INTRODUCTION

In recent years, tidal energy has attracted more attention owing to a greater predictability. Conventionally, tidal energy is harvested through turbines with rotating blades. Inspired by aquatic animals and birds, Wu proposed the idea of harvesting energy from wave using the oscillating foils.1 The application of oscillating foils to harvest energy from the uniform flow was first introduced by Mackinney and Delaurier.2 With the increasing importance of renewable energy, the interest in this novel concept has been rekindled in past decades.3,4 Compared with the rotary turbines, the oscillating foil devices have many potential advantages,3-5 including (a) benefit from the low speed environment (b) structural robustness (c) impact slightly upon the environment (d) shallow water application.

Using an unsteady panel code, Jones and Plazter6 demonstrated that the foil would change from energy consumption to energy generation at fixed heaving amplitude and oscillation frequency if the pitching amplitude is sufficiently large. Subsequently, the effects of kinematic parameters and flow evolution of the single foil experiencing a prescribed oscillation motion are thoroughly revealed by researchers using both computational and experimental methods.7,8 Furthermore,
modified motions\textsuperscript{9,10} and flexible foils\textsuperscript{11-13} are employed to improve the hydrodynamic and energy harvesting performance of an oscillating foil.

Recently, some researchers concentrated on the semi-activated system which with an actuated pitching motion but a free heaving motion. Zhu and Peng\textsuperscript{14} revealed that the semi-activated system has a positive power extraction over a large range of operational and mechanical parameters by using a linearized thin-plate model. Further computations using a Navier-Stokes model was performed, the results indicated that the vorticity control mechanisms, especially in the interaction between the foil and leading-edge vortices, affect the performance of the semi-activated system significantly.\textsuperscript{15}

Extensive study has been performed on semi-activated system.\textsuperscript{14-17} Using a Navier-Stokes model, Peng et al examined the device consisting of a single oscillating foil mounted on a damper and a rotational spring.\textsuperscript{5,18} In that study, self-induced and self-sustained oscillating motions were excited by incoming flow and the power harvesting was achieved from the heaving response.

Two oscillating hydrofoils in a suitable configuration may get a better energy extraction performance by comparison of a single foil. Akhtar et al\textsuperscript{19} examined the performance of a foil undergoing oscillating motion in the wake of another oscillating foil using 2D numerical simulation. The results indicated that the vortex shedding from the upstream foil is capable of increasing the thrust of the downstream foil significantly. Lehmam found that wing phase is effective in improving aerodynamic efficiency during flight by the removal of kinetic energy from the wake using computational model.\textsuperscript{20} In that study, the front foil is pitched while the backward foil keeps stationary. Deng et al\textsuperscript{21} numerically investigated the hydrodynamic interactions between 2 tandem foils undergoing fishlike swing motion. The results showed that a fish situated directly behind another one does not always undergo a lower thrust. Pourmostafa et al\textsuperscript{22} investigated the thrust coefficient and efficiency of 2 oscillating foils in tandem arrangement.

Kinsey and Dumas\textsuperscript{23} investigated the interaction between the wake of upstream foil and the downstream foil. They demonstrated that the relative position of the downstream foil plays an important role for energy harvesting performance. Xu revealed that energy harvesting of 2 tandem oscillating foils has a better performance for optimal oscillation frequency and appropriate foil separation distance.\textsuperscript{24} Karbasian et al\textsuperscript{25} investigated the possibility of power harvesting for oscillating foils in tandem arrangement. They found that it is possible to improve performance of an oscillating foil system through multi-stage foils arranged in tandem form. Jones et al\textsuperscript{26} developed a system with 2 foils in a tandem configuration. They concluded that the oscillating foil micro-hydropower generator has significant further development potential. Lefrançois investigated the power harvesting performance of a dual foils turbine for both parallel and tandem configurations.\textsuperscript{27} She carried out low-Reynolds (Re = 1100) numerical simulation using an in-house Lagrangian vortex method, and the results revealed that a power efficiency of 41\% is reached for 2 NACA0015 foils in tandem. In addition to numerical studies, field tests on a 2KW turbine prototype were performed by the Laval University researchers.\textsuperscript{28} The experiments confirmed the competitive performance of the oscillating foil hydrokinetic turbine compared to rotor-blade designs. Kim et al\textsuperscript{29} carried out experimental and consecutive numerical analyses of an oscillating tidal current generator with front-swing and rear-swing flappers.

Most of the existing studies on the 2 oscillating hydrofoils adopt the fully prescribed motion model. The downstream hydrofoil may benefit from the favorable wake interaction. However, it is difficult to keep the 2 hydrofoils in a fixed motion profile in practical applications. The hydrofoils motion will change constantly unless using the external control. Therefore, this study first presents a hydraulic system to achieve the fully flow-induced oscillating motion for 2 hydrofoils. Then, numerical simulations are carried out to review the effect of wake interaction on the response of 2 tandem hydrofoils.

### 2 | PHYSICAL MODEL

If a hydrofoil freely oscillates in both the pitching and heaving degrees of freedom, the power may be transferred from the flow to hydrofoils. Oscillating hydrofoils therefore may be used for harvesting power. A commercial implementation of an oscillating hydrofoils turbine would likely employ a multiple-hydrofoils system. For 2 hydrofoils system, Kinsey et al\textsuperscript{30} and Ma et al\textsuperscript{31,32} proposed a hydraulic system to couple the pitching motions of the first and second hydrofoils to the heaving motion of the second and first hydrofoils, respectively. The hydraulic system achieves the hydrofoils oscillating motion fully induced by flow. The hydraulic system is illustrated in Figure 1.

When 2 hydrofoils situate in the position of Figure 1, the first hydrofoil is in the neutral point of heaving motion with a maximum pitching angle. The second hydrofoil locates in the highest point of heaving motion with a zero pitching angle. The first hydrofoil is at the dead point of pitching motion because the hydrofoil may not pitched in the reverse direction. The second hydrofoil is at the dead point of heaving motion owing to a small lift force. However, the first hydrofoil has a trend of downward motion. Portion of the lift of the first hydrofoil is transmitted to pitch the second hydrofoil. Thus, the lift loaded on the second hydrofoil increases and the heaving motion crosses the dead point. Similarly, the first hydrofoil will overcome its pitching motion dead point when the second hydrofoil moved.
For the multiple-hydrofoils system, the spatial configuration of hydrofoils plays a crucial role on the energy harvesting performances. Two classical spatial arrangements are frequently used, namely, a parallel or a tandem arrangement. For the parallel arrangement, 2 hydrofoils experience the same flow field. That allows hydrofoils harvest more energy. Our previous work has confirmed the feasibility of the hydraulic system when the first and second hydrofoils have a parallel configuration.\textsuperscript{31,32} For tandem arrangement, 2 hydrofoils share the same flow field, the system can reach a higher energy extraction efficiency. However, the second hydrofoil will interfere with the wake of the first hydrofoil when 2 hydrofoils have a tandem configuration. In this study, the tandem arrangement is employed to analyze the effect of wake interaction on the response of fully flow-induced system. Therefore, 2 hydrofoils have a spatial configuration as shown in Figure 1.

Figure 2 presents a predicted profile of hydrofoils motion. The same color indicates the position of 2 hydrofoils at the same moment. Each hydrofoil is capable of oscillating in 2 degrees of freedom, namely, heaving motion $h(t)$ and pitching motion $\theta(t)$. In the figure, $l$ is the chord length. $L$ is the inter-hydrofoil spacing. In this study, the hydrofoil used is a NACA0015 with a pitching axis fixed at 1/3 chord from the leading edge. Where $F_L$ and $M$ indicate, respectively, the lift force and torque. The force coefficient $C_L$ and torque coefficient $C_M$ are defined as follows

$$C_L = \frac{F_L}{\frac{1}{2} \rho U_\infty^2 l}$$

where $\rho$ is flow density.

If no leakage in the hydraulic system, the heaving motion of the hydrofoil has a linear relation with the pitching motion of the other hydrofoil, and this relation can be expressed as

$$\begin{aligned}
\theta_1 &= \beta h_2 \\
\theta_2 &= -\beta h_1
\end{aligned}$$

As mentioned above, the lift loaded on the hydrofoil is used to maintain the heaving motion ($m\ddot{h}$), output energy ($c\dot{h}$) and pitch the other hydrofoil ($F_M$). The torque acting on the hydrofoil is merely used for pitching itself. Consequently, the equilibrium equations can be built in term with hydrodynamic and hydrofoils motion,\textsuperscript{31,32} as following:

$$\begin{aligned}
C_{L1} &= m\ddot{h}_1 + c\dot{h}_1 + C_{FM1} \\
C_{M1} &= I\ddot{\theta}_1 - C_{FM2}/\alpha \\
C_{L2} &= m\ddot{h}_2 + c\dot{h}_2 + C_{FM2} \\
C_{M2} &= I\ddot{\theta}_2 + C_{FM1}/\alpha
\end{aligned}$$
where the subscript 1 and 2 represent, respectively, the corresponding parameters related to the first hydrofoil (upstream hydrofoil) and the second hydrofoil (downstream hydrofoil). \( \dot{h}, \dot{h} \) and \( \dot{\theta} \) represent, respectively, the heaving acceleration, heaving velocity, and angular acceleration. \( \beta \) is a factor associated with the volume ratio between the cylinder and rotary actuator, expressed in \( m/rad \). \( \alpha \) is the factor associated with the radius of rotary actuator, and the dimension of \( \alpha \) is \( 1/m \). \( C_{FM} \) is the component force coefficient of one hydrofoil imposing the other hydrofoil, \( C_{FM} = F_M/I^2 \rho U_\infty^2 l \). For example, \( C_{FM} \) is the component force coefficient exerted by the first hydrofoil (upstream hydrofoil) on the second hydrofoil (downstream hydrofoil). It should be noted that \( C_{FM} \) may be positive or negative. A negative \( C_{FM} \) means that the pitching motion of one hydrofoil propels the heaving motion of the other hydrofoil, \( m^*, c^*, \) and \( I^* \) represent, respectively, the total mass coefficient, damping coefficient and rotational inertia coefficient, and which are defined as follows:

\[
m^* = m/\frac{1}{2} \rho U_\infty^2 l, \quad c^* = c/\frac{1}{2} \rho U_\infty^2 l, \quad I^* = I/\frac{1}{2} \rho U_\infty^2 l^2 \quad (5)
\]

where \( m, c, \) and \( l \) represent, respectively, the total mass (including the mass of hydrofoil and mechanical, and the added mass), damping of cylinder and rotational inertia of hydrofoil system. The mass of hydrofoil is insignificant discrepancy compared with the added mass.\(^3\) In this study, we assume that \( m^* = 1 \) and \( I^* = 0.1 \).

The power coefficient \( C_p \) extracted from the current is from the sum of heaving contribution \( C_{PL} \) and pitching contribution \( C_{PM} \):

\[
C_{PLi} = \frac{2}{\rho U_\infty^3 l} F_{Li}(t) \cdot \dot{h}_i \quad (6)
\]

\[
C_{PMi} = \frac{2}{\rho U_\infty^3 l} M_{Mi}(t) \cdot \dot{\theta}_i \quad (7)
\]

\[
C_{Pi} = C_{PLi} + C_{PMi} (\equiv c \dot{h}_i) \quad (8)
\]

Further define the time-averaged power coefficient by the sum of heaving contribution and pitching contribution:

\[
\bar{C}_P = \bar{C}_{PL} + \bar{C}_{PM} = \frac{1}{T} \int_0^T (C_{PL} + C_{PM}) \, dt \quad (9)
\]

where \( T \) is the fundamental period of oscillating motion. The overall energy harvesting efficiency is defined as

\[
\eta = \frac{\bar{C}_{P1} + \bar{C}_{P2}}{U_\infty \max(H_1, H_2)} \quad (10)
\]

where \( H \) is the hydrofoils’ swept distance. Hydrofoils’ swept distance is the distance between the highest and lowest points of the foil reached. It usually depends on the motion profile of trailing edge. The trailing edge motion can be expressed by the heaving motion and pitching angle. The \( \max(H_1, H_2) \) is the larger one of swept distance of 2 hydrofoils. Owing to the heaving motion and the flow condition, the effective angle of attack \( \alpha_\ast(t) \) is the combination of heaving induced angle and pitching angle, which can be expressed as follows:

\[
\alpha_\ast(t) = \arctan \frac{-h}{U_\infty} - \theta(t) \quad (11)
\]

### 3 | NUMERICAL APPROACH

The governing equations for the unsteady incompressible flow around the NACA0015 hydrofoil are the 2-D Navier-Stokes equations. It can be expressed as follows:

\[
\nabla \cdot \mathbf{u} = 0 \quad (12)
\]

\[
\frac{du}{dt} = f - \frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} \quad (13)
\]

where \( \mathbf{u} \) denotes the velocity, \( f \) is the body force, \( p \) is the pressure and \( \nu \) indicates the viscosity.

To compute the lift force and torque, the commercial code Fluent is employed to solve the Navier-Stokes equations of the hydrofoils. The use of the non-conformal sliding interface allows relative rotary motion between the exterior mesh zone and the hydrofoil near-body mesh zone. The strategy of meshing and the setting of boundary conditions are summarized in Figure 3. Triangle cells are applied for the meshing except boundary which employs quadrilateral cells. The EquiSize Skew which evaluates the quality of meshes is less than 0.6.

Kinsey and Dumas have demonstrated that the choice of turbulence model affects the time-averaged performance indicators slightly.\(^33\) The S-A (Spalart-Allmaras) has lower requirement for the quality of meshing. Therefore, simulations are performed at high Reynolds number (\( Re \approx 10^6 \)) using one-equation S-A turbulence model.\(^9,33\) The PISO (Pressure Implicit with Splitting of Operator) algorithm is selected for pressure-velocity coupling. A \( 10^{-5} \) absolute convergence criteria is set for the continuity and velocity components.

To solve the coupling equations, an iteration scheme is performed. The iteration scheme and hydrofoils motion are fulfilled via user defined functions compiled and linked to the code solver. The steps of iteration scheme are summarized as follows:
Step 1: At the initial stage, 2 hydrofoils are stationary. The pitching angle ($\theta_0$) of the upstream hydrofoils and heaving position ($H_0$) of the downstream hydrofoils are known. The other parameters are valued at zero.

Step 2: The lift and torque are obtained from the Fluent solver. Combined Eqs. (3) and (4), the heaving acceleration and pitching acceleration can be calculated using the same method.

\[
\begin{align*}
\ddot{H}_1^n &= \frac{C_{L1}-cC_{M1}}{m^* + a\beta L^2} \\
\ddot{H}_2^n &= \frac{C_{L2}-cC_{M1}}{m^* + a\beta L^2} \\
\ddot{\theta}_1^n &= \beta \ddot{H}_2^n \\
\ddot{\theta}_2^n &= \beta \ddot{H}_1^n
\end{align*}
\] (14)

where the superscript $n$ indicates the corresponding parameter at time step $n$. At the initial stage, $n$ is zero.

Step 3: In order to update the position of hydrofoils, the Runge-Kutta method is employed to calculate the heaving velocity and displacement at time step $n + 1$. It can be expressed as:

\[
\begin{align*}
\dot{H}^{n+1} &= \dot{H}^n + \frac{1}{6} \left( K_1 + 2K_2 + 2K_3 + K_4 \right) \Delta t \\
\dot{H}^{n+1} &= \dot{H}^n + \frac{1}{6} \left( L_1 + 2L_2 + 2L_3 + L_4 \right) \Delta t
\end{align*}
\] (15)

\[
\begin{align*}
K_1 &= \dot{H}^n, L_1 = \dot{H}^n \\
K_2 &= \dot{H}^n + L_1 \Delta t/2, L_2 = \dot{H}^n + L_1 \Delta t/2 \\
K_3 &= \dot{H}^n + L_2 \Delta t/2, L_3 = \dot{H}^n + L_2 \Delta t/2 \\
K_4 &= \dot{H}^n + L_3 \Delta t, L_4 = \dot{H}^n + L_3 \Delta t
\end{align*}
\]

velocity and pitching angle can be calculated using the same method.

Step 4: Repeat the above steps and update the position of hydrofoils.

In our previous studies, the meshing system and numerical set-up have been validated in terms of the grid parameters combinations. Therefore, the factors of $\alpha$ and $\beta$ keep, respectively, a value of 1 and 0.5.

4 | RESULTS AND DISCUSSIONS

The objective of this study is to review the effect of wake interactions on the response of 2 tandem hydrofoils. The system can achieve different oscillation frequencies and heaving amplitudes by changing the factors of $\alpha$ and $\beta$. A large number of numerical simulations have been carried out at different parameters combinations. Wake interactions have a similar effect on 2 hydrofoils response for different parameters combinations. Therefore, the factors of $\alpha$ and $\beta$ keep, respectively, a value of 1 and 0.5.
Heaving responses of hydrofoils are the significant indicator which demonstrates the feasibility of the hydraulic system. Therefore, the heaving responses of 2 hydrofoils are examined first, as shown in Figure 5. The figure demonstrates the feasibility of the hydraulic system for 2 hydrofoils with a tandem arrangement. The curve shape shows that 2 hydrofoils experience an irregular oscillating motion. A possible reason for this behavior is that the downstream hydrofoil operates in the wake of the upstream hydrofoil, and the intensities of wake interaction are dynamic change at different oscillation period. The average value of 5 periods is employed to indicate the response parameters, including the heaving amplitude and oscillation period. The reduced oscillation frequency $(f)$ is defined as $f = \frac{2\pi c}{u_T T}$.

For 2 parallel hydrofoils, the initial pitching angle has little effect on the hydrofoils response. This discovery seems to extend the results of 2 tandem hydrofoils. In Figure 5, although the heaving response curves do not overlap, slight difference is observed in the response of 2 hydrofoils for different initial pitching angles, as shown in Table 1. In the table, is the averaged lift coefficient of 5 oscillation periods.

The lift is the embodiment of hydrodynamic behavior which directly affects the system response. For 2 coupled oscillating hydrofoils, a large heaving amplitude of upstream hydrofoil means a large pitching amplitude for the downstream hydrofoil. The maximum pitching angle of the upstream hydrofoil is 45.83° while the downstream hydrofoil is 49.33°. However, the peak value of lift coefficient of the downstream hydrofoil is lower than that of the upstream hydrofoil owing to the existence of the velocity deficit. The mean velocity deficit in the upstream wake tends to lower the effective angle of attack experienced by the downstream hydrofoil as well as the mean dynamic pressure available. Figure 7 presents the flow field and pressure distribution around 2 hydrofoils at the same angle of attack of 18.1°. The moment $t$ is marked in Figure 6.

When the angle of attack exceeding the dynamic stall angle, the boundary layer will separate and form the vortex. In Figure 7A, the boundary layer of the upstream hydrofoil has already separated. A vortex is forming on the upper surface near the trailing edge. Based on the same freestream velocity, 2 hydrofoils have the same angle of attack. However, the effective angle of attack of the downstream hydrofoils is really smaller owing to the existence of the velocity deficit. There are no marked changes on the boundary layer of downstream hydrofoil, because the effective angle of attack does not exceed the dynamic stall angle. The blockage of upstream hydrofoil to the freestream results in a significantly lower dynamic pressure available for the downstream hydrofoil, as shown in Figure 7B.

In Figure 7C, although a low negative pressure zone is observed on the upper surface of downstream hydrofoil, the pressure difference between the upper and lower surfaces of the upstream hydrofoil is higher than that of the downstream hydrofoil. As a result, the lift of upstream hydrofoil is greater obviously than that of downstream hydrofoil. The lift coefficient is 1.757 for the upstream hydrofoil and 1.183 for the downstream hydrofoil.

Table 2 presents the hydrofoil response results for different inter-hydrofoil spacings. There is a common flow condition and no wake interaction for 2 parallel hydrofoils. Results of 2 tandem hydrofoils is seen to differ greatly from the corresponding data of 2 parallel hydrofoils. A larger difference resides in the heaving amplitude of 2 tandem hydrofoils. The heaving amplitude of downstream hydrofoil is significantly lower than that of upstream hydrofoil. The difference of

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**TABLE 1** Response parameters for different initial pitching angles

| $H_1/l$ | $H_2/l$ | $C_{F1}$ | $C_{F2}$ | $f$ |
|--------|--------|---------|---------|-----|
| $L = 4\,l$ |
| $\theta_0 = 50^\circ$ | $1.858$ | $1.708$ | $1.263$ | $1.117$ | $0.224$ |
| $\theta_0 = 75^\circ$ | $1.846$ | $1.675$ | $1.245$ | $1.128$ | $0.224$ |
| $L = 6\,l$ |
| $\theta_0 = 50^\circ$ | $1.553$ | $1.415$ | $1.068$ | $1.049$ | $0.216$ |
| $\theta_0 = 75^\circ$ | $1.553$ | $1.415$ | $1.119$ | $1.029$ | $0.216$ |

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**FIGURE 5** Evolution of heaving response of 2 hydrofoils ($L = 4\,l$)

**FIGURE 6** Plots of lift coefficient of 2 hydrofoils ($L = 5.5\,l$)
oscillation frequency between different inter-hydrofoil spacings is small, not exceeding 4.17%.

Unexpectedly, the heaving amplitude of 2 parallel hydrofoils is lower than that of 2 tandem hydrofoils at some cases. This makes sense considering that a higher oscillation frequency is found for the parallel arrangement. In other words, the hydrofoils have a faster heaving velocity for the parallel arrangement.

Inter-hydrofoil spacing has an obvious effect on the heaving amplitude of 2 hydrofoils. Generally, the difference between 2 hydrofoils should decline with increasing of inter-hydrofoil spacing, because the wake has more time to regain for a large inter-hydrofoil spacing. However, increasing the inter-hydrofoil spacing does not necessarily narrow the difference between the heaving amplitude of 2 hydrofoils. The heaving amplitude of upstream hydrofoil decreases with the increasing of inter-hydrofoil spacing, while the heaving amplitude of downstream hydrofoil does not change consistently with inter-hydrofoil spacing. When \( L = 3 l \), a difference of 19.75% resides in the heaving amplitude of 2 hydrofoils. When \( L = 4.5 l \), the difference between the heaving amplitude of 2 hydrofoils is 6.95%. Compared with the tandem arrangement, the difference between the heaving amplitude of 2 hydrofoils is extremely small for the parallel arrangement.

Figure 8 shows the velocity distribution around 2 hydrofoils at different inter-hydrofoil spacings. A relatively better wake recovery is observed for the large inter-hydrofoil spacing. Thus, the wake has a higher velocity flowing to the downstream hydrofoil. Specially, the pitching angle of the upstream hydrofoil at \( L = 4.5 l \) is greater than that of at \( L = 6 l \). The wake velocity flowing to the downstream hydrofoil is large at \( L = 6 l \). However, a larger difference exists in the heaving response of 2 hydrofoils for \( L = 6 l \). This indicates that wake interaction exists in the 2 tandem hydrofoils, though it is insignificant.

For 2 tandem hydrofoils, the interaction of the downstream hydrofoil with the shed vortices of the upstream hydrofoil can be qualified from weak to strong depending on the choice of parameters for the fully prescribed motion model. Favorable vortex interaction allows the downstream hydrofoil achieve a better hydrodynamic and energy harvesting performance.

However, the hydrofoils motion will vary with the changing of wake vortices interaction for the fully flow-induced system, especially, the pitching motion of hydrofoil is coupled with the heaving motion of the other hydrofoil. The strong wake interactions, whatever favorable or unfavorable, are not observed for the fully flow-induced system. There are several possible reasons for this behavior.

Firstly, for the flow-induced oscillation motion model, it is understandable that the maximum heaving velocity cannot exceed the freestream velocity. Our previous studies and Table 2 indicate that hydrofoils have a small oscillation frequency. As a result, the strength and quantity of the shed vortices are relatively weak. Secondly, the pitching motion of hydrofoil is coupled with the heaving motion of the other

| Table 2 | Response parameters for 2 hydrofoils at different inter-hydrofoil spacings |
|---------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|         | Tandem           | Tandem           | Tandem           | Tandem           | Tandem           | Tandem           | Tandem           | Tandem           | Tandem           |
|         | \( L = 3 l \)    | \( L = 3.5 l \)  | \( L = 4 l \)    | \( L = 4.5 l \)  | \( L = 5 l \)    | \( L = 5.5 l \)  | \( L = 6 l \)    | Parallel         |                 |
| \( f \) | 0.220            | 0.224            | 0.224            | 0.225            | 0.223            | 0.225            | 0.216            | 0.261            |                 |
| \( H_1/l \) | 1.896        | 1.864            | 1.846            | 1.749            | 1.706            | 1.722            | 1.555            | 1.776            |                 |
| \( H_2/l \) | 1.583        | 1.710            | 1.675            | 1.635            | 1.591            | 1.601            | 1.439            | 1.769            |                 |
| Difference | 19.75%      | 8.99%            | 10.15%           | 6.95%            | 7.26%            | 7.58%            | 8.06%            | 0.37%            |                 |
hydrofoil. The phase difference always exists in the 2 hydrofoils heaving motion (or pitching motion). Thus, the downstream hydrofoil is not always located the right behind of the upstream hydrofoil. Finally, hydrofoils motion is fully induced by the flow. When strong wake vortices interaction occurs, hydrofoils motion will be changed, and then the strong wake vortices interactions will be suppressed. This is the principal reason for the phenomenon that strong wake interactions are not observed for the motion model presented in this study.

Although the strong wake interactions are not observed, some special case should be clarified. In Figure 9, the lift curve of the downstream hydrofoil has a larger peak value. However, it not means the occurring of favorable and strong wake vortices interaction. The heaving amplitude of the upstream hydrofoil is higher than that of the downstream hydrofoil.

Figure 10 presents the vorticity field around 2 hydrofoils at representative moments. At moment $t_1$, the wake vortex of...
upstream hydrofoil can be observed near the head of downstream hydrofoil. It means vortex interaction existing in the 2 hydrofoils. However, the intensity of the wake vortex of upstream hydrofoil is weak and it affects the downstream hydrofoil slightly. At moment $t_2$, the lift of downstream hydrofoil reaches the peak value. The wake vortex interaction is not observed at this moment.

The maximum lift of the downstream hydrofoil is larger than that of the upstream hydrofoil, because the large pitching amplitude compensates the dynamic pressure losses of downstream hydrofoil through rising the effective angle of attack. The maximum pitching angle of the upstream hydrofoil is $53.85^\circ$, and the maximum pitching angle of downstream hydrofoil is $74.8^\circ$.

Table 3 presents the results of the energy harvesting performance for 2 hydrofoils. Both the results of 2 hydrofoils with tandem and parallel arrangements are presented. Table 3 indicates that the contribution from the heaving motion plays a significant role on the energy harvesting of oscillating hydrofoils. By comparison of the heaving motion contribution, the pitching motion contribution to overall power coefficient is negligible.

The pressure center of hydrofoil is situated in the vicinity of pitching axis under the condition of without vortex forming and shedding. The torque acting on the hydrofoil is relatively small. Consequently, little energy is needed in order to pitch the hydrofoil when the direction of pitching motion does not synchronize with the torque. In fact, the pitching motion has a positive contribution to the overall energy extraction of hydrofoils in most cases, which means that the pitching motion has a capability of output energy in the whole oscillation period.

Based on the prescribed motion model, Kinsey and Dumas revealed that the contribution to overall power harvesting is typically higher for the upstream hydrofoil in a proportion ranging from 55% to 75%. Similarly, the contribution of upstream hydrofoil to the overall power harvesting is typically higher for the flow-induced motion model presented in this study. However, the proportion of the upstream hydrofoil contribution to overall power harvesting is fairly low, not more than 60%. In some cases, the energy harvesting efficiency of the upstream hydrofoil is even lower than that of downstream hydrofoil, because the downstream hydrofoil has a small heaving amplitude.

In Table 3, the overall power coefficient declines with increasing inter-hydrofoil spacing. Although the power coefficient of 2 hydrofoils for the tandem arrangement is lower than that of the parallel arrangement, the tandem arrangement can achieve a higher energy harvesting efficiency.

Unexpectedly, the heaving amplitude of 2 hydrofoils is large for a short inter-hydrofoil spacing in Table 3. Moreover, our previous studies indicated that the system may have a poor energy harvesting performance when 2 hydrofoils have an irregular heaving response. Consequently, curves of hydrodynamic and power coefficients are plotted in Figure 11. The figure demonstrates that the system can output energy stability. The overall power coefficient will not be a negative value. The power coefficient of heaving motion contribution always

**FIGURE 10** Flow field around 2 hydrofoils corresponding to the moments $t_1$ and $t_2$ in Figure 9

**TABLE 3** Power coefficients for 2 hydrofoils at different inter-hydrofoil spacings

| L | $C_{PF1}$ | $C_{PF2}$ | $C_{PM1}$ | $C_{PM2}$ | $C_{P1}$ | $C_{P2}$ | $C_P$ | $\eta$ |
|---|---|---|---|---|---|---|---|---|
| 3 l | 0.672 | 0.562 | 0.028 | -0.018 | 0.695 | 0.544 | 1.240 | 19.58 |
| 4 l | 0.657 | 0.557 | 0.024 | -0.017 | 0.681 | 0.540 | 1.220 | 19.81 |
| 5 l | 0.585 | 0.523 | 0.006 | 0.01 | 0.590 | 0.533 | 1.123 | 19.69 |
| 6 l | 0.534 | 0.426 | -0.001 | 0.018 | 0.533 | 0.444 | 0.977 | 18.78 |
| Parallel | 0.816 | 0.812 | 0.025 | 0.027 | 0.841 | 0.839 | 1.680 | 14.18 |
keeps a positive in all period, and it has a larger peak value. The power coefficient of pitching motion contribution appears negative value frequently. At these moments, the energy of the other hydrofoil will be needed in order to pitch the hydrofoil.

The hydrodynamic coefficient curves appear many fluctuations. These fluctuations are attributable to the vortex forming and shedding. Figure 12 presents the vortex field around 2 hydrofoils near the hydrodynamic fluctuation. When $L = 3l$, 2 hydrofoils have a large oscillation amplitude. Both the angles of attack of 2 hydrofoils exceed the dynamic stall angle. When $L = 3l$, the vortex is shedding from the upstream hydrofoil surface. The forming of vortex enlarges the pressure difference between the upper and lower surfaces. The lift is improved to a high value. However, vortex shedding results in a sudden change in the pressure distribution around the hydrofoil. The hydrofoil has large torque coefficient at the moments of vortex shedding.

Table 2 shows that 2 hydrofoils have a small oscillation amplitude for $L = 6l$. The pitching angle of upstream hydrofoils does not exceed the dynamic stall angle. Its hydrodynamic coefficient curves are smoothly. Vortex is observed near the maximum lift of downstream hydrofoil. However, the intensity of the vortex is relatively weak. The hydrodynamic coefficient curves fluctuate slightly.

In should be noted that the large torque occurs at a small lift value in Figure 11. At these moments, the hydrofoil has a small pitching angle (angle of attack). The power coefficient curves indicate that the torque acting on the hydrofoil is in the same direction with the pitching motion. Consequently, the hydrofoil will be pitched by itself torque instead of the lift of the other hydrofoil. The hydrofoil has a relatively higher angular velocity at small pitching angle. Moreover, most of the lift is used to heave the hydrofoil rather than pitch the other
hydrofoil. As a result, the hydrofoils have a larger heaving amplitude and shorter oscillation period. As we know that, the power coefficient depends on three factors: the lift coefficient, the heaving velocity, and the synchronization of lift and heaving velocity. For the flow-induced oscillating motion model, the heaving velocity depends mostly on the lift. Therefore, the heaving velocity synchronizes well with the lift. Two hydrofoils have a larger lift and heaving velocity at $L = 3l$. The system can harvest more energy with a relatively high energy harvesting efficiency at a short inter-hydrofoil spacing.

## 5 | CONCLUSIONS

In this study, the pitching motion and heaving motion of one hydrofoil are respectively coupled with the heaving motion and pitching motion of the other hydrofoil by using a hydraulic system. It achieves a fully flow-induced oscillating motion of 2 hydrofoils. Numerical simulations are performed to analyze the effect of wake interactions on the response of 2 tandem hydrofoils.

When 2 hydrofoils have a parallel arrangement, slight differences are observed in the response of 2 hydrofoils, and the system can harvest more energy from freestream though the efficiency is relatively low. Two tandem hydrofoils have a higher energy harvesting efficiency though it harvests less energy. Obvious differences reside in the response of 2 tandem hydrofoils owing to the existence of wake interactions. The velocity deficit tends to lower the heaving amplitude and energy harvesting performance of the downstream hydrofoil. In some cases, the instantaneous lift can reach a higher peak value because the downstream hydrofoil has a larger pitching amplitude. However, without exception, the upstream hydrofoil has a greater time-averaged performance. The differences between the responses of 2 tandem hydrofoil have not a consistent trend with the inter-hydrofoil spacing.

For the flow-induced motion model, the wake interactions will change the response of 2 tandem hydrofoils. Therefore, the strong wake interactions will not appear in the 2 tandem hydrofoil, because it will be eliminated after the response of 2 hydrofoils changes. The contribution to the overall power harvesting is always higher for the upstream hydrofoil, but the proportion does not exceed than 60% owing to the coupling of 2 hydrofoils. These are different greatly with the results of prescribed motion model.
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