Study on the Energy Extraction Characteristics of a Flapping Hydrofoil with a Flow-Control Wall

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2026-08-10
ChinaRxiv

Abstract

To investigate the effects of unsteady flow control and dynamic walls on the energy-harvesting characteristics of a flapping foil, this study designed a two-dimensional flapping-foil computational model with a wavy wall. Based on the RANS model, the effects of the wavy-wall parameters, the distance between the hydrofoil and the wall, and the relative position between the hydrofoil and the wall crest on the hydrodynamic characteristics of the flapping foil were analyzed. The results show that, under the optimal wavy-wall shape parameters and relative position of the hydrofoil, the energy-harvesting efficiency of the flapping foil reaches 52.2%, which is 13.52% higher than Kinsey's computational result. The wavy wall can increase the flow velocity in the flow field, thereby increasing the surface pressure difference when the flapping foil approaches the low-velocity region near the wall. At the same time, it enhances vortex intensity and delays the dissipation of wake vortices; after shedding, the wake vortices adhere to the wall, strengthening the interaction between the flapping foil and the wall. The pressure difference on the flapping-foil surface drives its heaving and pitching motions, increases the amplitude of lift variation on the flapping-foil surface, and thereby improves the energy-harvesting efficiency of the flapping foil. This study aims to identify methods for improving flapping-foil energy-harvesting efficiency by modifying wall shape and to provide a new direction for further development in the field of flapping-foil energy harvesting.

Full Text

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Keywords: flapping hydrofoil; unsteady flow control; dynamic wall; wavy wall; RANS model; energy-harvesting characteristics

Chinese Library Classification No.: O35; TU311; P315.9
Document Code: A
DOI: 10.11776/j.issn.1000-4939.2026.04.017
Article No.: 1000-4939(2026)04-0913-10
CSTR: 32414.14.cjam.issn.1000-4939.2026.04.017

Study on energy extraction characteristics of flapping hydrofoil by flow control wall

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Abstract: In order to study the influence of unsteady flow control and dynamic wall on the energy performance of a flapping hydrofoil, a two-dimensional flapping hydrofoil calculation model with wavy wall surface is designed. Based on RANS model, the effects of wavy wall parameters, the distance between the hydrofoil and the wall, and the relative position of the wavy crest between the hydrofoil and the wall on the hydrodynamic characteristics of the flapping hydrofoil are analyzed. The results show that the energy efficiency of the flapping hydrofoil reaches 52.2%, which is 13.52% higher than the calculated result of Kinsey under the optimal wavy wall shape parameters and the relative position of the hydrofoil. The wavy wall can increase the flow velocity, which makes the surface pressure difference increase when the flapping hydrofoil is near the low flow velocity wall. At the same time, the vortex intensity is enhanced, and the wake vortex

Received date: 2024-06-13
Funding projects: National Natural Science Foundation of China (No. 52309114); Yunnan Provincial Basic Research Program Project (No. 202301AU070053)
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Citation format: Bao Yandong, Zeng Yun, Li Weizhong, et al. Study on the energy extraction characteristics of a flapping hydrofoil with a flow-control wall[J]. Chinese Journal of Applied Mechanics, 2026, 43(4): 913-922.
Bao Yandong, Zeng Yun, Li Weizhong, et al. Study on energy extraction characteristics of flapping hydrofoil by flow control wall[J]. Chinese Journal of Applied Mechanics, 2026, 43(4): 913-922.

dissipation is delayed. The wake vortex is adsorbed on the wall after falling off, and the interaction between the flapping hydrofoil and the wall is enhanced. The pressure difference on the surface of the flapping hydrofoil drives the rolling and rotation motion of the flapping hydrofoil, improves the variation amplitude of the lift force on the surface of the flapping hydrofoil, and thus improves the energy efficiency of the flapping hydrofoil. It is hoped that the method of improving the wall shape can improve the energy extraction efficiency of flapping hydrofoil, which can provide a new direction for the further development of flapping hydrofoil energy extraction research neighborhood.

Key words: flapping hydrofoil; unsteady flow control; dynamic wall; wavy wall; RANS model; energy extraction

Energy shortage has limited the development of industrial and agricultural production. Seeking new clean-energy channels is imminent, and wind power and hydropower, as clean energy, have attracted great attention from scholars in various countries

$$1-2$$

. As a tidal-current power-generation device, the flapping wing has unique advantages such as low noise, strong maneuverability, and suitability for shallow-water areas

$$3-5$$

. In recent years, extensive research has been conducted on improving the performance of flapping-wing tidal-current power-generation devices, and significant progress has been achieved

$$6-9$$

.

The existing literature mainly focuses on studying the influence of motion parameters, model improvement, algorithm optimization, and the addition of auxiliary driving devices on energy-harvesting characteristics under free-flow conditions

$$10-14$$

. In studies investigating the influence of walls on the hydrodynamic characteristics of flapping wings, Wu et al.

$$15$$

found that when the distance between the airfoil and the ground is relatively small, the lift coefficient experienced by the airfoil surface increases; Park

$$16$$

found that a wall near an airfoil in free flow affects the interaction between the wing and the fluid and enhances the hydrodynamic characteristics of the fluid. In addition, Shirai et al.

17

found in wind-tunnel experiments that the wind-tunnel wall delayed flow separation on the airfoil section, resulting in a decrease in the lift coefficient and an increase in the drag coefficient. These studies all show that walls can affect the hydrodynamic characteristics of flapping wings. With the introduction and use of unsteady flow-control methods, the emergence of flow-control structures such as slotted wings, jet devices, channels, and guide vanes has greatly promoted progress in research on flapping-wing energy harvesting

$18 - 21$

. Combining wall shape with flow-control methods has become a new idea in flapping-wing research. Chen et al.

22

found that curved walls have a relatively large influence on the lift experienced by the airfoil surface; therefore, the hydrodynamic characteristics of flapping wings can be studied from the perspective of wall shape, exploring methods to improve hydrofoil energy-harvesting efficiency. Subsequently, Young et al.

23

designed a bottleneck-shaped channel to study the efficiency of a flapping-wing generator, while Jiang et al.

24

introduced a diffuser as a guide shroud into a turbine based on an oscillating wing for investigation. The above results all indicate that after adopting a flow-control wall, the energy-conversion performance of the flapping wing is significantly improved. This study will design a wavy dynamic wall to improve the energy-harvesting characteristics of the flapping wing; the wall-shape concept is inspired by waves. Current studies have pointed out that waves have a relatively large influence on the motion of flapping wings and the variation of torsional stiffness, and that relatively large torsional stiffness can compensate for energy loss during the energy-harvesting process and improve the hydrodynamic performance of the flapping wing

$25 - 28$

. A wavy wall also has the function of controlling fluid vortex shedding and fluctuation, and it avoids the setting of complex parameters required for wave modeling. It is of great significance to study the effects of a wavy dynamic wall and unsteady flow control on the energy-harvesting characteristics of flapping wings.

Fig. 1 Schematic diagram of hydrofoil boundary and fluid domain

Figure 1: Fig. 1 Schematic diagram of hydrofoil boundary and fluid domain

In summary, research on the influence of wavy dynamic walls and unsteady flow control on the energy-harvesting characteristics of flapping wings is limited. Therefore, in this study, the RANS model is used to investigate, at $Re = 5 \times 10^5$, the influence of the shape parameters of a wavy flow-control wall, the distance between the hydrofoil and the wall, and the relative positions of the hydrofoil and the wall wave crest/trough on the energy-harvesting characteristics of the flapping wing, with the aim of providing data references for the further development of flapping-wing energy-harvesting research.

1 Flapping-wing model and equations of motion

1.1 Problem description

The model computational domain is shown in Fig. 1. The inlet is a velocity inlet, the outlet is a pressure outlet, and the upper and lower side walls are wavy walls. The governing equation for the wall shape is

$$y = A \sin(ft) + H \qquad (1)$$

where A is the fluctuation amplitude of the walls on both sides, f is the fluctuation frequency, and H is the distance between the hydrofoil and the wall.

图 1 水翼壁面及流体域示意图

Fig. 1 Schematic diagram of hydrofoil boundary
and fluid domain

The heaving and pitching motions of the flapping wing are defined by a UDF (user-defined function) and realized as rigid-body motion. The motion trajectory and motion velocity of the flapping wing are respectively shown in Eq. (2) and Eq. (3).

$$\begin{cases} h(t) = h_0 \sin(2\pi f_1 t + \Phi) \\ \theta(t) = \theta_0 \sin(2\pi f_1 t) \end{cases} \qquad (2)$$

$$\begin{cases} V_y(t) = 2\pi f_1 h_0 \cos(2\pi f_1 t + \Phi) \\ w(t) = 2\pi f_1 \theta_0 \cos(2\pi f_1 t) \end{cases} \qquad (3)$$

where $h(t)$ is the displacement of the hydrofoil in heaving motion; h_0 is the amplitude of the heaving motion; f_1 is the oscillation frequency; $\theta(t)$ is the rotation angle about the shaft; θ_0 is the rotation-angle amplitude; Φ is the

Fig. 2 Flapping hydrofoil motion model diagram

Figure 2: Fig. 2 Flapping hydrofoil motion model diagram

phase difference between the heaving motion and the pitching motion; $V_y(t)$ is the heaving velocity of the hydrofoil; and $w(t)$ is the angular velocity of rotation of the hydrofoil.

The displacement distribution of the flapping motion is shown in Fig. 2.

Figure 2 Schematic diagram of the flapping hydrofoil motion model

Fig. 2 Flapping hydrofoil motion model diagram

The reduced frequency f^* and Reynolds number Re are used to characterize the dimensionless parameters of unsteady fluid dynamics:

$$f^* = f_1 c / U_\infty \qquad (4)$$

$$Re = \frac{U_\infty c \rho}{\mu} \qquad (5)$$

where c is the chord length of the hydrofoil; U_∞ is the free-stream velocity; ρ is the density of water; and μ is the dynamic viscosity coefficient of water.

An orthogonal experimental design is adopted to investigate the influence of the wavy flow-control wall on the energy-harvesting characteristics of the flapping hydrofoil. The NACA0015 hydrofoil model is selected, with chord length $c =$ 0.25 m. Define x_p as the distance from the leading edge of the hydrofoil to the rotation shaft, and the rotation-center position is $x_p/c = 1/3$. The inlet is a velocity inlet, the outlet is a pressure outlet, and the wall is a standard wall. In the computations, the Reynolds number is $Re = 500\ 000$, $U_\infty = 2$ m/s, $f^* = 0.14$, $\theta_0 = 76.3^\circ$, $h_0 = c$, and $\Phi = 90^\circ$.

1.2 Flapping-hydrofoil energy-harvesting theory

During heaving and pitching, the flapping hydrofoil can extract energy from the fluid. The powers obtained from the heaving motion and pitching motion, $P_y(t)$ and $P_\theta(t)$, the net power P, and the mean power $\overline{P}$ are respectively

$$P_y(t) = Y(t) V_y(t) \qquad (6)$$

$$P_\theta(t) = M(t) w(t) \qquad (7)$$

$$P = P_y(t) + P_\theta(t) \qquad (8)$$

$$\overline{P} = \frac{1}{T}\int_0^T P dt \qquad (9)$$

where $Y(t)$ is the lift on the hydrofoil surface; $M(t)$ is the torque about the z-axis; P is the power generated by the lift and torque; and $\overline{P}$ is the mean power generated by the lift and torque over one period.

The flapping-hydrofoil lift coefficient $C_y(t)$, moment coefficient $C_m(t)$, mean lift coefficient $\overline{C}_{py}$, mean moment coefficient $\overline{C}_{p\theta}$, and net power coefficient $\overline{C}_p$ are respectively

$$\overline{C}_p = \overline{P}/0.5\rho U_\infty^3 c \qquad (10)$$

$$C_y(t) = Y(t)/(0.5\rho U_\infty^2 c) \qquad (11)$$

$$C_m(t) = M(t)/(0.5\rho U_\infty^2 c^2) \qquad (12)$$

$$\overline{C}_p = \overline{C}_{py} + \overline{C}_{p\theta} = \int_0^1 \left[C_y(t)\frac{V_y(t)}{U_\infty} + C_m(t)\frac{w(t)c}{U_\infty}\right] d(t/T) \qquad (13)$$

$$\eta = \overline{C}_p \frac{c}{d} \qquad (14)$$

where d is the swept height of the hydrofoil.

2 Numerical method

2.1 Governing equations

The solution for the flapping hydrofoil belongs to the problem of solving a viscous incompressible fluid [29]. The governing equations are based on the Reynolds-averaged N-S model.

1) Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (15)$$

where u_i is the velocity component of the fluid medium in the i-direction coordinate; and x_i is the coordinate position in the i-direction.

2) Momentum equation

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + u_j\frac{\partial u_j}{\partial x_i}\right) - u_i'u_j'\right] + f_i \qquad (16)$$

where t is the time variable; p is the static pressure; f_i is the body force in the i-coordinate direction; and $u_i'u_j'$ is the Reynolds stress term.

3) Turbulence model

The SST model can address such problems as insufficient numerical simulation accuracy in the near-wall region and poor performance for free-shear flows; at the same time, it can enhance wall treatment [30–31]. Therefore, the SST k-ω model is adopted.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \qquad (17)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \qquad (18)$$

where: k is the turbulent kinetic energy; ω is the dissipation rate of turbulent kinetic energy; Γ_k and Γ_ω are the effective diffusion coefficients of k and ω in the equations, respectively, $\Gamma_k = \mu + \frac{\mu_t}{\sigma_k}$, $\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega}$; the turbulent viscosity $\mu_t = \alpha^*\frac{\rho k}{\omega}$, and α^* is the low-Reynolds-number damping correction coefficient for turbulent viscosity; σ_k and σ_ω are the turbulent Prandtl numbers of k and ω, respectively; the turbulent kinetic energy generated by the mean velocity gradient during the calculation is

$G_k = \mu_t S^2$, the mean strain-rate tensor coefficient $S = \sqrt{2S_{ij}S_{ij}}$, where

$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$; G_ω is the production term of the effective diffusion coefficient ω,

$G_\omega = \alpha\frac{\omega}{k}G_k$, $\alpha = \frac{\alpha_\infty}{\alpha^*}\left(\frac{\alpha_0 + Re_t/R_\omega}{1 + Re_t/R_\omega}\right)$, $\alpha_\infty = 1$, $\alpha_0 = 1/9$, $Re_t = \rho k/\mu\omega$, $R_\omega = 2.95$; Y_k and Y_ω are the dissipation terms of k and ω caused by turbulence, respectively; D_ω is the cross-diffusion term; S_k and S_ω are user-defined source terms.

2.2 Mesh Model

The flow field is discretized using a structured mesh, as shown in Fig. 3. The y^+ value is a dimensionless number used to calculate the distance between the fluid velocity and the wall. The mesh boundary layer is divided according to

Fig. 3 Mesh diagram of flow field calculation domain

Figure 3: Fig. 3 Mesh diagram of flow field calculation domain

Fig. 4 The calculation results of four groups of grid numbers were compared with the literature

Figure 4: Fig. 4 The calculation results of four groups of grid numbers were compared with the literature

the y^+ value, which is taken as 0.8. The height of the first mesh layer on the hydrofoil surface is 0.000 017 4 m, the cell mesh quality is greater than 0.7, and the total number of meshes is 100,000.

Figure 3 Schematic diagram of the flow-field computational-domain mesh

Fig. 3 Mesh diagram of flow field calculation domain

2.3 Simulation Method and Validation

To ensure the reliability of the simulation scheme, this study uses the data of Kinsey et al. [32] to verify the time-step independence and mesh independence of the simulation method. In the computational condition, the hydrofoil NACA0015 is selected, the Reynolds number is $Re = 500\,000$, the free-stream velocity is $U_\infty = 2$ m/s, the reduced frequency is $f^* = 0.14$, $\theta_0 = 76.3°$, $h_0 = c = 0.25$ m, and the rotation-axis position is $x_p/c = 1/3$.

When the time-step number is $T/\Delta t = 2\,000$, four different mesh counts (50,000, 100,000, 150,000, and 200,000) are used to verify mesh independence, and the results are shown in Fig. 4(a) and Fig. 4(b). With a mesh count of 100,000, three different time-step lengths ($T/\Delta t = 1\,500$, $T/\Delta t = 2\,000$, and $T/\Delta t = 2\,500$) are used to verify time-step independence, and the results are shown in Fig. 5(a) and Fig. 5(b). The variation trends of the lift coefficient C_l and torque coefficient C_p are basically consistent with the research results of Kinsey et al. [32]. Table 1 shows the comparison between the calculation results and the literature results. The calculation error is smallest when the mesh count is 100,000 (mesh 2) and the time-step number is 2,000, at only 0.98%. This indicates that the numerical model is reliable; therefore, mesh 2 and the time-step length $T/\Delta t = 2\,000$ are selected for subsequent simulations.

(a) Lift coefficient

(b) Power coefficient

Figure 4 Comparison between the calculated results for four groups of mesh counts and the literature

Fig. 4 The calculation results of four groups of grid numbers were compared with the literature

(a) Lift coefficient

(b) Power coefficient

Fig. 5 The calculation results of three groups of time steps were compared with the literature

Table 1 Results of mesh and time-step independence calculations and comparison with the literature

Parameter	$\hat{C}_1$	$\overline{C_p}$	$\overline{C_p}$ error/%	Parameter	$\hat{C}_1$	$\overline{C_p}$	$\overline{C_p}$ error/%
Kinsey et al.[32]	2.784	0.819	–	Mesh 4	2.924	0.827	0.98
Mesh 1	2.828	0.835	1.95	Time step 1 500	2.887	0.852	4.03
Mesh 2	2.837	0.827	0.98	Time step 2 000	2.837	0.827	0.98
Mesh 3	2.906	0.828	1.10	Time step 2 500	2.913	0.839	2.44

3 Simulation Study

To analyze the influence of the presence of a wall on the flow field of the flapping-wing motion, the flow-field cloud diagrams for the cases of no wall, a flat wall, and a wavy wall were studied at $H = 2.5c$ and free-stream inflow $U_\infty = 2$ m/s, as shown in Fig. 6.

(a) No wall

(b) Flat wall

(c) Wavy wall

$0T$ $0.15T$ $0.5T$

Fig. 6 Comparison cloud image of flow field of non-wall, flat wall and wavy wall ($H = 2.5c$)

The figure presents the flow-field patterns for three types of walls at $t = 0T$, $t = 0.15T$, and $t = 0.50T$. It can be clearly seen that, when a wavy wall is adopted, the velocity in the flow field is relatively high, ranging from $4 \sim 6$ m/s. At $t = 0.15T$, when vortex shedding occurs at the leading edge of the foil, the velocity exceeds 8 m/s, while the velocity near the wall is below 2 m/s. The presence of the wavy wall increases the flow velocity around the flapping foil.

Moreover, at $t = 0.50T$, a small-area recirculation appears near the wall where the local velocity is relatively low. According to the general theory of subsonic flow: when the fluid velocity accelerates, the pressure on the contact surface between the flapping foil and the fluid decreases. Therefore, after the wavy wall is adopted, the flow velocity in the flow field increases, vortices appear around the flapping foil, and when the foil is close to the wavy wall, the flow velocity near the wall is relatively low; thus, when the flapping foil approaches the wall, the pressure difference increases, which is beneficial to lift generation during the hydrofoil motion.

3.1 Influence of the Distance Between the Hydrofoil and the Wall

Since the motion height of the hydrofoil is $d \approx \pm 2c$, in order not to affect the mesh quality of the hydrofoil boundary layer, $H = 2.5c$ is taken as the lower limit of the minimum value. The computed results of the lift power coefficient, torque power coefficient, mean power coefficient, and energy-harvesting efficiency under different values of the distance H between the hydrofoil and the wall are shown in Table 2. The peak lift power coefficient and the mean power coefficient of the flapping foil decrease as H increases, showing a decreasing trend; the torque power coefficient changes little when $H = 2.5c \sim 3.0c$, and tends to be stable when $H \geq 3.5c$. This indicates that the distance between the hydrofoil and the wall has a relatively large influence on the lift work of the flapping foil, and that the energy-harvesting characteristics of the hydrofoil are stronger when it is close to the wall. In addition, when $H = 2.5c$, the mean power coefficient is the largest and the energy-harvesting efficiency is the highest, reaching 27.6%.

Table 2 Energy properties of flapping hydrofoil at different H

Tab. 2 Energy properties of flapping hydrofoil at different H

H	$\hat{C}_{py}$	$\hat{C}_{p\theta}$	$\overline{C}_p$	η
$2.5c$	1.176	0.018	0.548	0.276
$3.0c$	1.091	0.013	0.530	0.256
$3.5c$	0.950	0.046	0.477	0.239
$4.0c$	0.909	0.046	0.454	0.228
$5.0c$	0.886	0.046	0.429	0.215

3.2 Influence of the Wall Undulation Frequency

This section investigates the energy-harvesting characteristics of the flapping foil under different wall undulation frequencies f, with $A = 1.0c$ and $H = 2.5c$. As shown in Fig. 7(a) and Fig. 7(b), the instantaneous power coefficient and the energy-harvesting efficiency of the hydrofoil first increase and then decrease as the wall undulation frequency increases. At $f = 0.0008$, 0.001, and 0.002 Hz,

Fig. 7 The variation law of power coefficient and energy extraction efficiency at different f

Figure 5: Fig. 7 The variation law of power coefficient and energy extraction efficiency at different f

both the instantaneous power coefficient and the energy-harvesting efficiency are higher than those for the straight wall, showing a gradually increasing trend. At $f = 0.001$ Hz, the interaction between the hydrofoil and the wall is optimal, the energy-harvesting characteristics of the flapping foil are stronger, the peak instantaneous power coefficient reaches 2.370, and the maximum efficiency can reach 43%. When $f = 0.004$ Hz, the peak instantaneous power coefficient decreases and is lower than that for the straight wall, and the energy-harvesting efficiency is the lowest.

(a) Instantaneous power coefficient

(b) Energy-harvesting efficiency

Fig. 7 The variation law of power coefficient and energy extraction efficiency at different f

3.3 Influence of the Wall Undulation Amplitude

Under the optimal wall parameters $f = 0.001$ Hz and $H = 2.5c$, the influence of different wall undulation amplitudes A on the energy-harvesting characteristics of the flapping foil is studied.

Figures 8(a) and 8(b) show the power coefficient and energy-harvesting efficiency of the flapping foil under different A. The instantaneous power coefficient first increases and then decreases as the wall undulation amplitude increases. At $t = 0.15T$, when $A = 2.0c$, the instantaneous power coefficient reaches its maximum value; however, over the entire period, the energy-harvesting efficiency is highest when $A = 1.5c$, reaching 52.2%, which is an improvement of 13.52% compared with the computational results of Kinsey et al. [32].

To reveal the influence of wall undulation amplitude on the energy-harvesting characteristics of the flapping foil and the mechanism of efficiency improvement, Fig. 9 presents the pressure cloud diagrams of the flapping foil for a straight wall and for a wavy wall with $A = 1.5c$. During $t = 0T \sim 0.50T$, the hydrofoil undergoes a downward flapping process under counterclockwise rotation; the upper surface is under positive pressure and the lower surface under negative···

increases sharply; the positive-pressure area is larger than the negative-pressure area, and the positive pressure drives the hydrofoil to flap downward, so that the hydrofoil can obtain energy from the fluid and the instantaneous power coefficient is positive. During $t = 0.50T \sim 1.00T$, the hydrofoil is in the clockwise rotating upstroke process; the positive pressure on the upper surface shifts from

Fig. 8(a) instantaneous power coefficient and Fig. 8(b) energy extraction efficiency

Figure 6: Fig. 8(a) instantaneous power coefficient and Fig. 8(b) energy extraction efficiency

Fig. 9 pressure cloud images

Figure 7: Fig. 9 pressure cloud images

the leading edge to the lower surface, and the upper surface gradually becomes a negative-pressure surface. The positive pressure drives the hydrofoil to flap upward, enabling the hydrofoil to obtain energy from the fluid. When a wavy wall is used, the negative-pressure area on the hydrofoil surface is larger than that for a flat wall, and the pressure value in the positive-pressure region is relatively large and is mainly concentrated near the hydrofoil. The pressure difference on the hydrofoil surface increases, driving the hydrofoil to undergo downward and upward motion. The net power of lift and torque obtained by the hydrofoil increases, and the energy-extraction efficiency is also improved.

(a) Instantaneous power coefficient (b) Energy-extraction efficiency

Figure 8 Variation laws of the instantaneous power coefficient and energy-extraction efficiency under different A

Fig. 8 The variation of power coefficient and energy extraction efficiency at different A

(a) Flat wall

(b) Wavy wall

$0T$ $0.25T$ $0.50T$ $0.75T$ $1.00T$

Pressure/Pa

Figure 9 Pressure cloud images of the flapping hydrofoil with a flat wall and with a wavy wall when $A = 1.5c$

Fig. 9 Pressure cloud image of flapping hydrofoil with flat wall and $A = 1.5c$ wavy wall

3.4 Influence of the Relative Position of the Hydrofoil and the Wall Peaks/Valleys

In this section, under the optimal wall parameters $f = 0.001$ Hz, $H = 2.5c$, and $A = 1.5c$, the influence of the relative position of the flapping hydrofoil with respect to the wall wave peaks and valleys on the energy-extraction characteristics of the flapping hydrofoil is investigated. Three simulation cases are set

Fig. 10 schematic diagram

Figure 8: Fig. 10 schematic diagram

up with the flapping hydrofoil at different positions, as shown by positions 1, 2, and 3 in Fig. 10.

As shown in Fig. 11(a) and Fig. 11(b), the variations of the lift power coefficient and torque power coefficient for positions 1, 2, and 3 are presented. Among them, the peak lift power coefficients at positions 1 and 3 are relatively large; the value is largest when the hydrofoil is at position 1 and smallest at position 2. Fig. 11(c) and Fig. 11(d) respectively show the instantaneous power coefficient and energy-extraction efficiency at the three positions. Comparing the variations of the instantaneous power coefficient, and at $t = 0.15T$, the lift power coefficient and the peak instantaneous power coefficient are the largest. The power coefficient and energy-extraction characteristics when the hydrofoil is near the wall valley position are both higher than those when it is farther from the wave valley (position 2).

Wave valley Wave peak

Figure 10 Schematic diagram of the relative positions of the hydrofoil and the wall peaks/valleys

Fig. 10 Schematic diagram of the relative positions of hydrofoil and boundary peaks and valleys

(a) Lift power coefficient

(b) Torque power coefficient

(c) Power coefficient

(d) Energy-extraction efficiency

Fig. 11 Energy extraction properties of flapping hydrofoil at different relative positions

As shown in Fig. 12, for the vorticity cloud images of the hydrofoil at the three positions at two instants, $t = 0.15T$ and $0.50T$, at $t = 0.15T$ the hydrofoil is undergoing rotational downstroke. The positive vortex on the lower surface is moving backward along the hydrofoil surface; the negative vortex attached to the upper surface gradually weakens; and the positive vortex at the tail moves downward along the trailing edge to the lower surface, forming a vortex with a tendency of greater intensity. The vortices at Positions 1 and 3 are relatively distinct. The vortices generated on the hydrofoil surfaces at Positions 2 and 3 are weaker and dissipate faster, not reaching the level of interaction between the wall surface and the hydrofoil; moreover, the vortex at Position 3 dissipates relatively quickly.

(a) Position 1

(b) Position 2

(c) Position 3

Fig. 12 Vorticity cloud image of flapping hydrofoil at different positions

At $t = 0.50T$, the hydrofoil at Position 1 reaches the lowest point of its motion. The leading edge of the hydrofoil contacts the flat vortices attached to the two side walls. The relatively large negative vortex generated at the tail of the hydrofoil sheds after moving backward with the positive vortex, while the new negative vortex generated at the trailing edge becomes larger as it moves backward with the positive vortex and is adsorbed onto the lower wall surface. This slows the dissipation of the positive vortex and strengthens the interaction between the hydrofoil and the wall surface. Compared with the wall region in the preceding text, the flow velocity is smaller, and the negative vortex on the wall surface moves along the leading edge of the hydrofoil to the lower surface of the foil. The lower flow velocity near the wall surface causes recirculation to form on the upper and lower surfaces of the flapping foil, as well as interaction with the negative vorticity on the wall surface.

As a result, the pressure difference on the flapping-foil surface increases. During the upward motion of the hydrofoil, it is pushed upward by the pressure difference on the hydrofoil surface, and the energy-harvesting efficiency of the hydrofoil is improved.

4 Conclusion

This study used the RANS method to investigate the effects of unsteady flow control and the distance H between a wavy wall and the hydrofoil, the wall undulation frequency f, the wall undulation amplitude A, and the relative positions of the flapping foil with respect to the wave crests and troughs of the wall on the energy-harvesting characteristics of the flapping foil. The results show that:

1) When vortices occur around the flapping foil and it approaches the wavy wall, the use of a wavy-wall flow field increases the flow velocity. The velocity in the flow field near the wall is relatively small, and when the flapping foil approaches the wall, the pressure difference increases, which is beneficial for the generation of lift during the motion of the hydrofoil.

2) When the spacing H between the flapping foil and the wavy wall is within the range $2.5c \sim 5.0c$, the energy-harvesting characteristics decrease as H increases; the maximum energy-harvesting efficiency is 27.6%.

3) As the value of f increases within the interval $0.000\,8 \sim 0.004$ Hz, the hydrofoil energy-harvesting characteristics first increase and then decrease. At $f = 0.001$ Hz, the maximum energy-harvesting efficiency is 43.1%.

4) As A increases within the range $0.25c \sim 2.0c$, the hydrofoil energy-harvesting characteristics first increase and then decrease. When $A = 1.5c$, the energy-harvesting efficiency of the flapping foil reaches a maximum of 52.2%, which is 13.52% higher than the calculation result of Kinsey. Therefore, the optimal control function for the wall shape in the fluid domain is $1.5c\sin(0.001t) + 2.5c$.

5) Unsteady flow control and the dynamic wall markedly increase the pressure difference on the hydrofoil surface, strengthen the vortex intensity, prolong the vortex dissipation time, interfere with the motion trend of the flapping foil, enhance the interaction between the flapping foil and the wall, improve the lift work capacity, and thereby increase the energy-harvesting efficiency.

The study indicates that a wavy dynamic wall and unsteady flow control can improve the hydrodynamic characteristics and energy-harvesting characteristics of the flapping foil. However, this study only examines the influence of two-dimensional wall shapes on the energy-harvesting characteristics of the flapping foil; three-dimensional wall shapes and their effects on the energy-harvesting characteristics of flapping foils remain to be studied.

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(Editor: Lü Ying)

Note: Figure translations are in progress. See original paper for figures.