] found the influence of the far field boundary on the flow field around air-foils and aerodynamic characteristics can be ne-

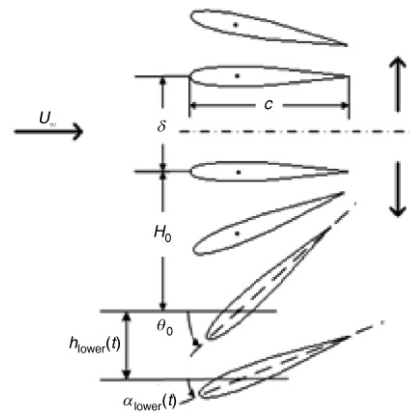


Figure 1. Sketch map of parallel dual foil arrangement and parameters

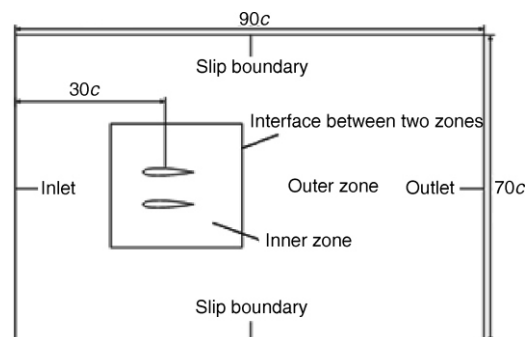


Figure 2. Sketch of the calculation domain and boundary conditions

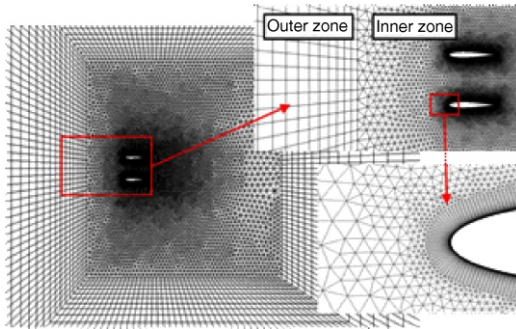


Figure 3. Mesh of calculation domain

glected if the outer zone boundary is at least $30c$ away from the foils surface. Therefore, the outer zone in this paper is setup as a rectangle whose side lengths are $70c$ and $90c$, respectively. As shown in fig. 3, the calculation domain uses the mixed type mesh. The outer zone and air-foil surface select the structure mesh, which is using the O-topology type. The part connected outer zone and air-foil surface is meshed by unstructured mesh. This kind of mesh can realize the dynamic change of mesh, and satisfied the computational accuracy. The angle of attack is 0° and the foil

surface has 500 nodes. The first row of mesh around the air-foil surface is $10^{-5}c$, y^+ is less than 1 in all working conditions, and the number of cells is $7.2 \cdot 10^4$.

The inlet of the calculation domain is set as free flow velocity, and U_∞ is 1 ms^{-1} . The outlet is set as the pressure outlet. The connection part of inner zone and outer zone is set as the interface of structured mesh and unstructured mesh. The foil surfaces adopt the no-slip boundary condition.

Kinematics

The dimensionless frequency, namely the reduced frequency, is adopted in this paper. It is defined:

$$k = \frac{2\pi fc}{U_\infty} \quad (1)$$

where f is frequency, c – the chord length of foil, and U_∞ is the free stream velocity.

The maximum effective angle of attack in the flapping motion is called the nominal angle of attack α_0 , which is defined:

$$\alpha_0 = \arctan \frac{2\pi f H_0 c}{U_\infty} + \theta_0 \quad (2)$$

where H_0 is the non-dimensional plunging amplitude and θ_0 – the pitching amplitude.

The different effective angle of attack motions can be realized by changing parameter K_e . The motions are described as eq. (3):

$$\alpha_e(t) = \begin{cases} \alpha_0 \sin^{-1} [K_e \sin(2\pi ft)] / \sin^{-1}(K_e) & 1 - K_e < 0 \\ \alpha_0 \sin(2\pi ft), & K_e = 0 \\ \alpha_0 \tanh[K_e \sin(2\pi ft)] / \tanh K_e, & K_e > 0 \end{cases} \quad (3)$$

The effects of different effective angle of attack motions on energy extraction performance are analyzed in this paper. The parameter K_e of effective angle of attack motion is selected as $-1, -0.8, 0, 1$, and 2 , respectively, to simulate the various flapping processes. The vari-

ation curves of five kinds of effective angle of attack motions are shown in fig. 4, and the reduced frequency k is 0.9.

The flapping foil motion in this paper is the plunging motion combined pitching motion. The plunging motion $h(t)$ adopts sinusoidal oscillation, and the different effective angle of attack motions are realized by pitching motion $\alpha(t)$. The plunging motion and pitching motion are defined:

$$\begin{aligned} h_{\text{upper}}(t) &= H_0 c \sin(2\pi f t - \varphi) \\ h_{\text{lower}}(t) &= H_0 c \sin(2\pi f t + \varphi) \end{aligned} \quad (4)$$

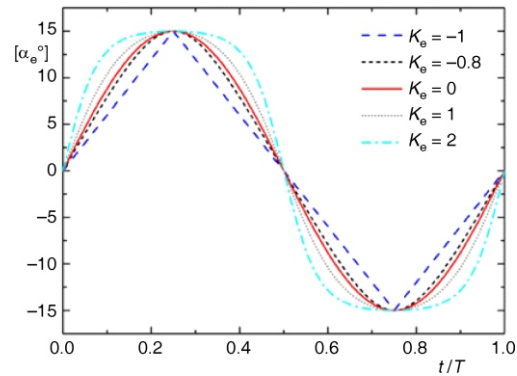


Figure 4. The variation curve of different effective angle of attack motions at $k = 0.9$

$$\alpha_{\text{upper}}(t) = [\alpha_e + \arctan(V_y(t)/U_\infty)] \quad \alpha_{\text{lower}}(t) = \alpha_e - \arctan(V_y(t)/U_\infty) \quad (5)$$

where φ is the phase difference between plunging and pitching motions.

Based on the parameter study of Kinsey *et al.* [4] about energy extraction performance of single foil, it is obtained that when the phase difference of plunging and pitching motion is 90° , the optimal extraction performance occurs at the pitching axis is 1/3 times chord length away from the leading edge. Accordingly, the pitching axis and the phase difference in this study are selected as same as Kinsey's research.

The energy extraction process is consisted of plunging motion and pitching motion. So the transient energy extraction power, P , is made up of the induced power of plunging and induced power of pitching, which defined:

$$P = F_y(t)V_y(t) + M(t)\omega(t) \quad (6)$$

where $F_y(t)$ is the aerodynamic lift in the Y direction, $M(t)$ – the torque around the pitching axis, and $\omega(t)$ – the pitching velocity of foil.

The non-dimensional energy extraction power coefficient C_p can be computed:

$$C_p = \frac{P}{\frac{1}{2}\rho U_\infty^3 c} \quad (7)$$

The average power coefficient C_{pm} in an oscillation cycle is described by eq. (8):

$$C_{pm} = C_{p_{hm}} + C_{p_{\theta m}} = \frac{1}{TU_\infty} \int_0^T [C_l(t)V_y(t) + C_m(t)\omega(t)]dt \quad (8)$$

The lift coefficient C_l and the torque coefficient C_m are defined:

$$C_l = \frac{F_y}{\frac{1}{2}\rho U_\infty^2 c} \quad (9)$$

$$C_m = \frac{M}{\frac{1}{2} \rho U_\infty^2 c^2} \quad (10)$$

The energy extraction efficiency, η , is defined as the ratio of the average extraction power of foil and the gross power in the air-foil's swept area, as eq. (11):

$$\eta = \frac{P_m}{\frac{1}{2} \rho U_\infty^3 A} = C_{Pm} \frac{c}{A} \quad (11)$$

where A is the swept area of flapping foil in vertical direction, A is $2H_0c$ based on Xiao's [12] research.

Validation studies

To validate the correctness of simulation, the grid independence and temporal independence validation of parallel dual foil with combined pitching and plunging motions at $Re = 1100$ are conducted. The validation working conduction is $k = 1$, $H_0 = 1$, $\theta_0 = 80^\circ$. Ten iterations are made for each calculation step. The average power coefficients and deviations at different grid numbers and time steps are listed in tab. 1. As shown in fig. 5, the curves of transient power coefficient

Table 1. Verification of the independence of grid and time step

Object	Grid numbers	Time step	C_{Pm}	Deviation [%]
Time step	$7.2 \cdot 10^4$	600	0.867	1.05
	$7.2 \cdot 10^4$	1200	0.858	—
	$7.2 \cdot 10^4$	2400	0.863	0.58
Grid numbers	$5.1 \cdot 10^4$	1200	0.872	1.63
	$7.2 \cdot 10^4$	1200	0.858	—
	$1.08 \cdot 10^5$	1200	0.860	0.23

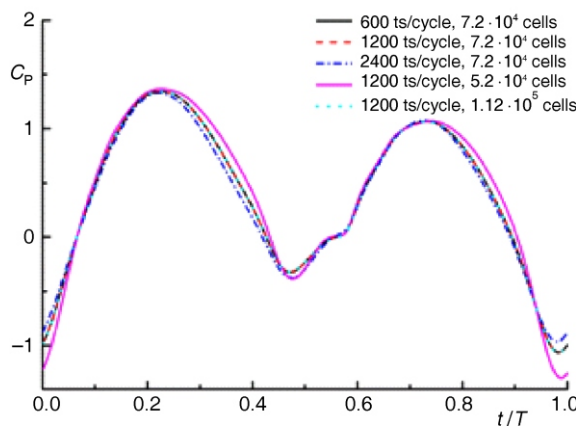


Figure 5. Variations of C_P with different time steps and grid numbers

in a cycle at different time steps (ts) and grid numbers are obtained. Obviously, the grid number of $7.2 \cdot 10^4$ cells and 1200 time steps per cycle are sufficient to the computational accuracy.

To ensure the correctness of numerical method, the thrust characteristics of single foil with plunging oscillation are numerical analyzed at $Re = 2 \cdot 10^4$, $H_0 = 0.175$. The variation curves of average thrust coefficient C_{Tm} is shown in fig. 6. The curves show that the simulation results in this paper agree very well with the numerical results of Young *et al.* [25] and the experimental data of Heathcote *et al.* [26]. As a result, the numerical method adopted in this paper is feasible.

Results and discussion

Power coefficient and efficiency

The effects of different effective angle of attack motions on parallel dual foil oscillations are concerned. The energy extraction processes of foils at various working conditions with different K_e are numerically simulated. For the convenience of study, we choose the Reynolds number is 1100, the non-dimensional plunging amplitude H_0 is 1, and the nominal angle of attack α_0 is 15° . The reduced frequency studied in this paper is from 0.7 to 1.1. As shown in fig. 7, the variations of average power coefficient and extraction efficiency with k at different K_e . With the increasing K_e from the negative to the positive, C_{pm} increases obviously in general. It means better energy extraction performance can be obtained when the motion is closer to the square wave. At different K_e , C_{pm} increases at first and then decreases with the increasing k . Therefore, every motion we discussed has an optimal reduced frequency which can get the maximum energy extraction rate. The optimal energy extraction performance occurs at $k = 0.9$ when $K_e = 0$. And when $K_e > 0$, the optimal energy extraction performance is observed at $k = 0.8$. From the figure, it can be found that C_{pm} decreases obviously at high frequency. It is because the pitching velocity is relatively high at high frequency. So the energy expenditure is larger during the high speed pitching process near the limit plunging position, and the output average power decreases clearly.

As shown in fig. 7, the variation law of extraction efficiency η is same as that of C_{pm} . When K_e is 2, the extraction efficiencies at most frequencies are the optimum at the corresponding frequency, except the high frequency conditions. The efficiency η achieves 25.8% at $k = 0.8$, which is the optimal efficiency in all working conditions we studied.

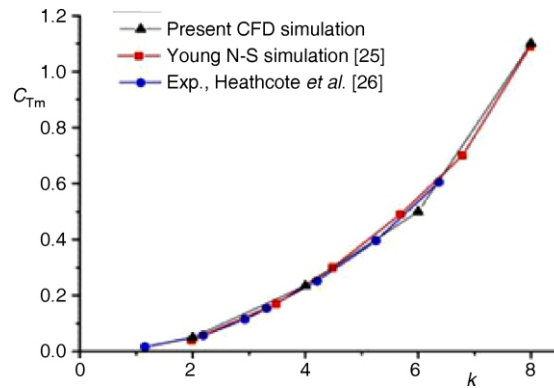


Figure 6. Variation of C_{Tm} with k at $Re = 2 \cdot 10^4$, $H_0 = 0.175$

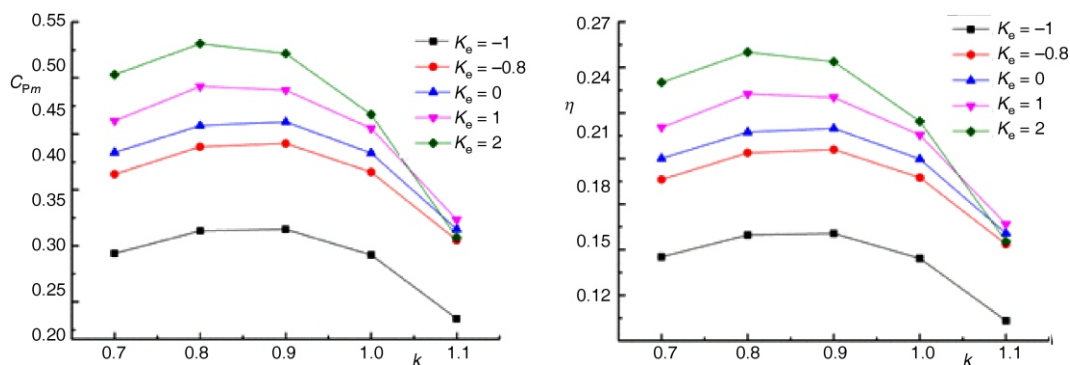


Figure 7. Variation of C_{Pm} and η with reduced frequency at different K_e

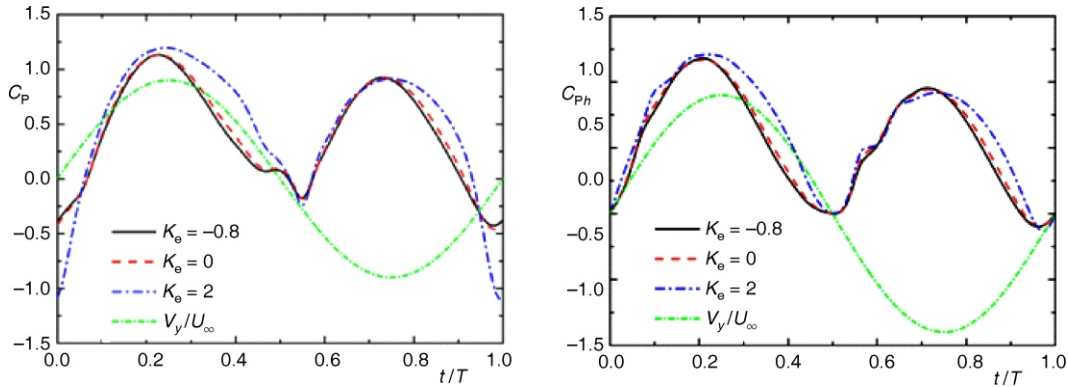


Figure 8. Variations of C_p and C_{ph} in a cycle with $k = 0.9$ at different K_e

In this study, the parallel foils complete the oscillation process by combined plunging motion and pitching motion. Figure 8 shows the variation of the total power coefficient C_p and the plunging induced power coefficient C_{ph} at $K_e = -0.8, 0, 2$ when $k = 0.9$. It can be observed that the tendencies of C_p and C_{ph} are similar. The peak values of C_p at up stroke and down stroke are basically same as those of C_{ph} respectively. They appear when the foils pass through the equilibrium position. This is because the plunging velocity in the equilibrium position is the highest, as well as the energy extraction is mainly completed by plunging motion. At the limit plunging position, the valley value of C_p is lower than that of C_{ph} . Because the plunging velocity is zero at this time, there is no energy extraction. And the processes which foil changing the pitching direction cost plenty of energy. With the increase in K_e , C_p at limiting position decreases obviously. This is due to the effective angle of attack motion which is more similar to the square wave, has higher pitching velocity at limit position. And the energy expenditure is higher. In two sections of $t/T = 0.2-0.5$ and $t/T = 0.8-1.0$, C_{ph} increases clearly with the increasing K_e . In these two sections, the foils are all pass through the equilibrium positions and move to the limit plunging positions. The trailing edge of foils occurs flow separation and the vortex shedding, which improves the energy extraction rate of foils effectively.

Lift coefficient

The synchronicity of plunging motion and aerodynamic lift brought by the foil oscillation is a significant reference to measure the energy extraction performance. As shown in fig. 9, the variations of the lift coefficient C_l and relative plunging velocity of the upper foil with different K_e at $k = 0.9$ are obtained. The lift coefficient displays periodical change with the foil oscillation. The peak value of C_l appears when the foil moves to the equilibrium position during the up stroke. The flow fields of parallel foils influence each other and C_l fluctuates slightly. The valley value is observed when the foil moves to the equilibrium position during the down stroke. With the increase in K_e , the range of C_l is markedly enlarged. In general, the synchronicity of plunging velocity and lift coefficient is best when $K_e = 2$. The increasing K_e improves the transient power coefficient and the energy extraction time in foil oscillation. As a result, the energy extraction rate improves.

Evolution of vorticity field

To investigate the aerodynamic characteristics and the evolution of flow field of parallel foils, the vorticity field at $K_e = -1$, $k = 0.7$, $K_e = 1$, $k = 0.7$, and $K_e = 1$, $k = 0.8$ during $t/T = 0-0.5$ are discussed. As shown in figs. 10(a) and 10(b), at the same frequency, the size of the trailing edge vortex at $t/T = 0$ increases clearly with the increasing K_e . When foils move to $t/T = 0.4$, the leading edge vortex moves to the posterior part of foil. The size of the leading edge vortex at $K_e = 1$ is evidently larger than the vortex at $K_e = -1$. This is due to the increase in K_e improves the pitching ampli-

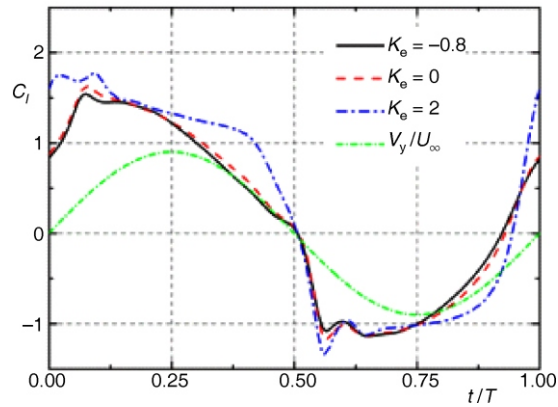


Figure 9. Variation of C_l of upper foil with different K_e at $k = 0.9$

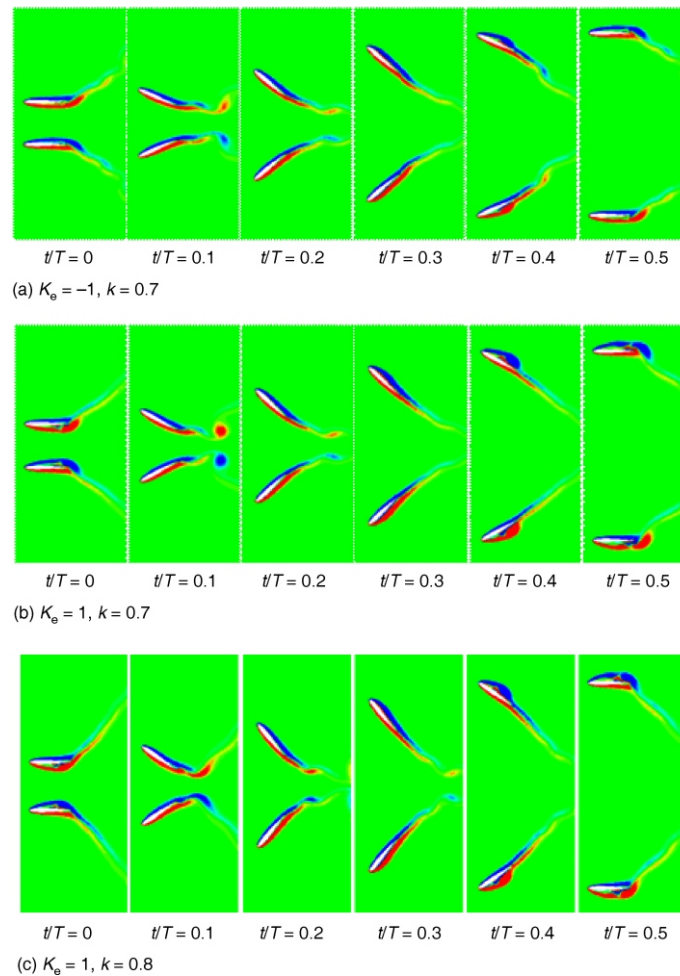


Figure 10. The evolution of vorticity fields at $t/T = 0-0.5$ with different conditions

tude of foil. The pitching velocity improves as well. Therefore, the vortex structure is enlarged in the high speed pitching process near the limit plunging position. The flow separation occurs. The energy extraction performance of foil improves by the increasing K_e .

Comparing the vorticity evolution of figs. 10(b) and 10(c), it can be found that the size of tailing edge vortex at $k = 0.7$ is larger when $t/T = 0$. With the oscillations of foils, the trailing edge vortex falls off and the new leading edge vortex appears again. As shown in the figure of $t/T = 0.4$, the leading edge vortex is formed more early at low frequency. And the size of the vortex structure is larger. However, the enlargement of the leading edge vortex results in the energy expenditure. The increasing frequency brings the higher plunging velocity of foils so that the energy extraction rate increases effectively. Therefore, the output power at $k = 0.8$ is higher.

Conclusions

This paper focuses on the arrangement of parallel dual foils, the combined pitching and plunging oscillation with different effective angle of attack motions at various working conditions are numerically analyzed. The effects of effective angle of attack motions on energy extraction performance are discussed. The evolution of vorticity fields are investigated as well. It can be found that the better extraction characteristics can be obtained when the motion is closer to the square wave. There is an optimal frequency at different effective angle of attack motions, which can get the best extraction performance. The optimal frequency k appears at 0.9 when $K_e = 0$, and it appears at 0.8 when $K_e > 0$. The change law of extraction efficiency η is same as that of C_{pm} . The efficiency achieves 25.8% at $k = 0.8$ when $K_e = 2$, which is the optimal efficiency in the range we discussed.

With the increase in K_e , the valley values of C_p and C_{ph} are obviously different. And the range of C_l is enlarged as well. The synchronism of lift coefficient and plunging motion is enhanced. The transient power coefficient is lifted by the increase of K_e . Therefore, the energy extraction performance improves.

The closer the effective angle of attack motions to the square wave, the larger the size of vortex structure around foils will be. The flow separation of vortex structure near the limit plunging position is heavier, and the extraction performance is better.

Nomenclature

A	– the swept area of air-foil oscillation, [m ²]
C_l	– lift coefficient
C_m	– torque coefficient
C_p	– power coefficient
C_T	– thrust coefficient
c	– air-foil chord length, [m]
f	– frequency, [Hz]
F_y	– aerodynamic lift in the Y-direction, [N]
H_0	– non-dimensional plunging amplitude
$h(t)$	– plunging motion
K_e	– parameter of effective angle of attack motion
k	– reduced frequency
M	– torque, [Nm]
P	– power, [W]
Re	– Reynolds number
T	– oscillation cycle, [s]
t	– physical time, [s]
U_∞	– free stream velocity, [ms ⁻¹]
$V_y(t)$	– plunging velocity, [ms ⁻¹]

Greek symbols

$\alpha(t)$	– pitching motion
α_e	– effective angle of attack
α_0	– nominal angle of attack
δ	– spacing of parallel foils, [m]
η	– efficiency
θ_0	– pitching amplitude, [°]
ρ	– density, [kgm ⁻³]
φ	– phase difference between plunging and pitching motions, [°]
ω	– pitching velocity, [rads ⁻¹]

Subscripts

h	– plunging motion
m	– average value

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