Enhancing the Performance of an Oscillating Wing Energy Harvester Using a Leading-Edge Flap

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Abstract: In this study, we investigated the power generation capability of an oscillating wing energy harvester featuring an actively controlled flap positioned at the wing’s leading edge. The findings revealed that attaching a leading-edge flap reduces fluid flow separation below the wing’s lower surface at the leading edge, resulting in smoother flow and increased velocity near the hinge region. The leading-edge flap increases the pressure difference across the wing’s surface, thereby enhancing the overall performance. In addition, the introduction of the leading-edge flap effectively elongates the wing’s effective projected length in the heaving direction, leading to increased thrust. We examined flap lengths ranging from 10% to 50% of the chord length, with the maximum pitch angles of the wing and flap varying from 75° to 105° and 30° to 55°, respectively. The optimal power generation was achieved using a flap length of 40% of the chord length, combined with maximum wing and flap pitch angles of 95° and 45°, respectively. These conditions yielded a 29.9% overall power output increase and a 20.2% efficiency improvement compared to the case without the leading-edge flap.

Keywords: energy harvester; flapping wing; leading-edge flap; pitching; heaving

1. Introduction

The global shift toward decreasing reliance on fossil fuels has motivated the investigation of alternative energy sources and methods, with a focus on enhancing their effectiveness. Energy harvesters based on flapping foils, inspired from natural movements, have gained traction as an effective means to extract energy from various natural sources, such as streams, rivers, tidal currents, and wind. This approach has garnered substantial interest in recent years [1,2]. The idea of utilizing a flapping motion for energy generation was initially introduced by Wu in 1972 [3], and later, in 1981, McKinney and Delaurier pioneered the extraction of energy from the heaving and pitching motions of a fluid using a flapping foil [4]. Subsequently, extensive research has been conducted on optimizing the energy-harvesting capabilities of flapping foils via the investigation of motion parameters [1,5,6], geometric and viscous parameters [2,7–10], and flow control methods [11–15].

Xiao et al. [6] introduced an innovative non-sinusoidal motion for oscillating hydrofoils within energy harvesters. They combined sinusoidal plunging movements with a nearly trapezoidal pitching motion to assess the impact on energy extraction performance. They found that a higher angle of attack results in enhanced power extraction. In comparison to sinusoidal motion, they observed substantial enhancements with the optimal pitching profile, boosting the power coefficient by up to 63% and the total efficiency by up to 50%. Wu et al. [16] investigated the effects of stroke deviation and variables such as the horizontal motion amplitude, phase difference, and frequency on the performance of flapping-foil energy harvesters. Their results emphasized that incorporating horizontal motion enhances the lift force, thereby improving the power generation capacity of the energy harvesters. Their study underscored the enhancement of power output performance owing to flapping-foil energy harvesters. Wang et al. [17] proposed a novel...
reversed-D trajectory and concluded that this specific trajectory motion can significantly enhance the power output. Swain et al. [18] investigated energy extraction performance by altering the flapping trajectory and the spatial arrangement of foils, identifying favorable wake interaction patterns that contribute to increased efficiency.

Shanmugam and Sohn [19] investigated various deflector designs aimed at improving power generation in flapping-foil energy harvesters. They examined the impact of upstream deflectors (N), the angle of inclination of these deflectors, and the spacing between the hydrofoil and the deflector on the performance. Their simulations highlighted the considerable influence of these parameters on the power generation efficiency of the energy harvesters. Wang et al. [20] analyzed the impact of density-stratified flow on energy extraction efficiency and its interaction with the pitching amplitude. They [21] proposed a tandem-hydrofoil-based tidal array with improved density and reduced costs. Petikidis and Papadakis [22] studied fully passive flapping foils in free surface flow, determining optimal submergence depths and assessing the influence of monochromatic waves. Dahmani and Sohn [23] introduced a novel approach using oscillating tandem wings inside a convergent duct to enhance power extraction in energy harvesting. The downstream hydrofoil was shown to be more influential, contributing 4–80% to the improved power output owing to the high incoming fluid velocity due to the duct design. In addition, they explored the impact of vertical interfoil spacing on tandem/parallel coupled oscillating wings, achieving a 23% increase in power extraction efficiency compared to traditional arrangements [24]. In these systems, maintaining stability is important, as it ensures consistent operation and reduces the risk of performance degradation. Zhao [25–28] explored the principles of stability as they pertain to the design and analysis of such systems. Building on these insights, recent advancements in piezoelectric harvesters, such as the development of a harvester with a U-shaped geometry [29], have led to significant improvements. This proposed model surpasses traditional models in efficiency, showcasing the evolution of energy-harvesting technology. Further contributing to this field, the creation of a semi-submersible piezoelectric harvester optimized for increased power output [30] underscores the growing potential of these technologies in a range of applications, driven by continuous improvements in design and optimization.

Flow control methods for harnessing energy from flapping-foil systems can be categorized into two types, passive control and active control, based on whether additional energy is required within the flow field [31]. Passive control techniques involve incorporating simple structures on or adjacent to the surface of the airfoil to enhance energy harvesting without introducing extra energy. Examples of passive control methods include passive foil deformation [32], Gurney flaps [33,34], and corrugated foils [35]. Passive control methods are cost-effective and relatively straightforward to install. However, they operate within predefined states and lack adaptability for real-time adjustments to meet changing requirements. In contrast, active control methods such as circulation control [36] and plasma actuators [37,38] can modify the flow field by adjusting excitation parameters as needed, making them more efficient compared to passive control methods.

Flaps are commonly used in lifting mechanisms in the aerospace industry owing to their simple structure, robustness, and effectiveness [39,40]. Flaps can be implemented in both passively and actively controlled forms. Although flaps have been extensively studied for their applications in single blades and vertical-axis wind turbines [41–43], the investigation into energy harvesting using flapping wings has mainly focused on Gurney flaps [33,34]. For example, Bing [33] revealed the introduction of a Gurney flap-influenced vortex generation at the trailing edge, which increased the pressure difference on the foil surface and improved the lift force, leading to a 21% improvement in energy-harvesting efficiency. On the other hand, any additional energy consumption resulting from the swing of the Gurney flap itself was not mentioned. Totpal et al. [44] studied the impacts of passive leading-edge flaps on flapping-wing energy harvesters at low cutoff frequencies. Although they observed an improvement in the heave force, this improvement was primarily limited to the initial stages of the flapping cycle when the heave speed was low,
and the synchronization between force and speed was poor, making overall flapping-wing control challenging. Alam and Sohn investigated [45] the impact of an actively controlled trailing-edge flap, accompanied by a comprehensive parametric analysis [46]. Their findings indicated that the implementation of the flap yielded advantageous outcomes in terms of enhancing power extraction performance.

In this study, we examined the potential for enhancing energy harvesting in oscillating wing systems via the addition of a controllable leading-edge flap. Our primary goal was to improve the performance of the energy harvester. To achieve this, we conducted a quantitative evaluation of numerous factors, including various flap lengths and maximum pitching angles for the wing and flap, to identify the optimized configurations that maximize power generation and enhance overall efficiency. Flap lengths varying from 10% to 50% of the chord length were systematically investigated. In addition, variations in maximum wing pitch angles spanning from 75° to 105° and maximum flap pitch angles ranging from 30° to 55° were examined. Through this comprehensive investigation, we aimed to reveal the relationships among these diverse parameters and their impacts on energy-harvesting performance.

2. Mathematical Modeling

2.1. Problem Description

We investigated the dynamics of unsteady fluid flow in an oscillating wing energy harvester using a two-dimensional model under turbulent flow conditions by examining the impact of a leading-edge flap on the performance of energy harvesting. Figure 1a presents a two-dimensional (2D) representation of the energy harvester with and without the flap. In addition, Figure 1b shows three-dimensional (3D) visualizations to view this configuration more clearly. This research primarily focuses on a comparative analysis of the wing’s performance with and without the leading-edge flap, shedding light on the role of the leading-edge flap in boosting energy-harvesting efficiency.

![Wing without flap](image1)

Wing without flap

![Wing with leading edge flap](image2)

Wing with leading edge flap

(a)
Figure 1. Configurations of an oscillating wing with and without a flap: (a) 2D view; (b) 3D view.

Table 1 provides an overview of the physical model and the optimal parameter settings needed to maximize the power generation in an oscillating wing energy harvester without a flap, as reported by Usoh et al. [9]. The oscillating wing model, when equipped with a leading-edge flap, maintains identical physical characteristics (e.g., thickness and total length). However, factors such as the length of the flap and the peak pitch angles of both the wing and flap are varied. The wing and flap are separated by a gap equivalent to half a percent of the wing’s chord length, and the junction between the wing and flap features a radius equal to half the plate thickness.

Table 1. Physical model parameters of the oscillating wing energy harvester.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile</td>
<td></td>
<td>Rectangular plate</td>
</tr>
<tr>
<td>Width</td>
<td>t</td>
<td>0.04c</td>
</tr>
<tr>
<td>Length of chord</td>
<td>c</td>
<td>1.0</td>
</tr>
<tr>
<td>Pivot point</td>
<td>x_p</td>
<td>c/3</td>
</tr>
<tr>
<td>Heaving amplitude</td>
<td>H/c</td>
<td>1</td>
</tr>
<tr>
<td>Pitching amplitude</td>
<td>θ_o</td>
<td>75°</td>
</tr>
<tr>
<td>Frequency</td>
<td>f*</td>
<td>0.14</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>Re</td>
<td>5 x 10^5</td>
</tr>
<tr>
<td>Phase angle</td>
<td>φ</td>
<td>90°</td>
</tr>
</tbody>
</table>

Figure 2 shows the oscillating wing kinematic in two scenarios: a wing without a flap (2a) and another wing with a leading-edge flap (2b). The incoming fluid velocity is $U_\infty$, and the wing’s chord length is $c$. The wing’s main body is pivotally attached at one-third of the chord length from the leading edge, enabling both heaving and pitching motions. Meanwhile, the flap, hinged at the wing’s leading edge, executes pitching motions relative to the wing’s main body. Notably, changes in the flap’s pitching profile, dictated by the angle of incidence, significantly affect the energy harvester’s performance. To evaluate the impact of attaching a leading-edge flap to an oscillating wing, its power generation capacity is compared with the maximum power output of a wing without a flap based on the optimum conditions obtained for a flapless wing outlined in Table 1 [9].
The wing’s heaving motion is described by Equation (1):

\[ h = H_0 \sin (\omega t + \phi) \]  

(1)

In this equation, \( h \) denotes the instantaneous amplitude of heaving motion, \( \omega \) is the angular frequency (expressed as \( \omega = 2\pi f \)) associated with the wing’s oscillation, \( t \) is the time, and \( \phi \) is the heave and pitch motion phase difference.

The pitch motion of the wing’s main body is governed by Equation (2):

\[ \theta = \theta_0 \sin (\omega t) \]  

(2)

Here, \( \theta \) represents the pitch angle of the main body. Similarly, the pitch motion of the flap is expressed by Equation (3):

\[ \psi = \psi_0 \sin (\omega t) \]  

(3)

Here, \( \psi \) represents the pitch angle of the flap. The force \( F_y(t) \) and the moment \( M(t) \) are associated with heaving and pitching relative to the wing’s pivot point, respectively. The corresponding average power outputs derived from these forces and moments are represented by \( \bar{P}_y \) and \( \bar{P}_m \), respectively, and \( \bar{P} \) represents the average total power output [33,34].

\[ \bar{P} = \bar{P}_y + \bar{P}_m = \int_0^T [F_y(t)V_y(t) + M(t)\Omega(t)]dt \]  

(4)

In this equation, \( V_y(t) \) denotes the instantaneous heaving motion of the wing, and \( \Omega(t) \) represents the angular velocity at time \( t \). The coefficients of heaving and pitching power are represented by \( C_{py} \) and \( C_{pm} \), respectively. The total averaged power extraction coefficient in a cycle is expressed as \( \bar{C}_{pt} \) and can be calculated by summing up the averaged power output coefficients obtained from \( M(t) \) and \( F_y(t) \) [47,48]:

\[ \bar{C}_{pt} = \bar{C}_{py} + \bar{C}_{pm} = \frac{\bar{P}}{0.5\rho U_\infty^2 c T}. \]  

(5)
Considering the combined effects of the main body and flap, the forces, moments, and power generated by both components were summed. The computation of the moment power for the flap incorporated the consideration of relative angular motion between the wing’s main body and flap. The efficiency of power generation in the oscillating wing energy harvester is denoted as $\eta$, obtained using Equation (6) [49]:

$$\eta = \frac{\bar{c}}{\bar{d}}$$

(6)

2.2. Numerical Method

The power extraction efficiency of the oscillating wing was simulated using the incompressible unsteady Reynolds-averaged Navier–Stokes equations. The $k-w$ SST turbulence model was employed, as adopted by other researchers in similar studies [17,48]. The computational model was solved using ANSYS commercial software version 20 (ANSYS, Canonsburg, PA, USA) and the overset method by dividing it into stationary and moving grid sections, as illustrated in Figure 3.

![Figure 3. Illustrations of the computational domain and boundary conditions: (a) computational domain; (b) sub-region grid.](image_url)

To ensure domain independence, a computational domain spanning from $-20c$ to $50c$ in length to $-25c$ to $25c$ in breadth was selected based on the observation that enlarging the domain size had an insignificant impact on the obtained results. At the inlet, outlet, and wing surface, the boundary conditions, velocity inlet, pressure outlet, and no-slip wall conditions were implemented. The pressure outlet was placed at 50c from the oscillating wing pivot point, as depicted in Figure 3a. Separate subgrids (moving grid) were utilized for the main body and the flap, as shown in Figure 3b. The movable grid areas for each part were organized into rectangular grids measuring $6c$ and $5c$. For pressure, momentum, and turbulent viscosity, the spatial discretization was conducted using the second-order upwind approach. The dynamic mesh method facilitated mesh motion, and the airfoil’s movement was input through user-defined functions. The presented analysis shows the data collected after the completion of the eighth stable periodic cycle, which included 2000 time steps.

To investigate the precision and dependability of the numerical simulations, studies on grid and time independence were conducted by altering the grid resolution and time
step. Three distinct mesh densities were employed: a coarse grid (D1), a medium grid (D2), and a fine grid (D3). These simulations were performed at a Reynolds number of $5 \times 10^5$ using a chord length of 1 and a pivot point located at $c/3$. The heave amplitude was set at $c = H_o = 1$, the maximum pitching amplitude, at 75°; the phase angle, at 90°; and the reduced frequency, at 0.14. Table 2 illustrates the influence of grid resolution and time step on the computed value of $\bar{C}_{pt}$. Based on the outcomes of the grid independence assessment, the D2 grid with a time step of $T/2000$ was chosen for the simulations to ensure both accuracy and reliability.

Table 2. Analysis of mesh independence in the flat plate case.

<table>
<thead>
<tr>
<th>Mesh in Stationary Domain</th>
<th>Mesh in Moving Domain</th>
<th>Time Steps in a Cycle</th>
<th>$\bar{C}_{pt}$</th>
<th>% Variation in $\bar{C}_{pt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$58.7 \times 10^3$</td>
<td>24.5 $\times 10^3$</td>
<td>T/2000</td>
<td>0.985</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T/1000</td>
<td>0.976</td>
</tr>
<tr>
<td>D2</td>
<td>$88.2 \times 10^3$</td>
<td>37.3 $\times 10^3$</td>
<td>T/2000</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T/4000</td>
<td>0.959</td>
</tr>
<tr>
<td>D3</td>
<td>$102.4 \times 10^3$</td>
<td>43.9 $\times 10^3$</td>
<td>T/2000</td>
<td>0.956</td>
</tr>
</tbody>
</table>

Further, we validated the results obtained upon comparison with the simulation results reported by Usoh et al. [9] and Kinsey et al. [48]. The validation process involved examining a flat plate and a NACA0015 airfoil. For the flat plate scenario, the simulation was conducted at $Re = 1100$, $H_o/c = 1.0$, $f^* = 0.14$, and $\theta_o = 75^\circ$. The calculated $C_{pt}$ values closely matched the results reported by Usoh et al. [9], as depicted in Figure 4a. For the NACA0015 airfoil, shown in Figure 4b, the simulations at $Re = 5 \times 10^5$, $H_o/c = 1.0$, $\theta_o = 75^\circ$, and $f^* = 0.14$ demonstrated a good match between the pushing force coefficient and the x-direction force coefficient in this study and those documented by Kinsey et al. [50]. These comparisons validate the applied numerical model and mesh used in this study.

**Figure 4.** Comparative analysis of the numerical results obtained in this study against the validation data: (a) comparison of the instantaneous $C_{pt}$ values for a rectangular-plate wing at $Re = 1100$ in comparison to the findings reported by Usoh et al. [9]; (b) comparison of the instantaneous $C_l$ and $C_D$ values for NACA0015 at $Re = 5 \times 10^5$, benchmarked against the findings reported by Kinsey et al. [48].

3. Results and Discussion

Our investigation presents an active flow control methodology aimed at improving the power generation of an oscillating wing. The effects of a rectangular-plate oscillating wing featuring a flap at the leading edge on the energy-harvesting performance are investigated during coupled heaving and pitching movements. The study further evaluates the wider applicability of this flow control technique (over a range of motion parameters) by
varying multiple parameters, such as the maximum pitch angles of the wing and the flap, as well as the flap length. Throughout the study, the following parametric conditions were kept constant: the nondimensional pivot point position ($x_p^\circ = 0.33c$), the heave amplitude ($H/c = 1.0$), the phase angle ($\varphi = 90^\circ$), and the frequency ($f^\circ = 0.14$).

### 3.1. Effect of Varied Maximum Flap Pitch Angles on Power Output

In this section, a comparative analysis of the energy-harvesting performance of a wing with an integrated flap is performed against a baseline foil without a flap at a fixed maximum wing pitch angle ($\theta_o$) of $75^\circ$. The flap length is maintained at 10% of the chord length ($c$), and the maximum flap pitch angle ($\psi_o$) is varied from $20^\circ$ to $50^\circ$.

Table 3 shows the average pushing power coefficient ($\bar{C}_{py}$), average moment power coefficient ($\bar{C}_{pm}$), and average total power coefficient ($\bar{C}_{pt}$) for the wing with a flap length of 10% of $c$ at $\theta_o = 75^\circ$. The power coefficients are tabulated against a range of $\psi_o$ values, along with the percentage change in $\bar{C}_{pt}$ relative to the wing without a flap (denoted as $\Delta\bar{C}_{pt}$). In this context, “plate” refers to the baseline wing without a flap, and the varying flap conditions are indicated by their respective maximum pitch angles, such as $\psi_o = 20^\circ$, $25^\circ$, and so on. The data exhibit a direct correlation between $\psi_o$ and $\bar{C}_{py}$, suggesting that an increase in the flap’s pitch angle enhances the average heaving power coefficient. Conversely, an inverse relationship is observed between $\psi_o$ and $\bar{C}_{pm}$, where larger flap pitch angles correlate with more negative values of the average moment power coefficient. $\bar{C}_{pt}$ displays a nonlinear association with $\psi_o$: it shows a modest increase as $\psi_o$ ascends from $20^\circ$ to $40^\circ$, followed by a decrease in $\bar{C}_{pt}$ beyond $40^\circ$. Notably, the power output increases by a maximum of 6% with a 10% flap length compared to the plate case.

**Table 3.** Total power extraction coefficients for the oscillating wing at $\theta_o = 75^\circ$, associated with different $\psi_o$ values, and the percentage increase in total power output compared to the wing without a flap.

<table>
<thead>
<tr>
<th>$\psi_o$</th>
<th>Plate ($0^\circ$)</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>35°</th>
<th>40°</th>
<th>45°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{py}$</td>
<td>0.929</td>
<td>0.953</td>
<td>0.97</td>
<td>0.985</td>
<td>1.01</td>
<td>1.056</td>
<td>1.078</td>
<td>1.073</td>
</tr>
<tr>
<td>$C_{pm}$</td>
<td>0.034</td>
<td>0.018</td>
<td>0.009</td>
<td>-0.015</td>
<td>-0.026</td>
<td>-0.034</td>
<td>-0.073</td>
<td>-0.098</td>
</tr>
<tr>
<td>$C_{pt}$</td>
<td>0.963</td>
<td>0.972</td>
<td>0.979</td>
<td>0.97</td>
<td>0.984</td>
<td>1.022</td>
<td>1.01</td>
<td>0.974</td>
</tr>
<tr>
<td>$\Delta C_{pt}$ (%)</td>
<td>-</td>
<td>0.9</td>
<td>1.6</td>
<td>0.7</td>
<td>2.2</td>
<td>6.1</td>
<td>4.8</td>
<td>1.1</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.373</td>
<td>0.377</td>
<td>0.379</td>
<td>0.376</td>
<td>0.381</td>
<td>0.396</td>
<td>0.391</td>
<td>0.377</td>
</tr>
</tbody>
</table>

Figure 5a,b show the variations in the pushing force coefficient ($C_p$) and the pushing power coefficient ($C_{pm}$) in time ($T$) for different $\psi_o$ cases outlined in Table 3. Notably, between the time intervals from 0.1 $t/T$ to 0.3 $t/T$, both $C_p$ and $C_{pm}$ increase as $\psi_o$ increases, indicating that the oscillating foil experiences enhanced pushing force and an increase in pushing power as $\psi_o$ increases during this interval. Figure 5c,d present the moment power coefficient ($C_{pm}$) and the total power coefficient ($C_{pt}$) throughout a cycle considering different $\psi_o$ cases. The variation in $C_{pm}$ values is similar for different cases until 0.3 $t/T$, whereas from 0.3 $t/T$ to 0.5 $t/T$, the $C_{pm}$ values decrease with $\psi_o$. During the interval from 0.15 $t/T$ to 0.35 $t/T$, the $C_p$ values also increase with increasing $\psi_o$. The total power output of the oscillating foil shows an upward trend with increasing $\psi_o$ values during this interval. However, the maximum $\bar{C}_{pt}$ is achieved at $\psi_o = 40^\circ$, as detailed in Table 3.
Figure 5. Comparative analyses of $C_y$, $C_{py}$, $C_{pm}$, and $C_U$ values within a cycle for the wing with a flap length of 10% of $c$ at $\theta_o = 75^\circ$ and varied $\psi_o$.

In Figure 6, streamline and vorticity, velocity magnitude, and pressure contour plots around the foil's surface are presented for various $\psi_o$ cases at 0.15 $t/T$ and $\theta_o = 75^\circ$. For a flat plate, fluid separation occurs below the leading edge on the lower surface of the wing, as illustrated in Figure 6a. However, this separation is significantly reduced at higher $\psi_o$ values by attaching a leading-edge flap to the wing, resulting in smoother fluid flow and increased velocity near the hinge region on the lower surface, as depicted in Figure 6b.
Figure 6. (a) Streamline and vorticity patterns, (b) velocity magnitude, and (c) pressure distribution of the wing with varied flap lengths at $\theta_o = 75^\circ$ with varied $\psi_o$ at 0.15 $t/T$.

Figure 6c displays the pressure contour plot, showing that the leading-edge flap reduces the lower surface pressure compared to the wing without a flap. In Figure 7, the pressure coefficient on the wing’s surface along the heaving motion is illustrated for various $\psi_o$ cases at 0.15 $t/T$ and $\theta_o = 75^\circ$. The presence of a flap decreases the surface pressure owing to the expanded high-velocity region in comparison to the plate, resulting in a greater pressure differential between the upper and lower surfaces and generating a stronger pushing force in the wing, with higher $\psi_o$ values compared to the plate. In addition, the flap notably increases the projected length in the wing’s heaving motion, positively influencing the pushing force at this specific moment.

Figure 7. Pressure coefficient across the wing surface during heaving motion at $\theta_o = 75^\circ$ with varied $\psi_o$ at 0.15 $t/T$.

3.2. Impact of Flap Length Variation on Power Output

To examine the role of the leading-edge flap length on the power output of the energy harvester, this section maintains constant $\theta_o = 75^\circ$ and $\psi_o = 40^\circ$. The study evaluates
changes in flap length relative to the chord length considering lengths of 0% (equivalent to a flat plate), 10%, 15%, 20%, 33% (pivot point), and 40%.

Table 4 summarizes the average coefficients of power (\(\bar{C}_{py}\), \(\bar{C}_{pm}\), \(\bar{C}_{pt}\)) and the percentage change in \(\bar{C}_{pt}\) (denoted as \(\Delta\bar{C}_{pt}\)) for the wing with different flap lengths at fixed \(\theta_o = 75^\circ\) and \(\psi_o = 40^\circ\). The \(\bar{C}_{py}\) values are maximum for a flap span of 20% of the chord length, beyond which the values start decreasing. Conversely, the magnitude of the \(\bar{C}_{pm}\) value steadily increases with the extension of the flap length. For a flap length of 10% of the chord, the \(\bar{C}_{pt}\) value is higher than the flat plate configuration but decreases progressively as the flap span increases. However, the \(\Delta\bar{C}_{pt}\) value steadily decreases as the flap span extends up to 20% of the chord length, experiencing a significant drop beyond this threshold. This indicates that beyond a certain flap length, an increase in flap length adversely affects the power output generation of the energy harvester system for the same \(\theta_o\) and \(\psi_o\).

**Table 4. Overall power coefficients for a wing with different flap lengths at \(\theta_o = 75^\circ\) and \(\psi_o = 40^\circ\).**

<table>
<thead>
<tr>
<th></th>
<th>Plate</th>
<th>10% of c</th>
<th>15% of c</th>
<th>20% of c</th>
<th>33% of c</th>
<th>40% of c</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{C}_{py})</td>
<td>0.929</td>
<td>1.056</td>
<td>1.112</td>
<td>1.159</td>
<td>1.124</td>
<td>1.110</td>
</tr>
<tr>
<td>(\bar{C}_{pm})</td>
<td>0.034</td>
<td>-0.034</td>
<td>-0.102</td>
<td>-0.166</td>
<td>-0.242</td>
<td>-0.259</td>
</tr>
<tr>
<td>(\bar{C}_{pt})</td>
<td>0.963</td>
<td>1.022</td>
<td>1.01</td>
<td>0.994</td>
<td>0.880</td>
<td>0.852</td>
</tr>
<tr>
<td>(\Delta\bar{C}_{pt}) (%)</td>
<td>-6.1</td>
<td>4.9</td>
<td>3.2</td>
<td>-8.6</td>
<td>-11.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8 illustrates the effects of different flap lengths on the pushing force (\(C_y\)), pushing power (\(C_{py}\)), moment power (\(C_{pm}\)), and total power (\(C_{pt}\)) coefficients within an oscillation cycle at fixed pitch angles (\(\theta_o = 75^\circ\) and \(\psi_o = 40^\circ\)). Figure 8a displays the variation in \(C_y\), revealing that adding a flap length of 10% of \(c\) increases \(C_y\) relative to the baseline “plate” case from 0.15 \(t/T\) to 0.4 \(t/T\). This increase becomes more pronounced with a flap span of 15% of \(c\), and it continues to grow up to 20% of \(c\). Beyond this flap length, the \(C_y\) values plateau, suggesting a threshold for enhancement through flap extension during this interval. Conversely, the interval from 0.4 \(t/T\) to 0.5 \(t/T\) is characterized by a marked and consistent reduction in \(C_y\) as the flap lengths continue to increase. Given that the wing’s vertical velocity (\(V_y\)) is higher from 0.1 \(t/T\) to 0.4 \(t/T\), even a modest increase in \(C_y\) due to changes in flap length has a significant impact on \(C_{py}\) as depicted in Figure 8b. Figure 8c indicates that the magnitude of the negative \(C_{pm}\) values intensifies with the increment in the flap length up to 0.25 \(t/T\), suggesting an increase in adverse moment power. Conversely, the positive \(C_{pm}\) values decline from 0.25 \(t/T\) to 0.5 \(t/T\), implying a reduction in favorable moment power during this period, particularly for longer flaps. This corresponds to a notable increase in the average negative moment power for larger flap lengths, consistent with the data in Table 4. As for the total power coefficient displayed in Figure 8d, there is an observable increase in \(C_{pt}\) with the lengthening of the flap from 0.1 \(t/T\) to 0.3 \(t/T\). However, this trend is reversed from 0.3 \(t/T\) to 0.5 \(t/T\), where \(C_{pt}\) begins to decrease. The results suggest that the total power output initially benefits from the increased flap length, which peaks at a certain point before starting to diminish, suggesting that an optimal flap length exists for maximizing the total power output under the specific pitch angles of \(\theta_o = 75^\circ\) and \(\psi_o = 40^\circ\).
Figure 8. Comparative analyses of $C_y$, $C_{py}$, $C_{pm}$, and $C_{pt}$ values within a cycle for the wing with varied flap lengths at $\theta_o = 75^\circ$ and $\psi_o = 40^\circ$ (a) $C_y$ (b) $C_{py}$ (c) $C_{pm}$ (d) $C_{pt}$.

Figure 9 presents the streamline and vorticity, along with pressure contour plots, around the foil’s surface for different flap lengths at specific instances of 0.25$t/T$. In Figure 9a, a flap span of 0% of $c$ (equivalent to a flat plate) leads to fluid flow separation below the lower surface of the wing’s leading edge. This flow separation decreases as the flap length increases to 10% of $c$, and it decreases further when the flap length reaches 15% of $c$. In Figure 9b, the associated pressure contour plots reveal that larger flap lengths result in an expanded region of lower pressures on the lower surface.
3.3. Effect of Varied Maximum Wing Pitch Angles

This section examines the influence of altering the maximum wing pitch angle from 75° to 95° while maintaining a constant flap length of 20% of c and a maximum flap pitch angle of 40°. The values in Table 5 reflect the average pushing power ($\bar{C}_{py}$), average moment power ($\bar{C}_{pm}$), and average total power output ($\bar{C}_{pt}$) to assess the performance across varied $\theta_o$. $\bar{C}_{py}$ increases from $\theta_o = 75°$ to 85°, reaching its peak at $\theta_o = 85°$, and it decreases thereafter, suggesting that a wing angle of 85° is optimal for generating the pushing power at this operating condition. Conversely, the absolute $\bar{C}_{pm}$ values exhibit a continuous
decrease as \( \theta_o \) increases. On the other hand, the variations in \( C_{pt} \) show an upward trend with higher wing angles, indicating that greater wing angles enhance power generation for a flap span of 20% of \( c \). These findings emphasize the importance of selecting an appropriate wing angle to maximize the power output of the oscillating wing with a fixed flap length. A pitch angle \( \theta_o \) of 90° strikes a balance between pushing power and moment power requirements, resulting in the optimum power generation at a flap span of 20% of \( c \) and \( \psi_o = 40° \).

**Table 5.** Values of \( \bar{C}_{py} \), \( \bar{C}_{pm} \), and \( \bar{C}_{pt} \) for oscillating wing equipped with leading-edge flap length 20% of \( c \), \( \psi_o = 40° \), and varied \( \theta_o \).

<table>
<thead>
<tr>
<th>( \theta_o )</th>
<th>75°</th>
<th>80°</th>
<th>85°</th>
<th>90°</th>
<th>95°</th>
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<tbody>
<tr>
<td>( \bar{C}_{py} )</td>
<td>1.160</td>
<td>1.207</td>
<td>1.212</td>
<td>1.163</td>
<td>1.071</td>
</tr>
<tr>
<td>( \bar{C}_{pm} )</td>
<td>-0.166</td>
<td>-0.139</td>
<td>-0.115</td>
<td>-0.056</td>
<td>-0.017</td>
</tr>
<tr>
<td>( \bar{C}_{pt} )</td>
<td>0.994</td>
<td>1.068</td>
<td>1.097</td>
<td>1.107</td>
<td>1.054</td>
</tr>
<tr>
<td>( \Delta C_{pt} ) (%)</td>
<td>3.2</td>
<td>10.9</td>
<td>13.9</td>
<td>14.9</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Figure 11 provides the pushing force, pitching moment, and power coefficients in time \( T \) for a flap length of 20% of \( c \), \( \psi_o = 40° \), and varied \( \theta_o \). Figure 11a,b illustrate the \( C_y \) and \( C_m \) variations over a cycle for different wing pitch angles spanning from 75° to 95° in 5° increments. Notably, from 0.1 \( t/T \) to 0.4 \( t/T \), \( C_y \) and \( C_{py} \) exhibit higher values when the wing’s maximum pitch angle is lower. However, from 0.4 \( t/T \) to 0.5 \( t/T \), \( C_y \) and \( C_{py} \) show an increase with higher maximum wing pitch angles. In addition, the absolute \( C_{pm} \) consistently increases up to 0.25 \( t/T \), indicating an increase in adverse moment power for longer flaps. From 0.25 \( t/T \) to 0.5 \( t/T \), the trend of increasing \( C_{pm} \) values continues, suggesting an increase in favorable moment power for the wing, as shown in Figure 11c. Notably, the rise in adverse moment power is less pronounced than that in favorable moment power, resulting in a marked decrease in the average negative moment power with higher \( \theta_o \) values, which agrees with the values presented in Table 5. Interestingly, the examination of \( C_{pt} \) values reveals a decreasing trend from 0.1 \( t/T \) to 0.4 \( t/T \) with a maximum increasing wing pitch angle, followed by an increase from 0.4 \( t/T \) to 0.5 \( t/T \) as the maximum wing pitch angle increases, as shown in Figure 11d.
Figure 11. Comparison of $C_y$, $C_{py}$, $C_{pm}$, and $C_{pt}$ within a cycle for the wing with a leading-edge flap of 20% of $c$, varied $\theta_o$ and $\psi_o = 40^\circ$ (a) $C_y$ (b) $C_{py}$ (c) $C_{pm}$ (d) $C_{pt}$.

Figure 12 presents the streamline and velocity magnitude and pressure contour plots for a wing with a leading-edge flap length of 20% of $c$ and $\psi_o = 40^\circ$ based on varying $\theta_o$ at intervals of 0.25 $t/T$. In Figure 12a, the streamline and velocity magnitude contours show a notable increase in velocity around the flap’s hinge area on the lower surface as $\theta_o$ increases. Figure 12b illustrates that the wing’s upper surface pressure significantly increases for $\theta_o = 90^\circ$.

Figure 13 depicts the distribution of pressure coefficients on the foil surface across different $\theta_o$ cases at 0.25 $t/T$. Figure 13 displays a continuous decrease in the wing’s lower surface pressure, particularly near the flap–wing junction, with increasing $\theta_o$. As $\theta_o$...
increases, the wing’s projected length along the heaving motion direction decreases, accompanied by an increase in the pressure differential across the wing surface.

Figure 13. Pressure coefficient on the wing surface during heaving motion for a flap length of 20% of c, \(\psi_o = 40^\circ\), and varied \(\theta_o\) at 0.25 t/T.

3.4. Combined Impact of Varying Flap Length and Maximum Pitch Angles of the Wing and Flap

Figure 14 illustrates the combined influence of the span of the flap (ranging from 10% to 50% of c), a maximum wing pitch angle (\(\theta_o\)) ranging from 75° to 105°, and a maximum flap pitch angle (\(\psi_o\)) varying from 30° to 55° on the resulting power output (\(\bar{C}_{pt}\)). When the flap’s extent is at 10% of c, \(\bar{C}_{pt}\) is maximized at \(\theta_o = 75^\circ\) across various \(\psi_o\) as shown in Figure 14a. The maximum \(\bar{C}_{pt}\) for varied \(\theta_o\) occurs at \(\psi_o = 40^\circ\), although the variation in power output across different \(\theta_o\) is small. As the span of the flap increases to 20% of c, the optimum \(\theta_o\) significantly rises to 90°, and the maximum \(\bar{C}_{pt}\) values are notably higher compared to the flap span of 10% of c, as depicted in Figure 14b. The optimal \(\theta_o\) is found to be the same for flap lengths of 25% and 33% of c, as shown in Figure 14c,d, respectively. However, the maximum power generation is attained for a flap span of 40% of c, beyond which it starts to decrease for various \(\theta_o\) and \(\psi_o\) values depicted in Figure 14e,f, respectively.

The optimum power output was achieved for the flap spans ranging from 40% to 50% of c, \(\theta_o = 95^\circ\text{–}100^\circ\), and \(\psi_o = 45^\circ\) and 50°. As the length of the flap increases, the optimum \(\theta_o\) gradually increases from 75° to 100°, whereas \(\psi_o\) varies between 45° and 50°. The optimal power generation was achieved with a flap span of 40% of c at \(\theta_o = 95^\circ\) and \(\psi_o = 45^\circ\). This configuration resulted in a 29.9% enhancement in power output and a 20.2% boost in efficiency relative to the wing configuration without a leading-edge flap.
4. Conclusions

We investigated a flat plate oscillating wing with an integrated leading-edge flap by focusing on its impact on energy-harvesting performance. Numerical simulations were conducted using the overset grid method under transient conditions, and the $k-\omega$ SST turbulence model was employed. Various parameters such as the flap length (from 10\% to 50\% of the chord length) and maximum pitch angles for the wing and flap (from 75\° to 105\° and from 30\° to 55\°, respectively) were quantitatively assessed to identify the configurations that maximize power generation and efficiency.

The results showed that the addition of the leading-edge flap leads to smoother fluid flow along the wing’s lower surface and a high-velocity region compared to the wing without a flap. In addition, an increase in the flap’s maximum pitch angle or the flap length enhances the wing’s effective projected length in the heaving direction. By analyzing the combined effects of varying flap length, wing angle, and flap angle, we identified the optimal configurations that yielded substantial power output enhancements. In particular, flap lengths within the range of 40\%–50\% of the chord length, combined with $\theta_o$ values from 95\° to 100\° and $\psi_o$ of 45\°–50\°, deliver peak power generation. The results demonstrate a remarkable 29.9\% increase in overall power output and a commendable 23\% efficiency enhancement compared to the baseline wing configuration without the flap.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( t_w )</td>
<td>The thickness of the wing</td>
</tr>
<tr>
<td>( d )</td>
<td>The total vertical movement</td>
</tr>
<tr>
<td>( x )</td>
<td>Wing’s projected length along heaving motion</td>
</tr>
<tr>
<td>( x_p )</td>
<td>The pitching center of the wing</td>
</tr>
<tr>
<td>( c )</td>
<td>Airfoil chord length</td>
</tr>
<tr>
<td>( h )</td>
<td>Wing’s heave amplitude (instantaneous)</td>
</tr>
<tr>
<td>( H_0 )</td>
<td>Wing’s heave amplitude (maximum)</td>
</tr>
<tr>
<td>( \theta(t) )</td>
<td>Wing’s pitch angle (instantaneous)</td>
</tr>
<tr>
<td>( \theta_o )</td>
<td>Wing’s pitch angle (maximum)</td>
</tr>
<tr>
<td>( \Psi(t) )</td>
<td>Flap’s pitch angle (instantaneous)</td>
</tr>
<tr>
<td>( \Psi_0 )</td>
<td>Flap’s pitch angle (maximum)</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Oscillation frequency</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Nondimensional reduced frequency ((fc/\Omega))</td>
</tr>
<tr>
<td>( C_y )</td>
<td>Coefficient of pushing force</td>
</tr>
<tr>
<td>( C_m )</td>
<td>Coefficient of pitching moment</td>
</tr>
<tr>
<td>( C_{py} )</td>
<td>Coefficient of pushing power</td>
</tr>
<tr>
<td>( C_{pm} )</td>
<td>Coefficient of pitching moment power</td>
</tr>
<tr>
<td>( C_{pt} )</td>
<td>Coefficient of total power</td>
</tr>
<tr>
<td>( \bar{C}_{pt} )</td>
<td>Coefficient of average total power</td>
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<td>( \Delta \bar{C}_{pt} )</td>
<td>Change in the average total power coefficient compared to the wing without the flap</td>
</tr>
<tr>
<td>( F_Y )</td>
<td>Pushing force</td>
</tr>
<tr>
<td>( F_X )</td>
<td>Drag force</td>
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References


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