Energy Extraction Performance of Tandem Ground-effect Hydrofoils

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Abstract. To study the influence of the spatial configuration of two tandem ground-effect hydrofoils on the power-extraction efficiency, this paper uses the overset grid method to establish a two-dimensional numerical calculation model based on the STAR-CCM+ software. The comparison of the numerical results of the single hydrofoil verifies the validity of the method. This paper systematically analyzes the influence of ground effect on the energy extraction performance of the hydrofoil, and further studies the changes in the hydrodynamic performance and energy extraction efficiency of the hydrofoil when two ground effect hydrofoils are tandem. The results show that: compared with a single ordinary hydrofoil, the energy extraction efficiency of the ground-effect hydrofoil is slightly improved. When the hydrofoil is close to the wall, its lift will be significantly increased due to ground effect. When two ground effect hydrofoils are tandem with a phase difference of 180 deg, the vortex generated by the upstream hydrofoil will significantly increase the absolute lift of the downstream hydrofoil, but the energy extraction efficiency will be reduced significantly.

1. Introduction
With the increasingly serious problems of resource shortage and environmental pollution, the development of renewable energy has received more and more attention. Compared with new energy sources such as solar energy, wind energy, wave energy, etc., Ocean tidal current has strong regularity, stable energy, and high development value. The majority of existing designs for tidal energy devices utilize either horizontal-axis or vertical-axis turbine-based energy converters. These devices can act both singly and in arrays [1]. However, the operation of both HAT and VAT requires large rotor diameter for large energy production. These introduce some disadvantages: requirement of large profile height on land and water depth underwater; high rotor tip speed and hence impact on surrounding ecology; and requirement of large kick-in speed and hence a low wind/tidal resource utilization or inapplicability in slow inflow energy sites [2]. But the oscillating hydrofoil tidal current generator based on the principle of bionics can better solve these problems. The hydrofoil tip speed in this device is low, the noise is also small, so it is more environmentally friendly. Without the centrifugal stress associated with rotating blades, the oscillatory devices are structurally robust [1].

The research on the energy extraction system of the oscillating hydrofoil first began in the wind power generation device experimental work of McKinney and Delaurier [3] in 1981, and then gradually developed into the tidal current power generation device. Kinsey and Dumas [4] conducted a series of numerical studies and found that the heave amplitude and frequency of the hydrofoil and other motion parameters have the greatest impact on the performance of the hydrofoil, while the geometric shape and viscosity parameters play a secondary role. After that, Kinsey [5] conducted a numerical study on two series hydrofoils and found that the position of the downstream hydrofoil relative to the upstream
hydrofoil will have a great influence on the energy extraction power. Jianan Xu [6-7] et al. studied the effects of various parameters and wake vortex on the energy extraction performance of the tandem hydrofoils through numerical and experimental studies, and found that the upstream hydrofoil play a leading role in the energy extraction process and contributes two-thirds of the total energy extraction, while the downstream hydrofoil accounts for only one-third of the total energy due to the unstable wake field from the upstream hydrofoil. In addition to increasing the number of hydrofoils and changing the motion parameters, using ground effects is also a way to improve the energy extraction efficiency. Through 2D and 3D numerical simulations, Zhu [8] found that the thickness of the wall and the hydrofoil will improve the energy extraction performance at certain frequencies. Liu [2] optimized the ground-effect hydrofoil device. Pourmahdavi [9] studied the impact of diving effects on the performance of tandem oscillating hydrofoil, and found that the interaction between the seafloor boundary layer and the oscillating hydrofoil would reduce the energy extraction efficiency. Tandem arrangement and ground effect are both effective methods to improve the energy capture efficiency of oscillating hydrofoil power generation devices, but there are relatively few studies on the combined effects of the two. To study the influence of the spatial configuration of two tandem ground-effect hydrofoils on the power-extraction efficiency, this paper uses the overlapping grid method to establish a two-dimensional numerical calculation model based on the STAR-CCM+ software, verifies the effectiveness of the method by comparing the numerical results with the existing ordinary single hydrofoil, and then systematically analyzes the influence of ground effect on the energy extraction performance of the hydrofoil, and finally focuses on the energy extraction performance characteristics of the tandem ground-effect hydrofoils.

2. Calculation model

2.1. Motion model

![Figure 1. Schematic diagram of tandem ground effect hydrofoils motion](image)

The motion of the tandem ground-effect hydrofoils is shown in Figure 1. The motion of the oscillating hydrofoil can be decomposed into vertical heave motion $H(t)$ and pitch motion $\theta(t)$. Regarding the lower wall as the x-axis, their expressions are as follows:

$$H(t) = H_0 \sin(2\pi ft + \varphi) + h + H_0$$  \hspace{1cm} (1)

$$\theta(t) = \theta_0 \sin(2\pi ft)$$  \hspace{1cm} (2)

Where $H_0$ is the amplitude of heave motion, $f$ is the frequency of oscillation of the hydrofoil, $\varphi$ is the phase difference between heave motion and pitch motion, $h$ is the distance from the lowest point of the hydrofoil shaft to the bottom wall, and $\theta_0$ is the amplitude of pitch motion.
The linear velocity $v(t)$ of the heave motion and the angular velocity $\omega(t)$ of the pitch motion of the hydrofoil are respectively defined as:

$$v(t) = \frac{dH}{dt} = 2\pi f H_0 \cos(2\pi ft + \varphi)$$ \hspace{1cm} (3)

$$\omega(t) = \frac{d\theta}{dt} = 2\pi f \theta_0 \cos(2\pi ft)$$ \hspace{1cm} (4)

In Figure 1, $U_\infty$ represents the free stream velocity. $d$ is the distance from the highest point to the lowest point of the hydrofoil trailing edge, that is, the maximum sweep range of the hydrofoil. $x_p$ is the distance from the hydrofoil shaft to the leading edge, and $L$ is the horizontal distance between the shafts of the two tandem hydrofoils. The flow field and motion parameter settings in this paper are mainly referred to [10], and the specific values are shown in Table 1.

### Table 1. Parametric details of the tandem oscillating hydrofoils.

| Parameter                              | Details/value |
|----------------------------------------|---------------|
| Hydrofoil profile                      | NACA0015      |
| free stream velocity ($U_\infty$)      | 2 m/s         |
| Chord length ($c$)                     | 0.25 m        |
| Pitching axis ($x_p$)                  | $c/3$         |
| Pitching amplitude ($H_0$)             | $c$           |
| Heaving amplitude ($\theta_0$)         | 60 deg        |
| Phase angle ($\varphi$)                | 90 deg        |
| Motion phase lag ($\varphi_{1,2}$)     | 180 deg       |
| Hydrofoil separation space ($L$)        | 5.4$c$        |
| Reynolds number (Re)                   | 500000        |
| reduced frequency ($f^*$)              | 0.14          |

Reynolds number and reduced frequency are defined as:

$$Re = \frac{\rho c U_\infty}{\mu}$$ \hspace{1cm} (5)

$$f^* = \frac{fc}{U_\infty}$$ \hspace{1cm} (6)

Where $\rho = 999$ kg/m$^3$ is the density of the fluid, $\mu = 9.99 \times 10^{-4}$ Pa·s is the dynamic viscosity coefficient, and $f = 1.12$ Hz is the motion frequency of the oscillating hydrofoil.

### 2.2. Energy extraction performance

The energy extraction performance of an oscillating hydrofoil is generally measured by the energy extraction power and efficiency. According to the reference [4], the energy extraction efficiency $\eta$ is defined as:

$$\eta = \frac{\bar{P}}{P_0}$$ \hspace{1cm} (7)

Where $P_0$ is the total energy contained in the inflow flowing through the swept area of the hydrofoil, which is specifically defined as:

$$P_0 = 0.5 \rho U_\infty^2 d$$ \hspace{1cm} (8)

Where $d$ is approximately 2.399$c$ under the various motion parameters in table 1.

$\bar{P}$ is the average energy extraction power of the hydrofoil, which is defined as:
\[
\overline{P} = \frac{1}{T} \int_0^T P(t)dt = \int_0^T P(t)dt
\]

Where \(P(t)\) is the instantaneous energy extraction power, which is defined as the sum of instantaneous heave energy extraction power and instantaneous pitch energy extraction power:

\[
P(t) = P_h(t) + P_m(t) = L(t)v(t) + M(t)\omega(t)
\]

Where \(L(t)\) and \(M(t)\) are the instantaneous lift and moment received by the hydrofoil respectively. In order to facilitate comparison, they and the instantaneous resistance \(D(t)\) need to be dimensionless:

\[
C_d = \frac{D(t)}{0.5 \rho U_o^2 c}, \quad C_l = \frac{L(t)}{0.5 \rho U_o^2 c}, \quad C_m = \frac{M(t)}{0.5 \rho U_o^2 c^2}
\]

In addition, the instantaneous power coefficient is defined as:

\[
C_p = \frac{P(t)}{0.5 \rho U_o^3 c} = \frac{1}{U_o} (C_l v(t) + C_m \omega(t))
\]

2.3. Model verification

This paper uses ICEM CFD to divide the hydrofoil mesh of the overlapping domain, and the STAR-CCM+ is used to divide the flow field mesh of the background domain. We use STAR-CCM+ software for numerical calculations. In order to make a more accurate comparison, the case of a single hydrofoil with a swing angle amplitude of 75° in the free flow field which has more complicated curves are calculated and compared with the numerical results in reference [10]. The result is shown in Figure 2.

**Figure 2.** Comparison of energy extraction power and hydrodynamic coefficient

It can be seen from Figure 2 that under the same hydrofoil motion and flow field parameters, the two-dimensional calculation model adopted in this paper is basically consistent with the calculation results in the existing literature, which proves the effectiveness of the method in this paper.
3. Single ground effect hydrofoil

The background domain mesh was re-divided, focusing on densifying the swept area of the hydrofoil near the lower wall in the flow field, especially the area from the lowest point of the trailing edge of the hydrofoil to the lower wall. Figure 3 shows the divided mesh and the boundary conditions of the flow field.

Using the various motion parameters in Table 1, the 4 cases of \( h \) being 0.5c, 0.3c, 0.25c and no wall are calculated. The calculation results are shown in Figure 4 and Table 2.

From the curve in Figure 4 and the data in Table 2, it can be seen that under the condition that the swing angle motion amplitude is 60° and the heave motion amplitude is c, relative to the condition of no wall, as \( h \) gradually decreases, the resistance of the hydrofoil remains basically unchanged, but the lift and moment increase significantly in the range of 0.45 \( T \) to 0.6 \( T \), and the smaller the \( h \), the more obvious the increase. In addition, the energy extraction power and efficiency also gradually increase with the decrease of \( h \), and they reach the maximum at 0.3~0.25c.
According to the flow field pressure cloud diagram at the time 0.5 T and \( h=0.25c \) as shown in Figure 5, it can be seen that the hydrofoil rotates clockwise around the shaft at this time, and obvious positive pressure appeared on the lower surface of the hydrofoils. However, under the condition of \( h=0.25c \), the pressure on the lower surface of the hydrofoil increases sharply due to the ground effect, so the \( C_l \) and \( C_m \) in Figure 4(b,c) will increase so significantly.

| \( h \)  | \( \bar{C}_d \) | \( \bar{C}_l \) | \( \bar{C}_m \) | \( \bar{C}_p \) | \( \eta \) (%) |
|--------|--------|--------|--------|--------|--------|
| No wall | 0.877  | 2.102  | 0.389  | 0.615  | 25.636 |
| 0.5c    | 0.895  | 2.355  | 0.400  | 0.648  | 27.011 |
| 0.3c    | 0.904  | 2.462  | 0.425  | 0.659  | 27.470 |
| 0.25c   | 0.900  | 3.000  | 0.506  | 0.657  | 27.386 |

| \( h \) | \( \bar{C}_l \) | \( \bar{C}_p \) | \( \eta \) (%) |
|--------|--------|--------|--------|
| Single hydrofoil | 3.000  | 0.657  | 27.386 |
| Hydrofoil_1   | 2.821  | 0.604  | 25.177 |
| Hydrofoil_2   | 3.789  | 0.444  | 18.508 |

Figure 5. Pressure cloud diagram at 0.5 T

4. Tandem ground-effect hydrofoils
In order to study the changes in the energy extraction performance of two tandem hydrofoils, especially the influence on the downstream hydrofoil, a numerical calculation model for the tandem ground effect hydrofoils is established. The upstream hydrofoil is set to hydrofoil_1, and the downstream hydrofoil is set to hydrofoil_2. Taking \( h=0.25c \), \( L=5.4c \), and \( \varphi_{1-2}=180\) deg.

It can be seen from Table 3 that in the tandem double ground-effect hydrofoils system, the upstream hydrofoil has a reduction in various values relative to the single ground-effect hydrofoil, but the
change is very small. However, the parameters of the downstream hydrofoil \_2 have changed a lot, except for the increase in the maximum lift, the other items are significantly reduced. The change in lift is mainly caused by the vortex generated by the upstream hydrofoil. It can be seen from the vortex diagram at time 0 \( T \) in Figure 6 (corresponding to time 0.5 \( T \) in Hydrofoil \_2) that there is a positive vortex between the two hydrofoils, which will produce a counterclockwise induced velocity in the surrounding flow field, which will lead to an increase in the lift of Hydrofoil \_2 over a period of time. But as the vortex continues to flow downstream of Hydrofoil \_2, the lift caused by its induced velocity gradually decreases to a negative value. In addition, Hydrofoil \_1 produces a negative vortex, which causes the lift of Hydrofoil \_2 to reduce further, so in the end, its minimum lift is much smaller than that of a single ground effect hydrofoil.

![Vortex diagram at time 0 \( T \)](image)

**Figure 6.** Vortex diagram at time 0 \( T \)

5. Conclusion

This paper uses the STAR-CCM+ software to divide the overlapping mesh, studies the energy extraction performance of a single ground-effect hydrofoil, and further studies the changes in the hydrodynamic coefficients and energy extraction power of the two hydrofoils in the tandem double ground-effect hydrofoil, and draws the following conclusions:

1. The ground effect can effectively improve the energy extraction performance of the hydrofoil. With the gradual approach of the lowest point of the hydrofoil shaft to the wall, its lift is significantly improved, and the energy extraction efficiency is also improved. When \( h \) decreases to 0.3~0.25c, \( \eta \) reaches its maximum.

2. When two ground-effect hydrofoils are tandem, the force and energy extraction performance of the upstream hydrofoil is slightly lower than that of a single ground-effect hydrofoil, but it is basically the same on the whole.

3. When the movement phase difference of the two ground effect hydrofoils is 180 deg, the force and energy extraction performance of the downstream hydrofoil will change greatly. The average energy extraction power is significantly reduced, while the maximum lift is significantly increased due to the upstream vortex.

6. References

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