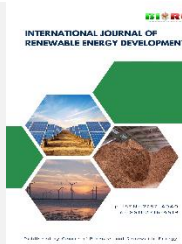




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Research Article

Free-surface effects on the energy-harvesting performance of a fully passive flapping foil

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Abstract. Fully passive flapping-foil energy harvesters offer structural simplicity and require no external actuation, but their self-excited motion and power extraction may be strongly affected by a deformable free surface during near-surface operation. This study aims to quantify how submergence depth affects energy-harvesting efficiency and to elucidate the associated changes in free-surface deformation, vortex evolution, load-motion phase coordination, and foil-surface pressure fluctuations. To this end, a two-dimensional numerical investigation is conducted on a fully passive NACA0015 flapping foil at a Reynolds number of 500,000 and a Froude number of 0.1581. The Volume of Fluid method and an overset-mesh technique are employed to resolve free-surface deformation and foil motion, respectively. The Reynolds number, foil geometry, pitching-axis location, and structural parameters are kept constant, while only the ratio of submergence depth to foil chord length is varied. The energy-harvesting efficiency exhibits a non-monotonic dependence on submergence depth. Among the examined cases, the maximum efficiency of 45.98% is obtained at a submergence-depth-to-chord ratio of 2.8, representing an improvement of approximately 8.16% over the unconfined baseline efficiency of 42.51%. When this ratio is 1.8 or less, strong free-surface deformation and wave radiation disrupt wake coherence and load-motion phase coordination, producing negative heaving-power intervals and substantially suppressing the positive pitching-power contribution. When the ratio reaches 3.5 or greater, the free-surface influence becomes weak and the efficiency approaches the unconfined baseline. The dominant Strouhal number of the heaving and pitching motions remains approximately 0.1, while pressure cross-correlation analysis shows that free-surface proximity attenuates pressure-fluctuation coherence without altering the leading-edge-vortex-governed propagation mechanism. These results demonstrate that moderate free-surface interaction can enhance energy extraction, whereas excessive interface proximity causes pronounced performance deterioration, providing a preliminary reference for selecting the deployment depth of fully passive flapping-foil energy harvesters.

Keywords: Fully passive flapping foil; Energy harvesting; Free-surface effect; Submergence depth; Vortex dynamics



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1. Introduction

As global fossil fuel consumption continues to escalate and the imperative of achieving carbon neutrality intensifies, the efficient exploitation of clean and renewable energy has emerged as a central topic in contemporary energy research (Xiao & Zhu, 2014). Among the numerous fluid kinetic energy harvesting technologies — including wind and tidal energy — bioinspired flapping-foil energy harvesting devices, drawing inspiration from the locomotion of birds in flight and fish in swimming, have attracted considerable attention in recent years (Wang *et al.*, 2026). Compared with conventional rotary hydraulic turbines, flapping-foil energy harvesting devices are capable of sustaining relatively high hydrodynamic loads even at low flow velocities, while offering distinct advantages including structural simplicity, low hydrodynamic noise, and minimal disturbance to aquatic ecosystems; these characteristics render them particularly promising for engineering applications in shallow-water rivers and nearshore tidal energy exploitation (Lv *et al.*, 2021). Numerical studies of hydrokinetic turbines have also shown that blade-profile

modifications can alter the pressure difference across the hydrofoil and its energy-conversion efficiency (Gomez *et al.*, 2025).

Flapping-foil energy harvesting devices are generally classified into three categories according to their motion control strategies: fully active, semi-passive, and fully passive systems. McKinney and DeLaurier (1981) first proposed the concept of oscillating-wing wind energy capture, after which researchers conducted extensive systematic investigations on fully active flapping foils — systems in which both heaving and pitching motions are forcibly driven by external actuators. In terms of performance, Kinsey *et al.* (2011) achieved an energy-harvesting efficiency exceeding 40% at high Reynolds numbers. Regarding parametric optimization, Wang *et al.* (2016) systematically compared the regulatory effects of various NACA foil profiles on leading-edge vortex shedding characteristics; Deng *et al.* (2014; 2007) clarified the vortex interference mechanisms associated with aspect ratio effects and tandem dual-foil configurations; Wang *et al.* (2025a) further proposed a combined control strategy incorporating a leading-edge rotating cylinder and a trailing-edge oscillating flap, demonstrating that geometry-

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kinematics cooperative control significantly enhances the energy-harvesting performance of active flapping foils. However, fully active systems rely on complex actuation mechanisms and control systems, which severely impedes their practical engineering implementation (Lua, 2026). To address this limitation, researchers have proposed semi-passive configurations requiring active control of only a single degree of freedom. Boudreau *et al.* (2019) demonstrated that a semi-passive flapping foil, in which pitching motion responds passively through a properly designed spring-damper system, can achieve a comparatively high overall energy-harvesting efficiency; Zhu (2011) and Peng and Zhu (2009) further elucidated, from both theoretical and numerical perspectives, the self-excited oscillation mechanism and optimal frequency response characteristics of semi-passive systems; Wang *et al.* (2025b) employed dynamic mode decomposition to systematically reveal the regulatory effects of pitching amplitude on wake vortex structure evolution and energy-harvesting efficiency in semi-passive flapping foils. Nevertheless, semi-passive systems still require external mechanisms to sustain the heaving motion, and their structural complexity and maintenance demands remain non-negligible (Zhu *et al.*, 2023a). By contrast, fully passive flapping-foil systems — in which both heaving and pitching motions are driven entirely by fluid-dynamic self-excitation — are regarded as the most promising configuration for practical engineering applications, owing to their maximally compact structure and the complete elimination of external energy input (Young *et al.*, 2013).

The motion of a fully passive flapping-foil system typically manifests as self-excited limit-cycle oscillations, and its dynamic behavior is intimately coupled with the evolution of the leading-edge vortex (LEV) and the dynamic stall mechanism: the low-pressure region formed by LEV shedding generates an aerodynamic moment that periodically reverses the pitching angle, which in turn sustains continuous work output from the heaving motion; the phase relationship between heaving and pitching motions is therefore the key factor governing efficient energy harvesting in such systems (Kinsey & Dumas, 2012). Veilleux and Dumas (2017) demonstrated, through an inverse determination of structural parameters combined with numerical gradient optimization, that fully passive flapping foils possess considerable energy-harvesting potential in unconfined flow fields; Zhao *et al.* (2021) systematically characterized the influence of structural parameters on the dynamic response and energy-harvesting performance of fully passive systems, providing quantitative guidance for device design. Regarding adaptability to complex inflow conditions, Oshkai *et al.* (2022) showed experimentally that upstream periodic vortical perturbations can effectively enhance the power output of a fully passive flapping foil only within a narrow resonance frequency band, indicating that the system exhibits strong sensitivity to perturbation frequency. However, all of the aforementioned studies were conducted under unconfined free-stream conditions, whereas in practical engineering deployment environments — such as shallow shoals, river channels, and nearshore coastal waters — flapping-foil devices inevitably operate in proximity to rigid walls or deformable free surfaces, fundamentally altering their hydrodynamic response.

Near-free-surface operation represents one of the most typical working conditions encountered by flapping-foil energy harvesting devices in practical engineering deployment. Unlike rigid wall confinement, the free surface functions as a deformable gas-liquid interface whose interaction with the flapping-foil system involves considerably more complex mechanisms: the wave radiation excited by foil motion

dissipates into the far field a portion of the fluid kinetic energy that would otherwise be available for harvesting, while the dynamic deformation of the free surface simultaneously feeds back to interfere with the evolution of the vortical structures in the vicinity of the foil (Qi *et al.*, 2025). It has been established that the effects induced by a free surface differ fundamentally from those of a rigid wall in terms of physical mechanism — rigid wall confinement typically enhances the pressure differential across the foil through a channel acceleration effect, thereby improving performance, whereas the free surface, owing to its compliant and deformable nature, introduces additional wave-making resistance and modifies the evolutionary pathway of the near-foil vortex structures under most operating conditions (Zheng *et al.*, 2024). For active flapping foils, the early work of Grue *et al.* (1988) demonstrated that the unsteady motion of a body near a free surface induces significant wave-making radiation resistance; Filippas and Belibassakis (2014) further analyzed the effects of the free surface and wave environment on the hydrodynamic characteristics of active flapping-foil thrusters, noting that wave excitation can improve the unsteady load distribution over the foil surface under specific operating conditions; Xu *et al.* (2017) systematically investigated the hydrodynamic characteristics of active flapping foils beneath a free surface using velocity potential theory, and both studies indicated that wave-making dissipation effects significantly impair the lift-force work output of the foil. For non-fully-active flapping-foil systems, He *et al.* (2022) found that a deformable free surface exerts a strongly nonlinear spatial influence on the power output of a semi-passive flapping foil; Liu *et al.* (2023) elucidated the interference mechanism of partial confinement boundaries on the work phase of flapping foils; Mann *et al.* (2025) further confirmed that, as submergence depth decreases, the leading-edge and trailing-edge shed vortices on the side adjacent to the free surface undergo violent interactions with the interface, resulting in accelerated vorticity dissipation and free-surface rupture, with a consequent sharp deterioration of the system's energy-harvesting performance.

In summary, previous studies have established a relatively systematic understanding of the hydrodynamic characteristics of active, semi-passive, and fully passive flapping-foil energy-harvesting systems in unconfined flows and under rigid-wall confinement. The influence of a free surface on active and semi-passive configurations has also been preliminarily investigated (Zhu *et al.*, 2023b). However, for fully passive systems relying entirely on self-excited oscillations, the influence of a deformable free surface on the coupled motion and energy-harvesting performance remains understood. In particular, the relationships among submergence depth, vortex evolution, load-motion phase coordination, unsteady hydrodynamic loading, and power extraction have not been systematically established.

To address this research gap, the present study numerically investigates a near-free-surface fully passive NACA0015 flapping foil using the VOF multiphase flow model and an overset-mesh technique. The Reynolds number, foil geometry, pitching-axis location, and structural parameters are kept unchanged, while only the non-dimensional submergence depth is varied to isolate its influence. The specific objectives are to quantify the variation in energy-harvesting efficiency and identify the favorable submergence range; elucidate the coupled effects of free-surface deformation, vortex shedding, motion response, and unsteady hydrodynamic loading on power extraction; and characterize the coherence and convection of foil-surface pressure fluctuations. By connecting the overall energy-harvesting performance with the underlying vortex

dynamics and pressure-fluctuation behavior, this study provides new physical insight into the non-monotonic influence of free-surface proximity on fully passive flapping-foil energy harvesting.

2. Problem description and numerical method

2.1 Physical model

The physical model of the near-free-surface fully passive flapping-foil energy harvesting system is illustrated in Fig. 1. The foil is suspended from a fixed frame via springs and dampers, possessing a heaving degree of freedom along the y -axis and a pitching degree of freedom about the z -axis; the pitch axis is located at a chordwise position of $\frac{x_p}{c} = \frac{1}{3}$ from the leading edge.

In accordance with Newton's second law, the non-dimensional governing equations of heaving and pitching motions for the fully passive flapping-foil system are expressed, respectively, as:

$$m_h^* \ddot{h}^* + S^* (\dot{\theta}^* \cos \theta - \dot{\theta}^{*2} \sin \theta) + k_h^* h + D_h^* \dot{h} = \frac{C_L}{2} \quad (1)$$

$$I_\theta^* \ddot{\theta}^* + S^* \dot{h}^* \cos \theta + k_\theta^* \theta + D_\theta^* \dot{\theta} = \frac{C_m}{2} \quad (2)$$

$$\begin{aligned} C_L &= \frac{F_h}{0.5\rho U_\infty^2 bc}, m_h^* = \frac{m_h}{\rho b c^2}, S^* = \frac{S}{\rho b c^3}, k_h^* = \frac{k_h}{\rho U_\infty^2 b}, D_h^* \\ &= \frac{D_h}{\rho U_\infty b c}, C_m = \frac{M_\theta}{0.5\rho U_\infty^2 b c^2}, \\ I_\theta^* &= \frac{I_\theta}{\rho b c^4}, k_\theta^* = \frac{k_\theta}{\rho U_\infty^2 b c^2}, D_\theta^* = \frac{D_\theta}{\rho U_\infty b c^3}, h^* = \frac{h}{c}, \dot{h}^* \\ &= \frac{\dot{h}}{U_\infty}, \ddot{h}^* = \frac{\ddot{h}}{U_\infty^2}, \dot{\theta}^* = \frac{\dot{\theta}}{U_\infty}, \ddot{\theta}^* = \frac{\ddot{\theta}}{U_\infty^2} \end{aligned}$$

wherein the non-dimensional definitions of all parameters are as given above. Here, C_L is the lift coefficient, C_m is the moment coefficient, F_h is the hydrodynamic force in the vertical direction, m_h is the equivalent heaving mass, k_h is the heaving spring stiffness, D_h is the heaving damping coefficient, I_θ is the pitching moment of inertia, M_θ is the pitching moment, k_θ is the pitching spring stiffness, D_θ is the pitching damping coefficient, h is the heaving displacement, θ is the pitching angle, U_∞ is the freestream velocity, ρ is the fluid density, b is the span, and c is the chord length. S ($S = m_\theta x_\theta$) is the static unbalance moment,

where m_θ is the equivalent pitching mass and x_θ is the offset distance of the center of gravity from the pitch axis (taken as positive when the center of gravity is located downstream of the pitch axis); when $S \neq 0$, the terms involving S in the equations of motion are inertial coupling terms, reflecting the dynamic coupling between heaving and pitching motions.

The governing equation system (Eqs. 1 and 2) is advanced in time using a fourth-order Runge–Kutta scheme to obtain the motion response history of the fully passive flapping-foil system. The state vector is introduced as:

$$y = \begin{bmatrix} h \\ \dot{h} \\ \theta \\ \dot{\theta} \end{bmatrix}, \dot{y} = f(y) = \begin{bmatrix} \dot{h} \\ f_h(y) \\ \dot{\theta} \\ f_\theta(y) \end{bmatrix} \quad (3)$$

$$\begin{cases} f_h(y) = \frac{I_\theta(F_h + S\dot{\theta}^2 \sin \theta - D_h \dot{h} - k_h h)}{m_h I_\theta - S^2 \cos^2 \theta} \\ \quad - \text{Scos} \theta (M_\theta - D_\theta \dot{\theta} - k_\theta \theta) \\ f_\theta(y) = \frac{m_h (M_\theta - D_\theta \dot{\theta} - k_\theta \theta)}{-\text{Scos} \theta (F_h + S\dot{\theta}^2 \sin \theta - D_h \dot{h} - k_h h)} \end{cases} / m_h I_\theta - S^2 \cos^2 \theta \quad (4)$$

Substituting the above equations into the fourth-order Runge–Kutta scheme:

$$\begin{cases} K_1 = f(y_n) \\ K_2 = f(y_n + \frac{\Delta t}{2} K_1) \\ K_3 = f(y_n + \frac{\Delta t}{2} K_2) \\ K_4 = f(y_n + \Delta t K_3) \end{cases} \quad (5)$$

$$y_{n+1} = y_n + \frac{\Delta t}{6} (K_1 + 2K_2 + 2K_3 + K_4) \quad (6)$$

Through iterative solution, the time histories of the foil's heaving displacement, pitching angle, and their corresponding translational and angular velocities are obtained.

The fully passive flapping foil extracts fluid kinetic energy through the coordinated heaving and pitching motions. To quantitatively characterize the energy-harvesting performance of the system, the cycle-averaged power coefficient is defined as:

$$\bar{C}_p = \bar{C}_{py} + \bar{C}_{p\theta} \quad (7)$$

where:

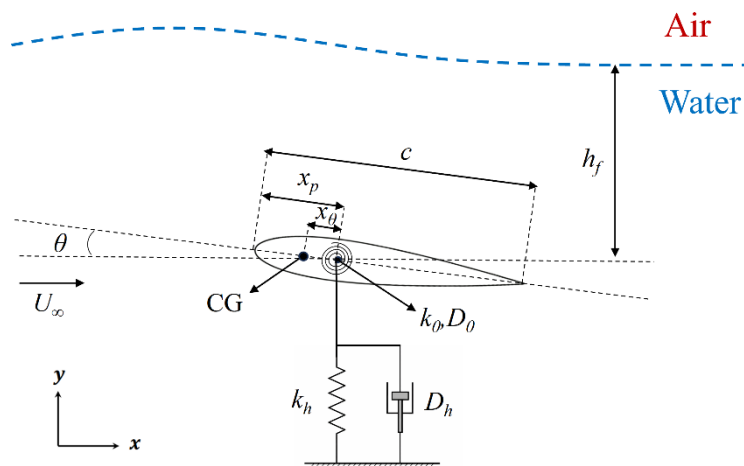


Fig. 1 Schematic of the physical model of the near-free-surface fully passive flapping-foil energy harvesting system.

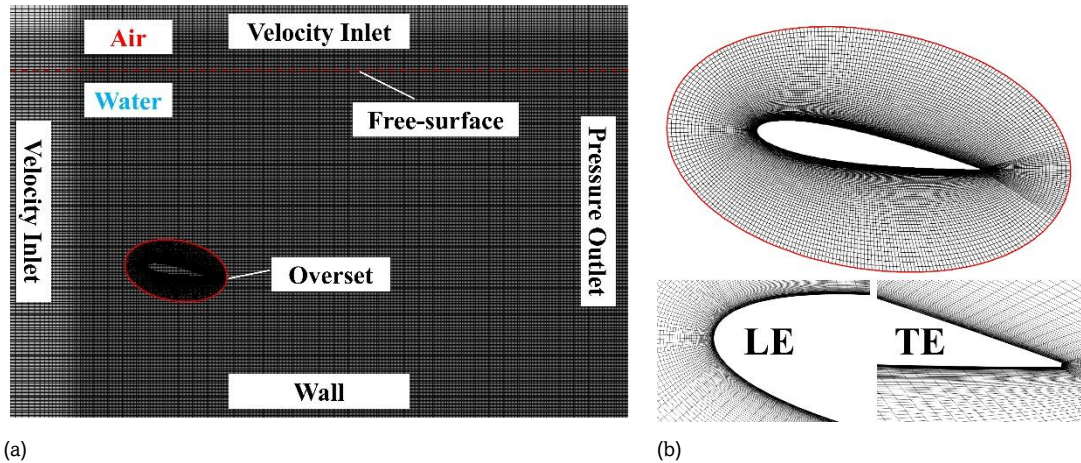


Fig. 2 Schematic of the computational domain boundary conditions and mesh configuration: (a) overall computational domain and boundary condition settings; (b) local mesh distribution in the vicinity of the foil surface.

$$\begin{cases} \bar{C}_{py} = \frac{1}{T} \int_t^{t+T} \frac{F_h \dot{h}}{0.5 \rho U_\infty^3 b c} dt \\ \bar{C}_{p\theta} = \frac{1}{T} \int_t^{t+T} \frac{M_\theta \dot{\theta}}{0.5 \rho U_\infty^3 b c} dt \end{cases} \quad (8)$$

The energy-harvesting efficiency η is defined as the ratio of the cycle-averaged extracted power $\bar{P}$ to the total kinetic energy flux of the incoming flow passing through the swept area of the foil P_a , where d denotes the peak-to-peak heaving displacement of the pitch axis (center of rotation), i.e., $d = h_{max} - h_{min}$.

$$\eta = \frac{\bar{P}}{P_a} = \frac{\frac{1}{T} \int_t^{t+T} P(t) dt}{0.5 \rho U_\infty^3 b d} \quad (9)$$

$$P(t) = F_h(t) \dot{h}(t) + M_\theta(t) \dot{\theta}(t) \quad (10)$$

In addition, the following kinematic characteristic parameters are introduced to further characterize the dynamic response of the fully passive flapping foil: the heaving amplitude $h_0 = \frac{h_{max} - h_{min}}{2}$, the pitching amplitude $\theta_0 = \frac{\theta_{max} - \theta_{min}}{2}$, the reduced frequency $f^* = \frac{f c}{U_\infty}$, and the Reynolds number $Re = \frac{U_\infty c}{\nu}$. Here, h_{max} and h_{min} are the maximum and minimum values of the heaving motion, respectively; θ_{max} and θ_{min} are the maximum and minimum values of the pitching angle, respectively; and ν is the kinematic viscosity of the fluid.

Following Kinsey and Dumas (2012), Veilleux and Dumas (2017) determined an optimized configuration for a fully passive flapping foil through inverse parameter identification and gradient-like optimization. To isolate the effect of submergence depth, the final optimized configuration reported by Veilleux and Dumas (2017) is adopted as the baseline in the present study. Accordingly, the Reynolds number ($Re = 5 \times 10^5$), foil profile (NACA 0015), pitching-axis location ($\frac{x_p}{c} = \frac{1}{3}$), and all non-dimensional structural parameters are kept unchanged, while only the non-dimensional submergence depth ($\frac{h_f}{c}$) is varied. Here, the chord length c is employed as the characteristic length to quantify the relative distance between the foil and the free surface. The investigated submergence-depth range is selected to cover the transition from strong near-interface interference to weak free-surface influence approaching the unconfined condition, thereby enabling the detrimental, beneficial, and asymptotic regimes to be compared. The adopted structural parameters are summarized in Table 1.

2.2 Numerical method and grid configuration

Figure 2 presents the computational domain and two-dimensional structured mesh configuration employed in the numerical simulation of the near-free-surface fully passive flapping foil. The computational domain dimensions are set to $200c \times 80c$. To account for the two-phase flow characteristics of the free surface, the Volume of Fluid (VOF) method is activated in ANSYS Fluent with the Open Channel Flow mode enabled. As shown in Fig. 2(a), the left boundary is specified as a pressure

Table 1

Non-dimensional structural parameters adopted from the optimized case reported by Veilleux and Dumas (2017) ($Re = 5 \times 10^5$)

Parameter	Value
m_h^*	3.036
k_h^*	1.206
D_h^*	1.501
I_θ^*	0.095
k_θ^*	0.031
D_θ^*	0.119
S^*	-0.029

inlet (Pressure Inlet), the right boundary as a pressure outlet (Pressure Outlet), and both the upper and lower boundaries as velocity inlets (Velocity Inlet) consistent with the incoming freestream velocity; a no-slip wall condition is imposed on the foil surface. To effectively simulate the large-amplitude unsteady motion of the flapping foil without inducing mesh distortion, the overset mesh (Overset Grid) technique is employed to accommodate the relative motion between the component mesh and the background mesh, with inter-mesh flow field information transferred via the Overset Interface interpolation scheme. As shown in Fig. 2(b), the mesh is refined in the vicinity of the foil surface to ensure a non-dimensional wall distance of $y^+ < 1$ in the near-wall region; local mesh refinement is simultaneously applied in the foil wake region and in the vicinity of the free surface to accurately resolve the evolution of wake vortical structures and the dynamic deformation of the free-surface profile.

The pitching and heaving responses of the foil are obtained by solving Eqs. (1) and (2) in real time through a user-defined function (UDF), which subsequently drives the overset-mesh motion. A transient pressure-based solver is employed, with pressure-velocity coupling achieved using the Coupled algorithm. Turbulence closure is performed using the $k-\omega$ SST model, while a second-order upwind scheme is used for spatial discretization. A first-order implicit scheme is adopted for temporal discretization, with a time-step size of $\Delta t = 0.005$ s, as determined by the time-step independence study in Section 3.1. At each time step, the inner iterations are terminated when the scaled residuals of continuity, momentum, k , and ω decrease below 10^{-4} . Each case is simulated for 10 complete oscillation cycles, and the data from the final cycle are used for statistical analysis.

3 Method validation

3.1 Sensitivity of grid and timestep

To assess the influence of mesh density and time-step size on the numerical results, a sensitivity analysis is conducted for a near-free-surface case at submergence depth $\frac{h_f}{c} = 2.8$, with the structural parameters kept consistent with those in Table 1. Under the prerequisite of maintaining $y^+ < 1$ in the near-wall region, three mesh configurations (Grid 1, Grid 2, and Grid 3) are constructed by adjusting the number of circumferential nodes N_θ , radial nodes N_r , and vertical nodes in the vicinity of the free surface N_f ; the specific parameters are summarized in Table 2. Figure 3(a) presents the time histories of the lift coefficient C_L for the three mesh configurations, with Grid 2 taken as the reference to compute the peak relative error of each scheme. The results indicate that the discrepancy between Grid 1 and Grid 2 is negligible and falls within an acceptable range,

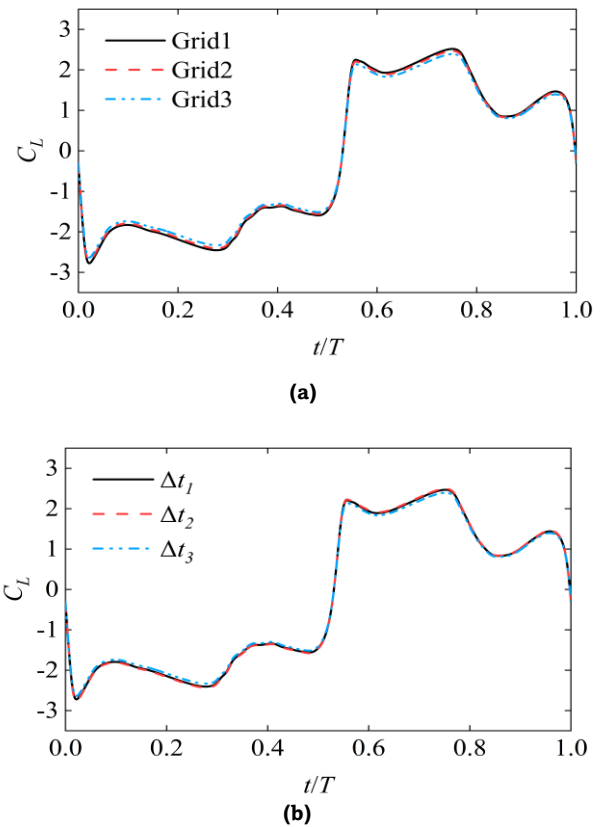


Fig. 3 Grid and time-step independence study: (a) effect of mesh resolution on lift coefficient C_L ; (b) effect of time-step size on lift coefficient C_L .

whereas Grid 3 exhibits a comparatively pronounced deviation. Considering both computational accuracy and resource consumption, Grid 2 is selected as the standard mesh for all subsequent computations. On this basis, a time-step independence study is further carried out using Grid 2, with the results shown in Fig. 3(b) and Table 2. The lift coefficient curves obtained with $\Delta t_1 = 0.005$ s and $\Delta t_2 = 0.0025$ s show good agreement, whereas the computational error increases significantly at $\Delta t_3 = 0.01$ s. Accordingly, $\Delta t_1 = 0.005$ s is adopted for the numerical solution of all subsequent cases.

3.2 Validation

Since no directly comparable numerical results for a near-free-surface fully passive flapping foil are available in the literature, validation is performed separately by comparing against computational results for a foil in an unconfined flow and

Table 2
Summary of grid refinement schemes and time-step independence study

Grids	Time step (s)		N_θ	N_r	N_f	Peak of C_L	Error
Grid 1	Δt_1	0.005	600	540	120	2.518	1.985 %
Grid 2	Δt_1	0.005	400	360	90	2.469	---
Grid 3	Δt_1	0.005	270	240	60	2.392	3.119%
Grid 2	Δt_2	0.0025	400	360	90	2.493	0.972%
Grid 2	Δt_3	0.01	400	360	90	2.396	2.957%

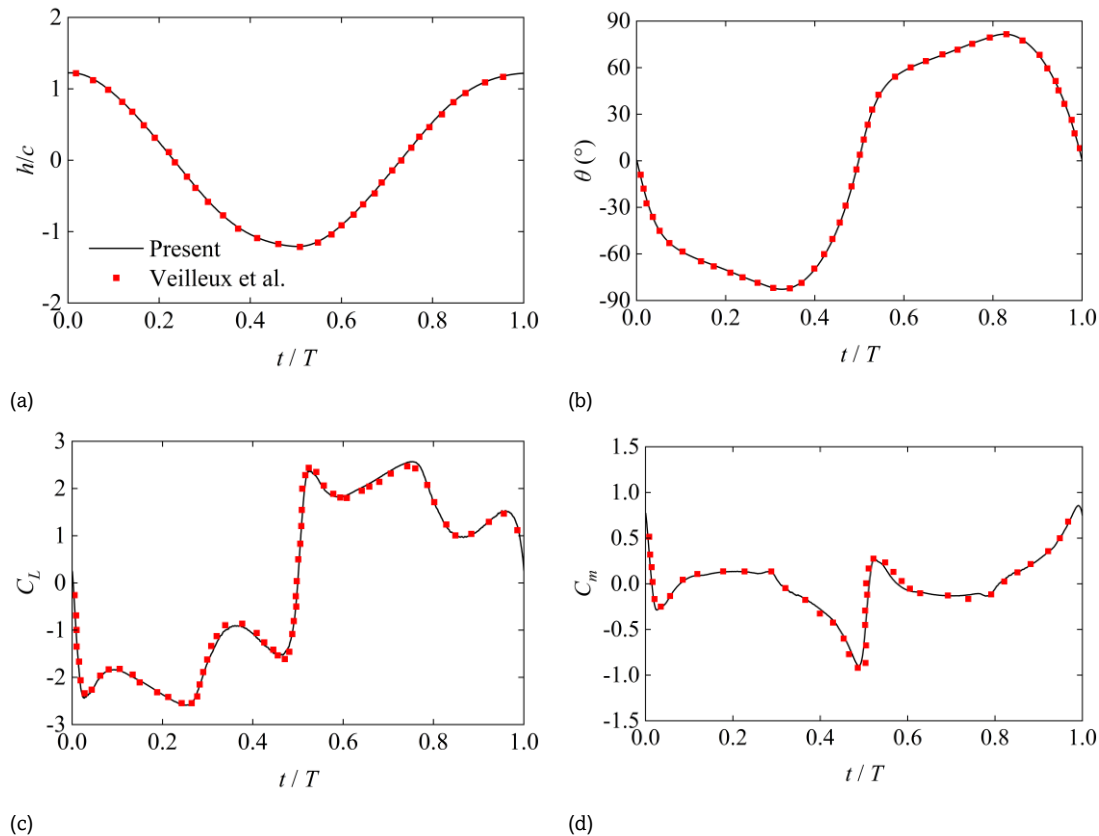


Fig. 4 Validation of numerical results against the numerical results of Veilleux and Dumas (2017): (a) heaving displacement $\frac{h}{c}$; (b) pitching angle θ ; (c) lift coefficient C_L ; (d) pitching moment coefficient C_m .

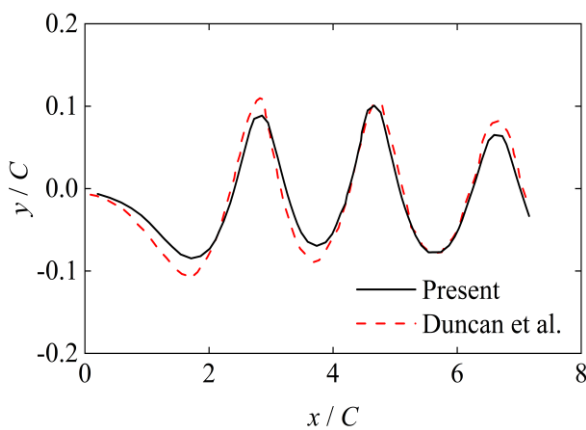


Fig. 5 Validation of numerical free-surface wave profiles against the experimental data of Duncan ($Re=1.624 \times 10^5$, $Fr=0.5672$).

for a static hydrofoil near a free surface. To verify the reliability of the numerical methodology employed in the present study for flapping-foil simulations, the simulation results obtained under the unconfined flow condition ($Re=5 \times 10^5$) are compared with the numerical data of Veilleux and Dumas (2017). Figure 4 presents the time histories of the instantaneous heaving displacement $\frac{h}{c}$, pitching angle θ , lift coefficient C_L , and moment coefficient C_m over one complete oscillation cycle. The results demonstrate that the present simulation results are in good agreement with the reference data in terms of waveform characteristics, amplitude, and phase, thereby validating the accuracy and reliability of the numerical method employed.

To further validate the accuracy of the VOF method in capturing free-surface wave profiles, an additional validation case is computed for a NACA0012 hydrofoil at an angle of attack of 5° and a submergence depth of $\frac{h_f}{c}=0.953$, under conditions of $Re=1.624 \times 10^5$ and $Fr=\frac{U_\infty}{\sqrt{g c}}=0.5672$. The resulting free-surface wave profile is compared with the experimental data of Duncan (1983), as shown in Fig. 5. The numerical results show good agreement with the experimental data in terms of wave phase and overall profile, and the minor amplitude discrepancy observed is primarily attributable to the inherent simplification of three-dimensional end effects in the two-dimensional numerical simulation. The foregoing comparison demonstrates that the VOF model employed in the present study is capable of effectively capturing the dynamic deformation characteristics of the free-surface profile in the vicinity of the foil.

4 Results and discussion

4.1 Energy-harvesting performance and flow characteristics

Figure 6 presents the variation of the energy-harvesting efficiency η of the fully passive flapping foil as a function of submergence depth $\frac{h_f}{c}$; all cases are conducted under conditions of $Re=5 \times 10^5$ and $Fr=0.1581$. The horizontal dashed line in the figure corresponds to the baseline case without free-surface confinement ($\eta=42.51\%$). The results reveal that the free-surface effect exerts a distinctly non-monotonic influence on the energy-harvesting efficiency of the fully passive flapping foil. At $\frac{h_f}{c} \leq 1.8$, strong free-surface

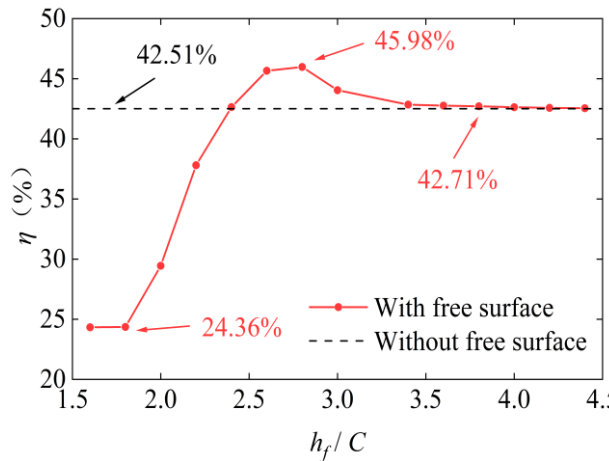


Fig. 6 Variation of energy-harvesting efficiency η of the fully passive flapping foil with submergence depth $\frac{h_f}{c}$ ($Re = 5 \times 10^5$, $Fr = 0.1581$; dashed line denotes the baseline case without free-surface confinement).

interference causes η to drop substantially. As submergence depth increases, η gradually recovers and surpasses the baseline value, attaining a peak of approximately 45.98% at $\frac{h_f}{c} = 2.8$, demonstrating a pronounced free-surface enhancement

effect. At $\frac{h_f}{c} \geq 3.5$, the free-surface effect progressively diminishes and η approaches the level of the baseline case without free-surface confinement. To systematically elucidate the mechanism by which the free surface modulates the energy-harvesting efficiency of the fully passive flapping foil, three representative submergence depths are selected for subsequent analysis: $\frac{h_f}{c} = 1.8$ (strong suppression regime), $\frac{h_f}{c} = 2.8$ (optimal energy-harvesting regime), and $\frac{h_f}{c} = 3.8$ (negligible free-surface effect regime), corresponding to three characteristic states of performance deterioration, performance enhancement, and convergence toward the baseline, respectively, for in-depth flow field analysis and mechanistic investigation.

Figure 7 compares the instantaneous vorticity fields over one oscillation cycle at three representative submergence depths. At ($\frac{h_f}{c} = 2.8$) and 3.8, leading- and trailing-edge vortices of alternating signs are shed periodically and convect downstream in an organized manner, forming a coherent antisymmetric vortex street. This regular vortex evolution produces repeatable unsteady loading and maintains the phase coordination between the hydrodynamic forces and foil motion, thereby supporting continuous positive power extraction through the heaving motion. Compared with ($\frac{h_f}{c} = 3.8$), the more concentrated near-interface vorticity layer at ($\frac{h_f}{c} = 2.8$) indicates a stronger but still moderate free-surface interaction. The resulting local flow enhancement increases the unsteady

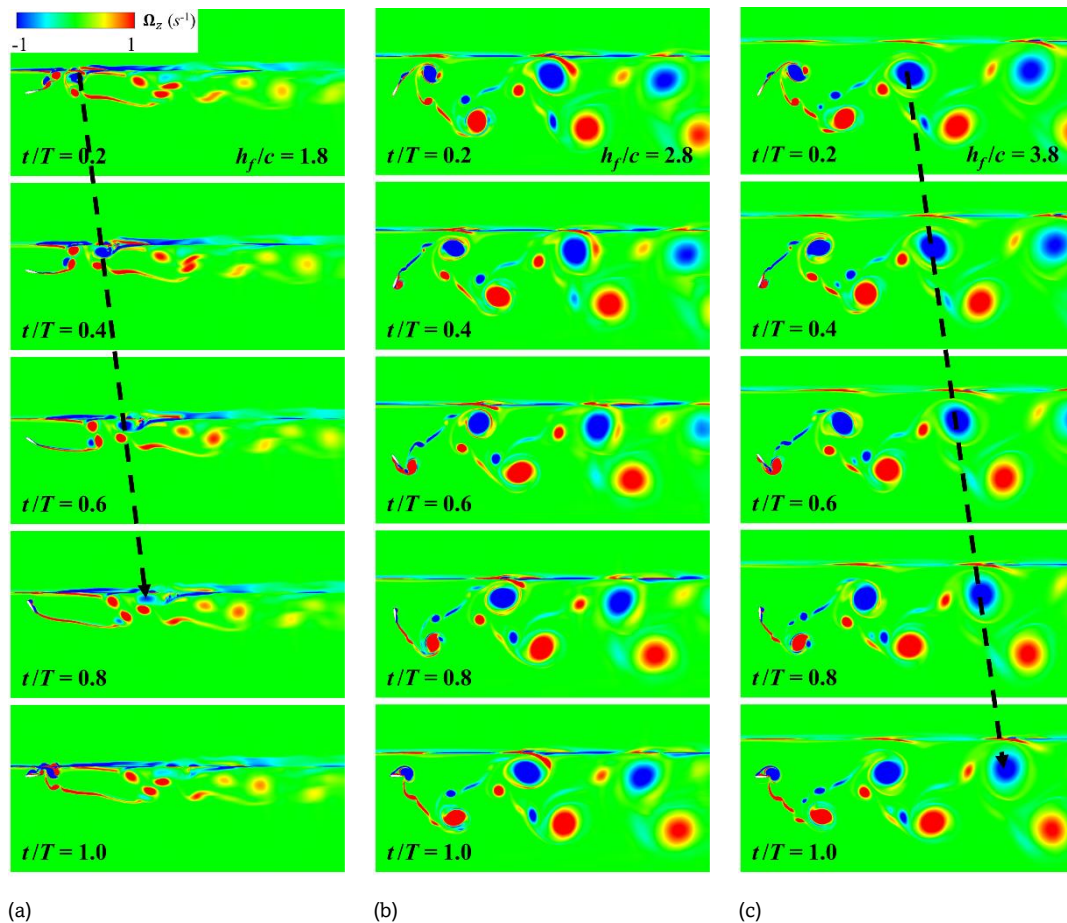


Fig. 7 Instantaneous vorticity fields of the fully passive flapping foil at different instants within one oscillation cycle ($\frac{t}{T} = 0.2-1.0$) for different submergence depths $\frac{h_f}{c}$ ($Re = 5 \times 10^5$, $Fr = 0.1581$): (a) $\frac{h_f}{c} = 1.8$; (b) $\frac{h_f}{c} = 2.8$; (c) $\frac{h_f}{c} = 3.8$. The black dashed lines indicate the trajectories of representative shed vortices.

hydrodynamic loading without disrupting the organized vortex evolution, which contributes to the maximum energy-harvesting efficiency observed at this depth.

At ($\frac{h_f}{c}=1.8$), the vortices shed on the free-surface side interact strongly with the deforming interface and can no longer convect downstream regularly. The leading- and trailing-edge vortices are stretched and fragmented into small-scale structures, while part of the vorticity accumulates near the trailing edge, resulting in the loss of wake coherence and half-cycle symmetry. This disorganized vortex evolution enhances vorticity dissipation and wave-radiation losses and produces irregular hydrodynamic loading. Consequently, the load-motion phase coordination deteriorates, leading to the negative heaving-power interval and the substantial reduction in positive pitching power shown in Figs. 8 and 9. These mechanisms explain the pronounced deterioration of energy-harvesting performance at shallow submergence.

To further elucidate the origins of the differences in energy-harvesting efficiency among the three representative submergence depths, Figure 8 presents a comparative analysis of the heaving displacement $\frac{h}{c}$, pitching angle θ , lift coefficient C_L , and pitching moment coefficient C_m over one complete oscillation cycle for the three cases. For the two deeper submergence cases ($\frac{h_f}{c}=2.8$ and $\frac{h_f}{c}=3.8$), the curves exhibit highly consistent trends, with both heaving and pitching motions displaying well-defined half-cycle antisymmetric characteristics; the kinematic trajectories of the first and second half-cycles are approximately mirror-symmetric. The pitching angle θ varies over a range of approximately -80° to 90° , and both C_L and C_m exhibit regular large-amplitude periodic oscillations, indicating that free-surface interference with the foil motion is limited at these submergence depths and that the

system is capable of sustaining stable, high-efficiency limit-cycle oscillations. By contrast, the motion response and hydrodynamic characteristics undergo significant changes at $\frac{h_f}{c}=1.8$. The heaving amplitude $\frac{h}{c}$ is markedly reduced, the variation range of the pitching angle θ narrows to approximately -10° to 60° , and the half-cycle symmetry of the motion is disrupted. Concurrently, the peak value of C_L drops substantially and the waveform exhibits pronounced distortion; unlike the deeper submergence cases in which C_m oscillates regularly above and below zero, the C_m at $\frac{h_f}{c}=1.8$ remains nearly stationary in the vicinity of zero for the majority of the cycle, exhibiting only a single pronounced positive peak at the instant when the pitching angle approaches its maximum value ($\theta \approx 60^\circ$), indicating that the periodic work capacity of the pitching motion is severely impaired and that it is unable to provide sustained effective driving of the pitching motion. The foregoing compression of motion amplitudes and distortion of hydrodynamic characteristics collectively indicate that the strong free-surface interference disrupts the phase coordination between heaving and pitching motions and augments the energy dissipation associated with the undulating free surface, thereby leading to a significant reduction in energy-harvesting efficiency at $\frac{h_f}{c}=1.8$.

Figure 9 compares the instantaneous evolution of the total power coefficient C_p and its heaving component C_{py} and pitching component $C_{p\theta}$ over one oscillation cycle at three submergence depths $\frac{h_f}{c}$. As indicated by Eq. (8), the instantaneous power is the product of the hydrodynamic load and the corresponding kinematic velocity; the power curves therefore collectively reflect the degree of phase coordination between the loads and the motions. Overall, the energy

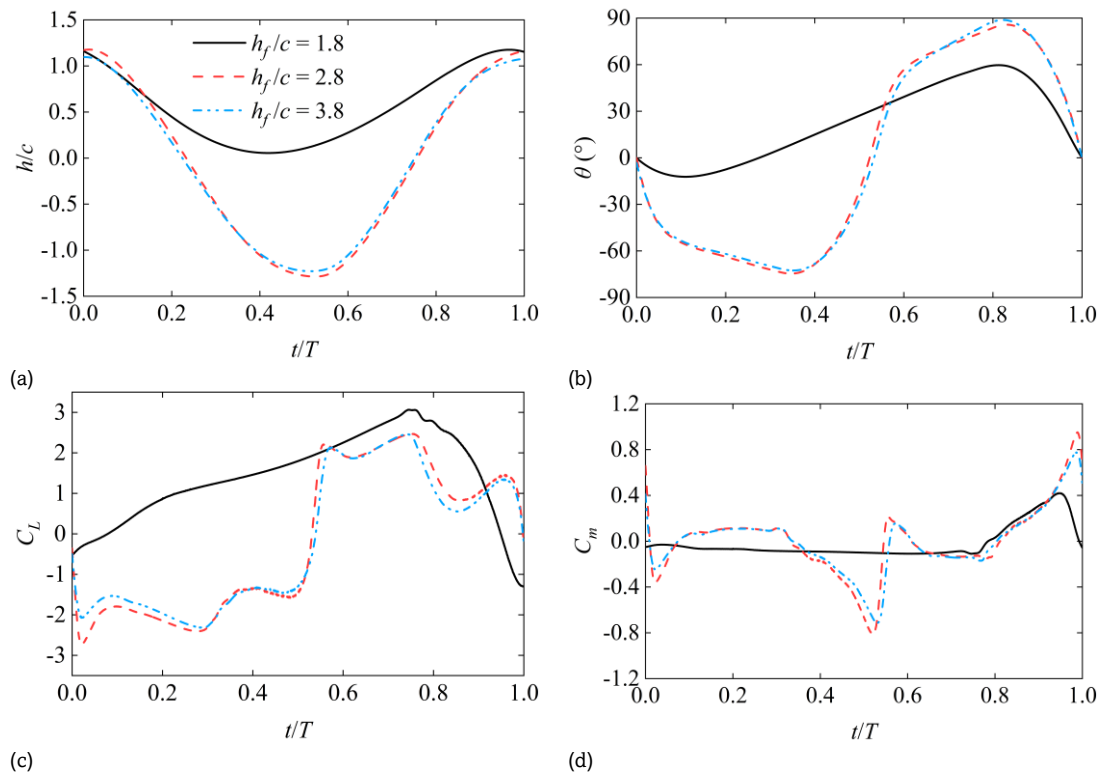


Fig. 8 Comparison of motion response and hydrodynamic characteristics of the fully passive flapping foil over one complete oscillation cycle at three submergence depths $\frac{h_f}{c}$ ($Re = 5 \times 10^5$, $Fr = 0.1581$): (a) heaving displacement $\frac{h}{c}$; (b) pitching angle θ ; (c) lift coefficient C_L ; (d) pitching moment coefficient C_m .

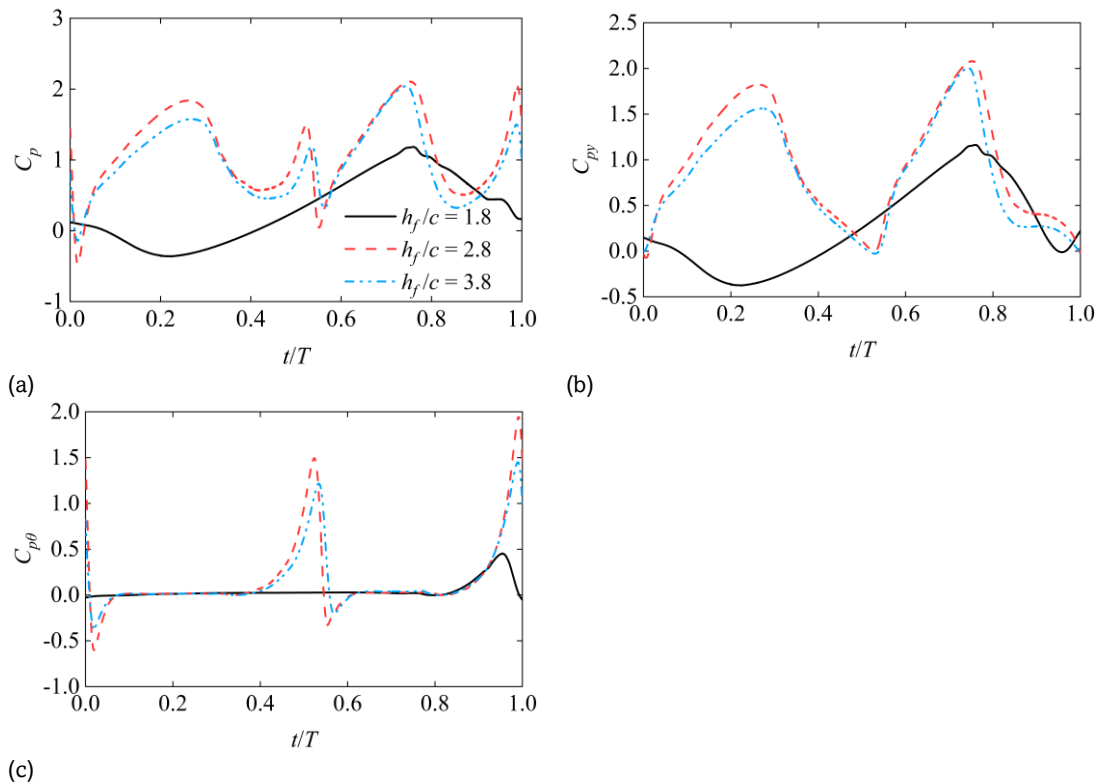


Fig. 9 Instantaneous variation of the total power coefficient C_p , heaving power coefficient C_{py} , and pitching power coefficient $C_{p\theta}$ over one oscillation cycle at three submergence depths $\frac{h_f}{c}$ ($Re = 5 \times 10^5$, $Fr = 0.1581$): (a) C_p ; (b) C_{py} ; (c) $C_{p\theta}$.

harvesting of the system is dominated by the heaving component: C_{py} maintains a relatively large amplitude throughout the entire cycle, whereas $C_{p\theta}$ appears only in the form of brief pulses during the extremely short intervals around pitching reversal ($\theta \approx 0$, where the pitching angular velocity is at its maximum), remaining close to zero at all other instants.

For the two selected cases at moderate submergence depths ($\frac{h_f}{c} = 2.8$ and 3.8), C_{py} exhibits an approximately symmetric double-peaked structure between the first and second half-cycles, consistent with the half-cycle antisymmetric characteristics of the heaving–pitching motions shown in Fig. 8; the peak values of each component at the optimal case $\frac{h_f}{c} = 2.8$ are slightly higher than those at $\frac{h_f}{c} = 3.8$, corresponding to the marginally higher energy-harvesting efficiency of the former in Fig. 6. Furthermore, C_{py} at the moderate submergence cases remains essentially positive throughout the entire cycle with no pronounced negative region, indicating that the heaving force is always aligned with the direction of motion and that energy is continuously extracted. By contrast, a pronounced negative region appears in the interval $\frac{t}{T} \approx 0.1$ – 0.4 for the $\frac{h_f}{c} = 1.8$ case, indicating that the foil expends energy doing work on the fluid rather than extracting energy during this phase; moreover, free-surface wave energy absorption causes a substantial reduction in the peak heaving-force work output at this shallower depth. The pitching angle range and pitching moment coefficient C_m at this case are both compressed (see Fig. 8), causing $C_{p\theta}$ to remain nearly zero throughout the entire cycle and the pitching motion to almost completely lose its capacity for positive work output. It is thus evident that the weakening of heaving-force work capacity and the loss of pitching-moment work capacity together result in a cycle-averaged power at the shallow

submergence case that is far lower than at the moderate submergence cases, thereby quantitatively corroborating the conclusion of sharply reduced energy-harvesting efficiency at shallow submergence depths observed in Fig. 6.

To examine the influence of submergence depth on the frequency characteristics of the fully passive flapping-foil motion, Figure 10 presents the spectral distributions of the heaving displacement $\frac{h}{c}$ and pitching angle θ for $\frac{h_f}{c}$ in the range of 1.6 – 4 , where $St_h = \frac{f_h c}{U_\infty}$ and $St_\theta = \frac{f_\theta c}{U_\infty}$, with color representing the corresponding normalized amplitude. Across the entire range of submergence depths examined, the dominant frequencies of both the heaving and pitching signals are locked at $St \approx 0.1$, with the dominant frequency locations in excellent mutual agreement, indicating that the system consistently sustains frequency-locked limit-cycle oscillations between the heaving and pitching motions. It is noteworthy that the energy content of the dominant frequency band does not vary monotonically with depth: its amplitude reaches a maximum in the vicinity of $\frac{h_f}{c} \approx 2.4$ – 2.8 , precisely corresponding to the peak efficiency range in Fig. 6, demonstrating that moderate free-surface confinement enhances the energy input to the dominant-frequency motion without altering the oscillation frequency.

As submergence depth decreases to $\frac{h_f}{c} < 2.0$, the dominant-frequency band amplitude weakens markedly and energy spreads into neighboring frequency bands, reflecting that strong free-surface interference renders the limit-cycle oscillations of the flapping foil increasingly irregular; the system energy-harvesting efficiency correspondingly drops below 30% (see Fig. 6), which is mutually corroborated by the breakdown of half-cycle motion symmetry observed in Fig. 8. In addition, the pitching spectrum (Fig. 10(b)) exhibits a weak-amplitude

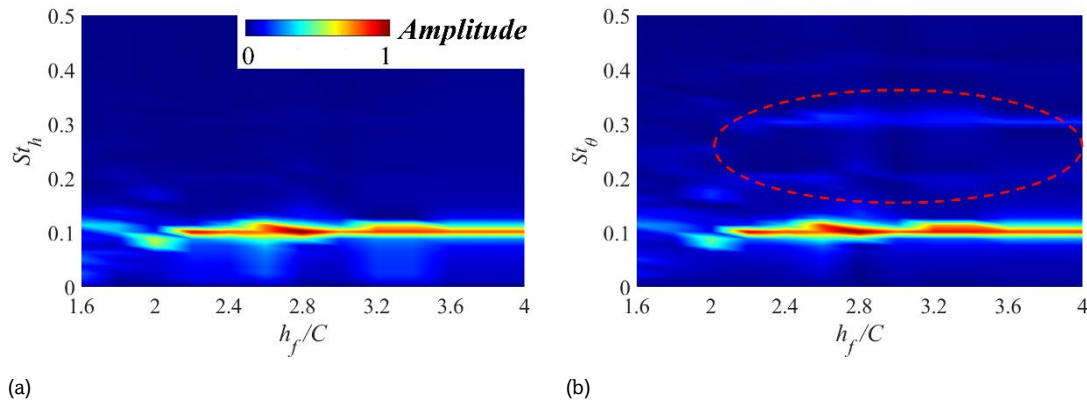


Fig. 10 Spectral comparison of heaving displacement and pitching angle at different submergence depths $\frac{h_f}{c}$ (color represents normalized amplitude, $Re=5\times 10^5$, $Fr=0.1581$): (a) heaving St_h ; (b) pitching St_θ .

frequency band traversing all depths at $St_\theta \approx 0.2$ and 0.3 (approximately twice and three times the dominant frequency, respectively), whereas the heaving spectrum contains virtually no such components. This indicates that the pitching motion contains pronounced second- and third-order harmonics, rendering its spectral composition considerably more complex than that of the heaving motion.

Figure 11 presents the instantaneous evolution of the near-foil free-surface wave profile over one oscillation cycle ($\frac{t}{T}=0-1.0$) at three submergence depths, where $\frac{\Delta h}{c}$ denotes the wave elevation relative to the undisturbed free surface, extracted from the iso-contour of gas-phase volume fraction $\alpha_w=0.5$; the

streamwise coordinate $\frac{x^*}{c}$ is referenced to the initial position of the pitch axis ($x^*=x+x_p$) as the origin. For the two deeper submergence cases ($\frac{h_f}{c}=2.8$ and 3.8), the free-surface undulation is confined to a narrow region directly above the foil and decays rapidly in both the upstream and downstream directions, with an overall wave amplitude that is very small ($|\frac{\Delta h}{c}|$ on the order of ± 0.005); the wave amplitude decreases further with increasing submergence depth. Meanwhile, the wave profiles at $\frac{t}{T}=0$ and $\frac{t}{T}=1.0$ are nearly coincident, indicating that the interface responds to the foil motion with good periodicity. Comparing the two, the wave amplitude on

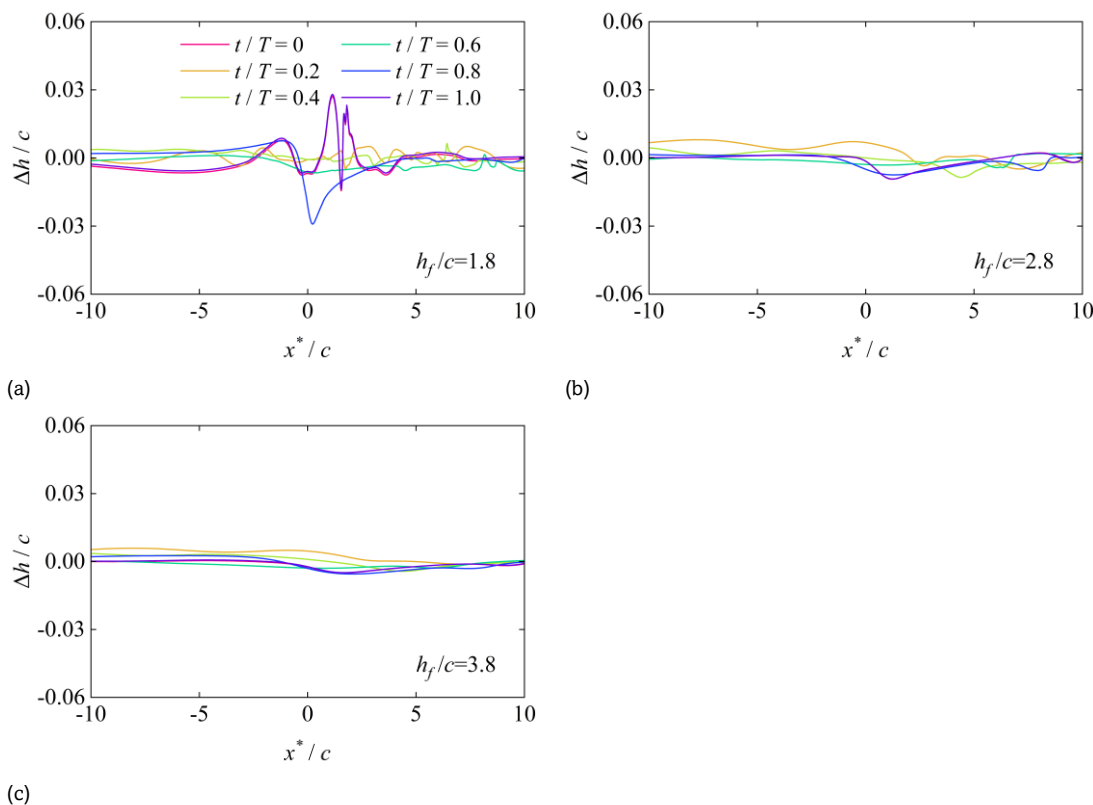


Fig. 11 Instantaneous evolution of the near-foil free-surface wave profile over one oscillation cycle at different submergence depths ($Re=5\times 10^5$, $Fr=0.1581$): (a) $\frac{h_f}{c}=1.8$; (b) $\frac{h_f}{c}=2.8$; (c) $\frac{h_f}{c}=3.8$.

the downstream side of the foil at $\frac{h_f}{c} = 2.8$ is slightly stronger than at $\frac{h_f}{c} = 3.8$, consistent with the characteristics of stronger free-surface effect and highest energy-harvesting efficiency at the former.

When the submergence depth decreases to $\frac{h_f}{c} = 1.8$, the free-surface response is substantially enhanced: the overall wave amplitude increases by approximately one order of magnitude, and the distance over which the disturbance propagates downstream is markedly extended, indicating that the foil motion transports considerably more energy in the downstream direction in the form of wave radiation at this depth. Even so, the wave profiles at $\frac{t}{T} = 0$ and $\frac{t}{T} = 1.0$ remain essentially coincident at the primary peak directly above the foil, demonstrating that the free-surface deformation is still directly driven by the periodic motion of the fully passive flapping foil and retains good cycle-to-cycle reproducibility. Further comparison of the interface wave profile with the foil pitching motion reveals a strong phase correlation between the two: at $\frac{t}{T} \approx 0.8$, the free surface above the foil exhibits a pronounced trough, at which instant the pitching angle θ of this case in Fig. 8(b) precisely attains its positive extremum; at $\frac{t}{T} = 0$ and 1.0 , the pitching angle returns to the vicinity of its equilibrium position, and the free surface above the foil transitions to a pronounced crest. This demonstrates that the pitching motion of the flapping foil is the dominant factor driving the deformation of the near-foil free surface, and that the interface response is most intense at the instants of large pitching angle. From the perspective of spatial distribution, the interface undulation is primarily concentrated directly above the foil ($x^* \approx 0$), with the upstream side remaining consistently undisturbed and the downstream side trailing a sustained wave wake. This near-field, large-amplitude interface response that is strongly phase-coupled with the pitching motion in turn interferes with the stable evolution of the surrounding vortical structures, which is mutually corroborated by the sharp reduction in energy-harvesting efficiency at this case in Fig. 6 and the breakdown of vortex street coherence in Fig. 7.

The non-monotonic variation in energy-harvesting efficiency can therefore be interpreted as a competition between the hydrodynamic enhancement induced by moderate free-surface confinement and the energy dissipation and dynamic disruption caused by excessive interface proximity. At ($\frac{h_f}{c} = 2.8$), the moderate confinement strengthens the local flow and unsteady hydrodynamic loading in the vicinity of the foil, while the free-surface deformation and wave-radiation loss remain limited. Consequently, the organized vortex street and the phase coordination between the heaving and pitching motions are preserved, leading to enhanced positive work output, primarily through the heaving motion. At ($\frac{h_f}{c} = 1.8$), the intensified free-surface deformation and wave radiation remove a larger fraction of the available flow energy. Meanwhile, the interaction between the interface and the shed vortices disrupts the wake coherence and the load-motion phase relationship, producing negative heaving-power intervals and an almost complete loss of positive pitching power. At sufficiently large submergence depths, the interaction between the foil and the free surface progressively weakens, and the energy-harvesting performance approaches that of the unconfined baseline case.

4.2 Coherence characteristics of foil-surface pressure fluctuations

To quantitatively reveal the modulation mechanism of the free surface on the spatial coherence of foil surface pressure

fluctuations at different submergence depths $\frac{h_f}{c}$, spatio-temporal cross-correlation analyses are performed separately on the pressure fluctuation signals p' on the upper and lower surfaces of the foil. The normalized cross-correlation coefficient between an arbitrary chordwise position x on the foil surface and the reference point x_c is defined as:

$$\gamma(x, x_c, \tau) = \frac{\overline{p'(x, t)p'(x_c, t + \tau)}}{(\overline{p'^2(x, t)}\overline{p'^2(x_c, t)})^{1/2}} \quad (11)$$

where τ is the time delay. Given that the pressure signal near the leading-edge stagnation point is subject to a strong adverse pressure gradient and is highly localized in nature, the pressure fluctuation p' at $\frac{x}{c} = 0.2$ is selected as the reference point x_c — this location lies within the initial formation region of the leading-edge vortex (LEV) and can stably characterize the pressure fluctuation response on the leading-edge side of the foil. The monitoring points on the foil surface are distributed uniformly along the chordwise direction with a spacing of $\Delta(\frac{x}{c}) = 0.1$.

Figure 12 presents the distributions of the spatial-temporal cross-correlation coefficient $\gamma(x, \tau)$ of the pressure fluctuations p' on the upper surface (US) and lower surface (LS) of the foil at three submergence depths. The peak correlation ridge of γ for each case (indicated by black markers in the figure) exhibits a consistent positive inclination along the chordwise direction — that is, the time delay τ required to reach maximum correlation increases monotonically as the monitoring point moves downstream. This inclined structure indicates that the foil surface pressure fluctuations propagate from the leading edge toward the trailing edge at a finite convection velocity, the physical essence of which is the chordwise convection process of the leading-edge vortex (LEV) following its formation — that is, the convection of the LEV governs the spatial-temporal evolution of the unsteady surface pressure fluctuations on the foil, with both the upper and lower surfaces exhibiting similar propagation characteristics.

It is noteworthy that the morphology of the γ peak correlation ridges at the three submergence depths is highly similar, indicating that the presence of the free surface does not alter the fundamental propagation mechanism of foil surface pressure fluctuations governed by LEV convection. In particular, at $\frac{h_f}{c} = 1.8$, despite the large number of small-scale disorganized vortical structures emerging on the side adjacent to the free surface as shown in Fig. 7, the spatial-temporal coherence of the foil surface pressure fluctuations remains essentially consistent with those at the deeper submergence cases. This demonstrates that the disorganized near-free-surface vortical structures are primarily confined to the free-surface side and do not significantly alter the generation and convection pathway of the LEV on the foil surface side; the influence of the free surface on foil surface loading is manifested primarily through modifications to the intensity and phase of the pressure fluctuations, rather than through changes to the propagation mechanism itself.

To further compare the chordwise evolution of foil surface pressure fluctuation coherence at different submergence depths, Figure 13 presents the chordwise distributions of the peak cross-correlation coefficient γ_{max} on the upper and lower surfaces for each case. All cases attain a local maximum at the reference point $\frac{x}{c} = 0.2$ ($\gamma_{max} = 1$), consistent with the definition of the reference point. Overall, γ_{max} remains above 0.95 for all cases, indicating that the foil surface pressure fluctuations maintain a very high degree of coherence along the chordwise

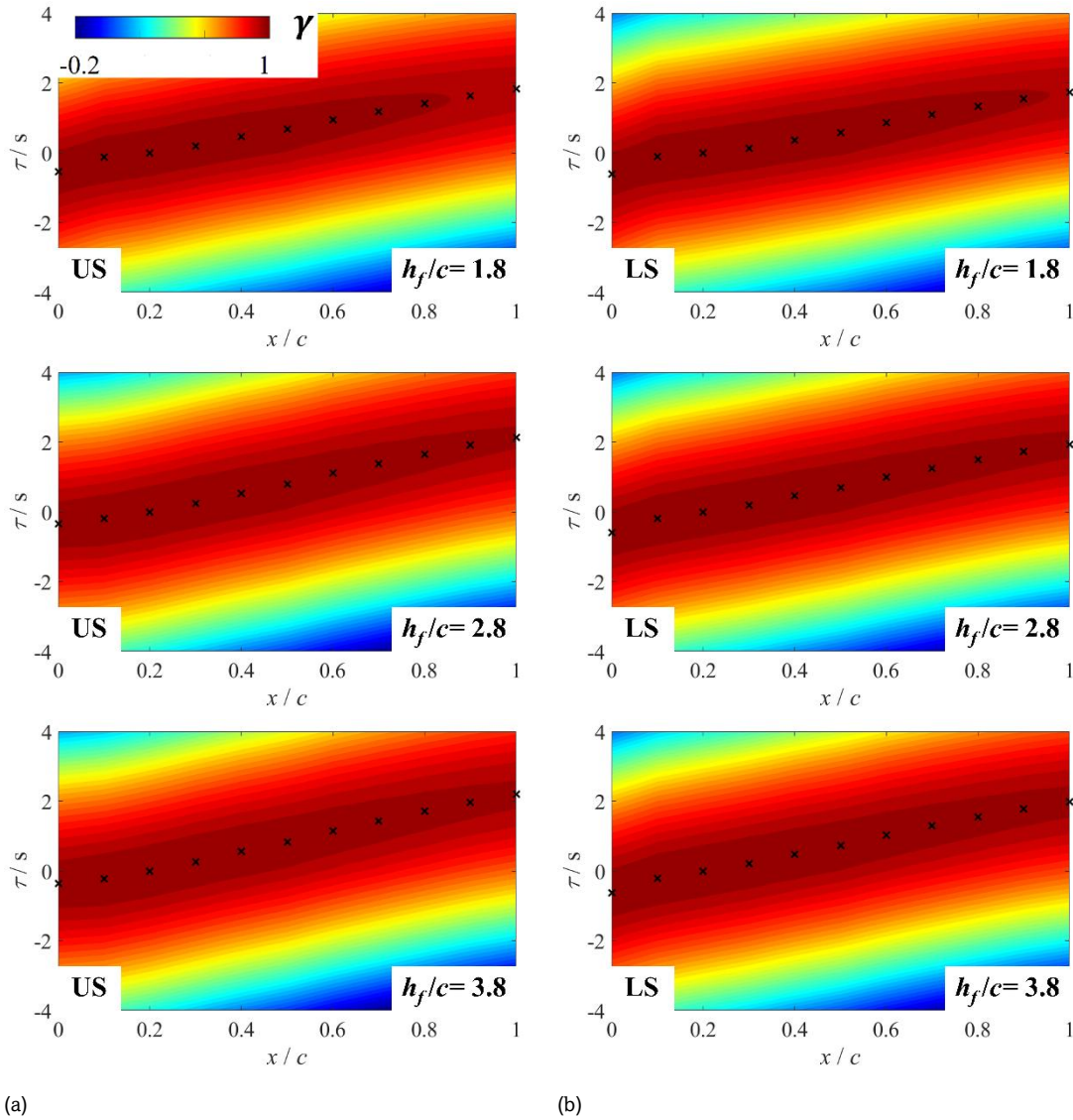


Fig. 12 Distributions of the spatio-temporal cross-correlation coefficient $\gamma(x, \tau)$ of pressure fluctuations p' on the upper and lower surfaces of the foil at different submergence depths $\frac{h_f}{c}$ (reference point $\frac{x}{c}=0.2$, $Re=5\times 10^5$, $Fr=0.1581$): (a) upper surface (US); (b) lower surface (LS).

direction, further corroborating the LEV-convection-dominated pressure fluctuation propagation mechanism identified in Fig. 12.

Further comparison reveals that the chordwise decay of γ_{max} depends on both the submergence depth and the surface location, with the differences concentrated primarily in the aft portion of the chord and most pronounced at the trailing edge (values near the leading edge are generally close to 1 due to proximity to the reference point). On one hand, γ_{max} on both the upper and lower surfaces decreases as submergence depth is reduced; on the other hand, at a given submergence depth, the coherence decay on the upper surface (US), which is closer to the free surface, is markedly faster than on the lower surface (LS). This indicates that the upper surface is subject to more direct influence from the unsteady perturbations of the free surface, causing its chordwise pressure fluctuation coherence to deteriorate more rapidly, while the lower surface, being farther from the interface, retains a more regular pressure fluctuation propagation characteristic.

Based on the peak time delay τ_{max} of the pressure fluctuation at each monitoring point relative to the reference point, the chordwise convection velocity is defined as $U_\omega = \frac{\Delta x}{\Delta \tau_{max}}$, and is obtained by linearly fitting τ_{max} at each monitoring point downstream of the reference point against the non-dimensional chordwise position $\frac{x}{c}$, yielding $U_\omega = \frac{cd(x/c)}{d\tau_{max}}$ (where c is the chord length); its physical significance is the chordwise convection velocity of the leading-edge vortex (LEV). As shown in Figure 14, τ_{max} increases approximately linearly with chordwise position for all cases, and τ_{max} is negative upstream of the reference point ($\frac{x}{c} < 0.2$), indicating that the pressure fluctuation phase in this region leads that of the reference point, consistent with the picture of disturbance propagating from the leading edge in the downstream direction.

The convection velocity exhibits two systematic trends. First, the convection velocities on both the upper and lower surfaces increase as submergence depth decreases, reaching their highest values at $\frac{h_f}{c}=1.8$ ($0.426U_\infty$ and $0.428U_\infty$ for the US

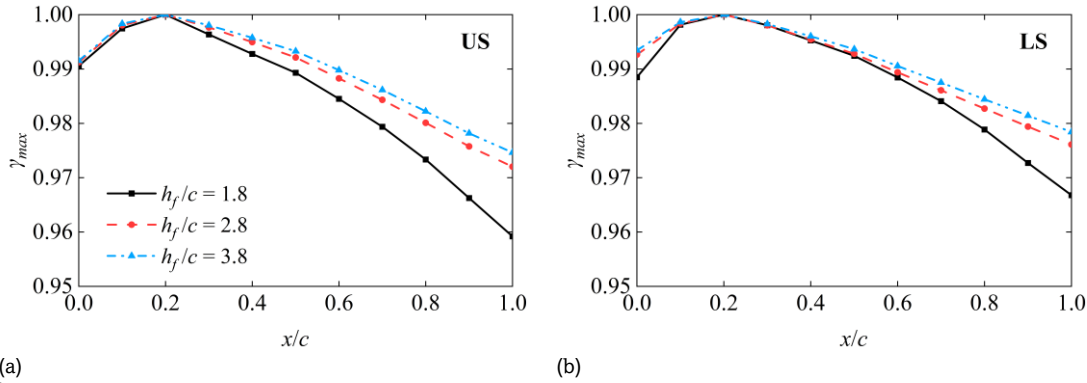


Fig. 13 Chordwise distributions of the peak cross-correlation coefficient γ_{max} of foil surface pressure fluctuations at different submergence depths $\frac{h_f}{c}$ (reference point $\frac{x}{c}=0.2$, $Re=5\times 10^5$, $Fr=0.1581$): (a) upper surface (US); (b) lower surface (LS).

and LS, respectively), indicating that the proximity effect of the free surface augments the local flow velocity in the vicinity of the foil. Second, at the deeper submergence cases ($\frac{h_f}{c}=2.8$ and 3.8), the convection velocity on the lower surface (LS) is markedly higher than on the upper surface (US); as submergence depth decreases, the difference between the upper and lower surfaces progressively narrows, converging toward equality at $\frac{h_f}{c}=1.8$. This surface-to-surface discrepancy can be interpreted in conjunction with the coherence distributions in Fig. 13: the upper surface is in close proximity to the free surface and is most directly subject to the unsteady perturbations of the interface, causing the chordwise convection of its LEV to be retarded by the disturbance, which corresponds to the faster coherence decay observed on the upper surface; the lower surface is farther from the interface and subject to weaker perturbation, so the generation and convection of the LEV more closely resemble regular unidirectional propagation, resulting in a higher convection velocity and better coherence. At the shallowest case of $\frac{h_f}{c}=1.8$, strong free-surface interference substantially elevates the convection velocity across the entire foil surface, masking the surface-to-surface difference. Taken together, Figs. 13 and 14 demonstrate from the perspectives of both coherence and convection velocity that free-surface perturbations act primarily on the upper surface, causing the propagation of its pressure fluctuations to be characterized by simultaneously reduced coherence and retarded convection.

5. Conclusions

Numerical simulations were conducted to investigate the energy-harvesting performance of a near-free-surface NACA0015 fully passive flapping foil at $Re=5\times 10^5$ and $Fr=0.1581$. The energy-harvesting efficiency exhibited a non-monotonic dependence on submergence depth. Strong free-surface interference at $\frac{h_f}{c}\leq 1.8$ sharply reduced the efficiency, whereas a maximum efficiency of 45.98% was obtained at $\frac{h_f}{c}=2.8$, representing an improvement of approximately 8.16% over the unconfined baseline of 42.51%. At $\frac{h_f}{c}\geq 3.5$, the free-surface influence became weak and the efficiency approached the baseline value.

Moderate free-surface interaction preserves the coherent antisymmetric vortex street and the phase coordination among foil motion, hydrodynamic loading, and vortex shedding, thereby enhancing positive power extraction dominated by the heaving motion. At excessively shallow submergence, intensified free-surface deformation and wave radiation disrupt wake coherence and motion symmetry, producing negative heaving-power intervals and substantially suppressing the positive pitching-power contribution. The heaving and pitching motions remain frequency-locked at $St\approx 0.1$, with the dominant-frequency energy being strongest over $\frac{h_f}{c}\approx 2.4-2.8$. Pressure cross-correlation analysis further shows that leading-edge-vortex convection governs the chordwise propagation of surface pressure fluctuations. The free surface modifies their coherence and convection characteristics without altering this

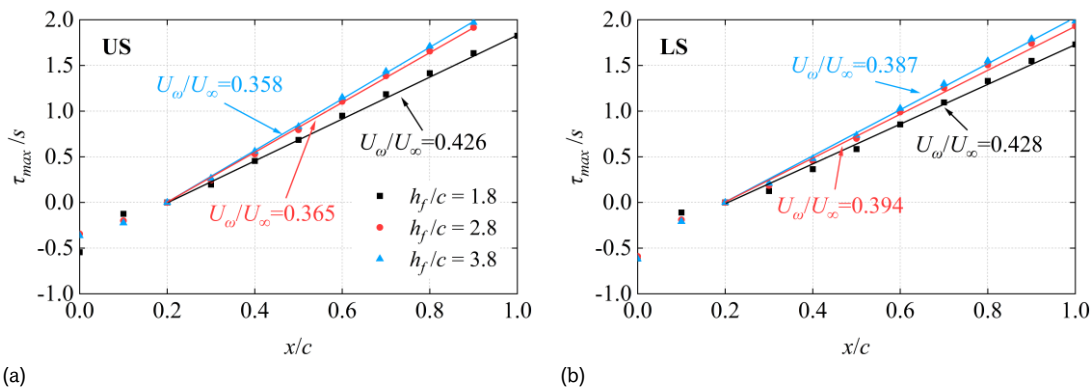


Fig. 14 Chordwise distributions of the peak time delay τ_{max} of foil surface pressure fluctuations p' and the LEV convection velocity U_ω at different submergence depths $\frac{h_f}{c}$ (reference point $\frac{x}{c}=0.2$, $Re=5\times 10^5$, $Fr=0.1581$): (a) upper surface (US); (b) lower surface (LS).

fundamental propagation mechanism, with the upper surface adjacent to the interface being more strongly affected.

Under the flow conditions, foil geometry, and structural parameters considered in this study, $\frac{h_f}{c} = 2.8$ may serve as a preliminary reference for deploying fully passive flapping-foil energy harvesters in rivers, estuaries, and coastal environments, whereas excessively shallow installation should be avoided. This optimum should not be regarded as universal because the present study is limited by the two-dimensional rigid-foil assumption, the use of a single turbulence model, and the neglect of three-dimensional tip effects, structural flexibility, ambient waves, inflow shear, and environmental turbulence. Future research should therefore incorporate three-dimensional simulations and experiments, flexible foils, broader Reynolds- and Froude-number ranges, and realistic unsteady environmental conditions.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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