Relying on Dynamically Morphing Blades to Increase the Efficiency of a Cycloidal Rotor

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Abstract. The configuration of the airfoil has a significant impact on its aerodynamic performance. This paper aims to improve the aerodynamic efficiency of the cycloidal rotor system by using dynamically morphing blades. Three different camber morphing concepts (leading edge deflection, trailing edge deformation and cambered NACA profile) have been applied to a baseline 2-bladed system with rotating and pitching NACA0015 aerofoils. Then, based on these camber concepts, 2D URANS numerical simulations were conducted for blades with different morphing degrees using OpenFOAM. The simulation results verified that the flow field condition could be optimized and significantly higher thrust and efficiency could be achieved by properly tuning the morphing control. Especially, in the case of 10% trailing edge camber and 16% NACA camber, compared with baseline case, 28.1% and 43.5% higher figure of merit values were obtained, respectively. The simulation files and the results for the last rotor revolution of each case presented in this paper are available in the following dataset: https://doi.org/10.18419/darus-2191.

1. Introduction
The cycloidal propeller is a novel concept of a rotary-wing system, where the rotation axis is parallel to the blade span. It has the advantages of providing 360° thrust force and maintaining constant flow velocity along the blade span. Consequently, it has the potential to achieve higher aerodynamic efficiency when compared with conventional propellers or helicopter rotors. Inspired by this, the cycloidal rotor is considered to be a promising candidate for the propulsion system for various applications[1], such as VTOL vehicles, Unmanned Air Vehicles(UAVs), and Micro Air Vehicles(MAVs).

The unsteady aerodynamic phenomena of a cycloidal rotor are greatly affected by its blade configuration. According to a previous investigation[2], by adopting the continuously leading edge morphing to the cycloidal rotor system, the massive flow separation and the dynamic stall vortex can be mitigated or even removed. Therefore, the dynamically morphing control has great potential in flow field optimization and efficiency improvement.

2. Methods
2.1. Camber Morphing Concepts
To evaluate the performance of the camber controlled cycloidal rotor, various camber methods are first derived to define the shape of morphing airfoils. Specifically, the airfoil deformation is
realized by superimposing different camber line functions onto the baseline symmetric airfoil.

The first morphing method is the NACA camber concept\[3\]. According to the definition, the symmetric NACA airfoil (Fig. 1(a)) is described by the half-thickness function, defined as:

\[
y_t = \frac{t}{0.2} \left( 0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4 \right)
\]  

(1)

where \(x\) represents the normalized blade chord and \(t\) is the normalized airfoil thickness. Particularly, for the cambered NACA airfoil (Fig. 1(b)), an additional camber line function is required to determine the morphing configuration. In detail, the camber line function is a second order polynomial segment function, denoted as:

\[
y_c = \begin{cases} 
-\frac{m}{p^2} (p - x)^3, & 0 \leq x < p \\
\frac{m}{(1-p)^2} \left(1 - 2p + 2px - x^2\right), & p \leq x \leq 1
\end{cases}
\]  

(2)

where \(p\) is the position of maximum camber as a percentage of the chord, \(m\) denotes the maximum degree of deformation. Note that the shape of the cambered NACA airfoil (Fig. 1(b)) is modelled by overlaying the thickness distribution (purple dash line, which is identical with the symmetric thickness distribution(1)) onto the camber line function (red dash line). The coordinates of the upper and lower surface of the cambered NACA airfoils are calculated respectively by\[3\]:

\[
\begin{align*}
\text{Upper:} & \quad x_u = x - y_t \sin \alpha, \quad y_u = y_c + y_t \cos \alpha \\
\text{Lower:} & \quad x_l = x + y_t \sin \alpha, \quad y_l = y_c - y_t \cos \alpha
\end{align*}
\]  

(3)

where \(\alpha\) indicates the slope of the camber line at each position.

A wide range of cambered NACA airfoils are modelled by varying the maximum camber degree \(m\) and its location \(p\). Moreover, based on the concept of cambered NACA airfoil, more generalized morphing methods can be derived efficiently by introducing different polynomial camber line functions into the system.

According to previous researches, airfoils with trailing edge (TE) deformation\[4\] and dynamically drooped leading edges\[5\] (LE) have great potential to significantly reduce or eliminate the dynamic stall and the massive flow separation. Therefore, the investigation regarding the effect of trailing and leading edge deformation are also included in this work.

In particular, the trailing edge deformation is first achieved by overlapping a third-order polynomial shape function\[6\] to the trailing edge section of baseline configuration. In this case, the camber line function is denoted as:

\[
y_c = \begin{cases} 
0, & 0 \leq x < p \\
\frac{-m}{(1-p)^2} (x - p)^3, & p \leq x \leq 1
\end{cases}
\]  

(4)

where \(p\) represents the non-dimensional start location of trailing edge morphing and \(m\) denotes the degree of maximum camber. Subsequently, the leading edge deformation can be achieved by applying a similar third-order polynomial segment function, which can be expressed as:

\[
y_c = \begin{cases} 
-\frac{m}{p^2} (p - x)^3, & 0 \leq x < p \\
0, & p \leq x \leq 1
\end{cases}
\]  

(5)
to the leading edge section of the symmetric NACA airfoil, where \( p \) is the non-dimensional end location of leading edge morphing and \( m \) indicates the maximum camber degree. The airfoils with deformed trailing and leading edge are illustrated in Fig. 2 and 3, respectively. In addition, the configurations tested in this work are outlined in Table 1.

![Figure 2. TE camber, \( p = 0.7, 0 < m \leq 16\% \). Figure 3. LE camber, \( p = 0.3, 0 < m \leq 12\% \).](image)

| Camber Method | Camber Position | Max. Camber |
|---------------|-----------------|-------------|
| NACA Camber   | \( p = 0.40 \)  | \( m \in [0, 16\%] \) |
| TE Camber     | \( p = 0.70 \)  | \( m \in [0, 16\%] \) |
| LE Camber     | \( p = 0.30 \)  | \( m \in [0, 12\%] \) |

2.2. Numerical Setting

A structured mesh is constructed for the whole computational domain by using the meshing tool Pointwise. Specifically, the initial rotor system investigated in this work consists of two baseline NACA0015 airfoils, with the chord length \( c = 0.2 \text{ m} \). The aspect ratio and chord-by-radius ratio of the blades are selected, according to Kellen’s optimization analysis[7].

The entire mesh revolves around the centre of the domain, while the pitch motion around the pivot point is only applied to a small circular area surrounding the blades. Particularly, the pitching and the non-pitching domains are separated by the Arbitrary Mesh Interface (AMI), which enables the communication between disconnected adjacent grids.

After the mesh construction, two-dimensional incompressible URANS numerical simulations are conducted on the cycloidal rotors with morphing blades by utilizing the open-source CFD tool OpenFOAM. All simulations are iteratively solved by the PIMPLE algorithm[8], which is a pressure-based solver and can be regarded as the combination of Pressure Implicit with Splitting of Operator (PISO) solver and Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) solver. Furthermore, the k-\( \omega \)-SST model[9] is implemented in this work to solve the turbulent closure problem, due to its highly accurate prediction of the dynamic stall phenomena for oscillating airfoils[2]. Relevant information about numerical setting of the rotor system with morphing blade is summarized in Table 2.

2.3. Periodical Morphing

The schematic of the coordinate system and rotor parameters are shown in Fig. 4 where \( \theta \) represents the pitching amplitude and \( \psi \) indicates the azimuth angle.

Generally, for conventional cycloidal rotors, the thrust is mainly produced by the pitching motion of the blade. In this work, the dynamically morphing configuration of the airfoil contributes to the lift generation as well. Moreover, both the pitching amplitude \( \theta_t \) and camber morphing degree \( m_t \) vary periodically over the azimuth angle, as depicted in Fig. 5. Specifically, a symmetric sinusoidal pitching motion is defined in the system, expressed as

\[
\theta(t) = \theta_0 \sin(\psi)
\]
Table 2. Parameters of the rotor system in the CFD simulation.

| Parameter               | Value          | Parameter               | Value          |
|-------------------------|----------------|-------------------------|----------------|
| Number of Blades        | 2              | Angular Velocity        | 17.453 rad/s   |
| Chord Length            | 0.20 m         | y^+                     | < 8            |
| Rotation Radius         | 0.32 m         | Cell Count              | 123408         |
| Blade Span              | 0.80 m         | Reynolds Number         | 72000          |
| Baseline Airfoil        | NACA0015       | Courant Number          | [1, 2]         |

where $\theta_0$ stands for the maximum pitching amplitude (set as 20° for all cases). Besides, the periodical variation of camber degree $m(t)$ is governed by a half-cosine function, defined as:

$$m(t) = \begin{cases} 
\frac{m_0}{2}[\cos(2\psi) + 1], & 0^\circ \leq \psi < 180^\circ \\
-\frac{m_0}{2}[\cos(2\psi) + 1], & 180^\circ \leq \psi < 360^\circ 
\end{cases}$$

(7)

where $m_0$ is the maximum camber degree for the cycle ($\psi = 90^\circ$ and $270^\circ$). Particularly, the $m(t)$ value is negative for the lower part of the cycle, which indicates that the inverse camber is applied in this section. Additionally, the inverse cambered aerofoil is symmetrical about the blade chord to the cambered one with the corresponding positive camber degree.

Figure 4. Coordinate system and parameters.

Figure 5. Periodical pitching and camber morphing setting.

3. Results
The objective of this work is to achieve better aerodynamic performance by using morphing blades. Therefore, force power analysis and flow field visualization are conducted to compare the performance of the rotor systems with cambered configurations given in Table 1.

The simulation files and the results for the last rotor revolution of each case presented in this paper are available in the following dataset: [https://doi.org/10.18419/darus-2191](https://doi.org/10.18419/darus-2191)
3.1. Force and Power Analysis

In this section, resultant thrust $F_{res}$, power $P$, and efficiency are calculated to evaluate the performance of camber controlled rotor systems. Especially, the efficiency of the cycloidal rotor is qualified in terms of power loading and figure of merit [7]. In detail, the figure of merit ($FoM$) is defined as the ratio of the ideal power required in the hover state to the actual power required. Generally speaking, $FoM$ can be introduced to predict the overall aerodynamic performance. Another employed dimensional quantity is the power loading ($PL$), which represents the minimum power required for the system with a given weight.

To begin with, the effect of the NACA camber concept is studied. As illustrated in Fig. 6(a), the moderate increases in thrust and required power with increasing camber degree are observed. For the cases with 4%, 8%, 12%, and 16% cambered NACA airfoils, 18.0%, 36.8%, 60.4%, and 77.5% higher thrust are observed, respectively. Meanwhile, 6.74%, 25.7%, 48.1%, and 65.0% more power are required by the blades. Furthermore, the gain in thrust is always greater than the power increment, which leads to better efficiency for cases with cambered NACA airfoils. Besides, in the case of 16% NACA camber, the $FoM$ reaches the value of 0.607 (43.5% higher than the baseline case), which is the highest value that can be achieved in this work.

Figure 6(b) depicts the variation of thrust, power, and efficiency for the cases with TE deformation. Similarly, significantly higher resultant thrust and power can be achieved with the increasing camber degree. Specifically, for the cases with 4%, 8%, 12%, and 16% TE camber morphing, 31.9%, 59.7%, 86.4%, and 116% higher thrust are observed, respectively. Meanwhile, 28.2%, 58.8%, 100%, and 156% extra power are required by the morphing blades. Accordingly, the value of power loading will first exhibit a slight increment, followed by a continuously descending trend, as the TE camber degree increases. Moreover, the best result of $PL$ is obtained when the camber degree is around 4%. Furthermore, the variation of the figure of merit over the TE camber degree experiences a similar behaviour, and it will reach the maximum value of 0.542 (28.1% higher in comparison with baseline case) in the case of 10% TE morphing.

Figure 6(c) presents the results for cases with cambered LE. From the figure, both $F_{res}$ and $P$ experience a moderate decrease with the increasing LE camber degree, if the camber degree is less than 8%. Subsequently, the resultant force continues to decrease, while the required power reaches its minimum value of 1.409 (14.5% less than the baseline case) in the case of $m = 8\%$. As a consequence, the value of both power loading and figure of merit would first increase and then decrease, as more camber is introduced. Besides, the best results of $PL$ (with the value of 0.557, 9.0% higher than the baseline case) and $FoM$ (with the value of 0.451, 6.62% higher than the baseline case) are achieved by the case $m = 4\%$.

3.2. Downwash Velocity

The induced velocity in the negative y-direction is termed downwash velocity. It varies the effective angle of attack (AoA) of the blade and changes the incident flow velocity. Previous research has proved that the downwash velocity in the rotor wake is of similar magnitude to the tangential velocity of the blade rotation [10]. Therefore, it has a great influence on the aerodynamic performance of the cycloidal rotor system.

As shown in Fig. 7, more intense and concentrated downwash velocity was observed for the cases with 8% NACA and TE camber. Consequently, for the case with relatively large NACA and TE camber, more reduction in the effective AoA and change in inflow velocity could be expected when the blade is passing through the lower end of its trace. Besides, in the cases of LE camber, since the thrust angle varies from 96.4° (baseline case) to 92.7° (8% LE camber), the area affected by large downwash velocity exhibits a clockwise shift. Moreover, no obvious change in velocity magnitude is observed in comparison with the baseline case.
Figure 6. Force, power and efficiency results.

(a) NACA camber, $p = 0.4$, $0 < m \leq 16\%$

(b) TE camber, $p = 0.7$, $0 < m \leq 16\%$

(c) LE camber, $p = 0.3$, $0 < m \leq 12\%$

Figure 7. Downwash velocity for cases with different camber concepts.
3.3. z-Vorticity Field Contour

The z-vorticity contours for cases with different camber concepts are illustrated in Fig. 8. Specifically, for the baseline case, when the blade is passing through the upper half of its trace, the leading edge vortex (LEV) would appear near the position $\psi = 120^\circ$. Subsequently, the vortex develops rapidly and spans the entire surface at the position $\psi = 176^\circ$. Furthermore, when the blade is in the lower half of the trajectory, fluid flows smoothly on the surface of the symmetric airfoils and no vortex is observed.

![Vorticity field for cases with different camber concepts.](image)

- $\psi = 90^\circ$ Baseline
- $\psi = 120^\circ$ NACA 12%
- $\psi = 180^\circ$ TE 12%
- $\psi = 270^\circ$ LE 4%
- $\psi = 300^\circ$

Figure 8. Vorticity field for cases with different camber concepts.

In the case of camber NACA airfoils, it is evident that the formation and development of the LEV at the position $120^\circ < \psi < 180^\circ$ is eliminated. However, at the lower half, the presence of a vortex and its detachment at the outer side (pressure side) of the oscillating blade, as well as the distorted boundary vorticity, could be observed near the lower end, i.e., $260^\circ < \psi < 310^\circ$, due to the cambered configuration and the intensified downwash effect. As a result, reduction in lift and increasing pressure loss could be expected for the case with cambered NACA airfoils near the lowest point of its cycle.

For the cases with large TE camber, from the figure, the size of the LEV at the upper half is slightly reduced. Moreover, at the top and bottom of the trace, vortex shedding could be observed in the wake region due to the deformed TE configuration. Accordingly, when the blade passes through the vortex shed from the preceding blade, the LEV is induced on the outer surface of the oscillating blade. The result verified that the blade vortex interaction effect is
important for the cases with relatively large TE camber. Besides, this effect may also become significant for rotors with more blades, as cycloidal rotors often have 4 or 6 blades.

Moreover, in the cases with moderate LE deformation, the formation and development of the vortex at the upper half is eliminated. Additionally, there are no signs of vortex development and severe flow separation during the entire cycle. It can be inferred that the flow field structure could be optimized by implementing such LE morphing control.

4. Conclusions
In this work, three camber methods were developed to define the morphing airfoils. Then, based on these morphing concepts, the current cycloidal rotor model was extended to allow the modelling of dynamically morphing blades. Subsequently, numerical simulations were performed for cases with different cambered configurations, the results can be concluded as follows:

- For the cases with cambered NACA airfoils, the moderate increases in thrust and the required power with increasing camber degree are obtained. Moreover, the highest value for both figure of merit and power loading could be achieved by utilizing such a camber concept. In particular, in the case with 16% camber NACA airfoils, the FoM reaches the value of 0.61, which is the highest value that can be achieved in this work.
- For the cases with cambered TE, significantly higher resultant thrust and power can be achieved as the TE camber degree grows, while the efficiency would first increase and then decrease with increasing camber degree.
- For the cases with cambered LE, the resultant thrust and the required power decrease as the LE camber morphing degree increase. Besides, a slight improvement in efficiency could be expected when the camber degree is less than 4%.

Overall, the simulation results verify that the cases with cambered TE achieve the highest thrust increment while cases with cambered NACA airfoils show the best improvement in efficiency. For future work, the optimization of the flow condition will be realized by finding the optimal combination of cambers types and tuning their phase and maximal amplitude.

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