Influence of inflow angle on flexible flap aerodynamic performance

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Abstract. Large scale wind turbines have larger blade lengths and weights, which creates new challenges for blade design. This paper selects NREL S809 airfoil, and uses the parameterized technology to realize the flexible trailing edge deformation, researches the dynamic aerodynamic characteristics in the process of continuous flexible deformation, analyses the influence of inflow angle on flexible flap aerodynamic performance, in order to further realize the flexible wind turbine blade design and provides some references for the active control scheme. The results show that compared with the original airfoil, proper trailing edge deformation can improve the lift coefficient, reduce the drag coefficient, and thereby more efficiently realize flow field active control. With inflow angle increases, dynamic lift-drag coefficient hysteresis loop shape deviation occurs, even turns into different shapes. Appropriate swing angle can improve the flap lift coefficient, but may cause early separation of flow. To improve the overall performance of wind turbine blades, different angular control should be used at different cross sections, in order to achieve the best performance.

1. Introduction

Wind turbine development has presented the trend of scale from small to large, location from land to ocean, position from offshore to deep sea. The blade length increases with the power increasing, leading to a flexible deformation, causing aerodynamic performance changes, formed a typical nonlinear fluid-structure interaction problem. Research shows that when the wind turbine blade length reached more than 30 m, the geometric nonlinear characteristics significantly enhanced; when blade length reached more than 60 m, wind turbine blade airfoil trailing edge showed flexible features [1-2].

At present, the flexible structure research mainly focuses on smart morphing wings in the field of aerospace, in the field of wind turbine blades basically focuses on material, structural performance and control institutions [3-7]. Since Andrew systematically applied smart flexible structure in 50 kW blade for the first time [8], the study of flexible blade is always based on the joint design of bending and twisting with airfoil structure not changed [9-12], active flexible flap airfoil research suggests that appropriate flexible deformation can improve aerodynamic performance. Wind turbine blade is made of airfoil sections with different chord lengths and twist angles and different cross sections have different angles of attack, this article selects specific inflow angles to study the flap aerodynamic characteristics.

In fact, airfoil flexible design can also greatly enhance the structure performance, active control of flap tail can reduce fatigue load of 48% or higher [13].
We select NREL S809 airfoil, using the parameterized technology to achieve its flexible trailing edge deformation, study the influence of inflow angle on flexible flap aerodynamic characteristics and transition point, provide some references for further realize the flexible wind turbine blade design and the active control scheme.

2. Deformation mechanism

As shown in figure 1, take NREL S809 airfoil as the original airfoil, define H point on the chord line as the hinge point, the part backward swings up and down around that point, keeping the chord length and thickness unchanged. The profile is determined by the Bezier interpolation. With the inflow velocity $U_\infty$ direction keeping unchanged, then the angle of attack $\alpha_t$ increases when the trailing edge (T) swings down, so define the swing angle $\beta_t$ (the angle between the attachment of H point and T point and the original chord line at any time) is positive when the tail rotates clockwise from the original position.

![Figure 1. Sketch of swing angle and deformation of flexible flap.](image)

The flap tail flexibly swings according to the sine law:

$$\beta_t = \beta_0 + \sin\left(2\pi t \cdot T^{-1}\right)\beta_{\max}$$

(1)

where $\beta_0$ is the initial swing angle, $\beta_{\max}$ is the maximum swing angle, $t$ is time, $T$ is swing period.

For airfoil with flexible deformation, with the inflow direction keeping unchanged, according to the definition of angle of attack, the corresponding value is:

$$\alpha_t = \alpha_0 - \arctan\left(\frac{y_T}{x_T}\right)$$

(2)

where, $\alpha_0$ is the initial angle of attack; $x_T$, $y_T$ is the coordinate of the T point.

The corresponding relation between angle of attack and swing angle is as follows:

$$\alpha_t = \alpha_0 + \arctan\left(\frac{(1-k) \cdot \sin \beta_t}{k + (1-k) \cdot \cos \beta_t}\right)$$

(3)

where, $k$ is the proportion of segment LH to the chord $c$: $k = LH \cdot c^{-1}$, i.e. the nondimensional position of the hinge point.

3. Meshing and calculation conditions

We used reforming dynamic mesh technique; the flow field calculation domain is shown in figure 2, the mesh distribution is shown in figure 3, the upstream inflow zone is a semicircle of $r = 10c$, the dynamic grid zone is a circular region of $r = c$, the downstream wake zone is a square of $20c \times 20c$.

Control equations: static aerodynamic characteristics calculation used potential flow equation coupled with the boundary layer equation, the dynamic aerodynamic characteristics calculation used the RANS equation and $k-\varepsilon$ turbulence model, inflow Reynolds number $Re = 8 \times 10^5$. 

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Boundary conditions: inlet velocity, pressure outlet, no slip wall condition is used on airfoil surface. Swing angle control: the initial angle is 0°, flexible tail swing period is 2s and time step is 0.01s, angular range is -25°~25°. Flap parameters: NREL S809 airfoil as original airfoil, take 0.750c as hinge point. Inflow angles: select -5°, 0°, 5°, 10° as inflow angles for flexible flap numerical simulation.

4. Results and analysis
Dynamic lift-drag characteristics were analysed with changing of angle of attack, swing angle and flow time below.

Figure 4 shows the dynamic lift-drag characteristics curve along with the changing of angle of attack with $\phi = -5^\circ, 0^\circ, 5^\circ, 10^\circ$. The closed curve is dynamic lift-drag coefficients of flap, the open curve is static lift-drag coefficients of S809 original airfoil. Comparing the static and dynamic lift-drag characteristics, it can be found that the dynamic process of the flap makes its lift-drag coefficients do not change along the static curve, which on the one hand is due to the dynamic response of the process has obvious hysteresis phenomenon to time, on the other hand is due to with the same actual angle of attack, the swing angle change leads airfoil camber to change, thus influence the aerodynamic characteristics.

Comparing flap dynamic process at different inflow angles, it can be found that with the increase of $\phi$ starting from zero, the flap lift coefficient increases overall, to $\phi=5^\circ$ the curve flips from $\circ$ shape to $\infty$ shape, continually increase to $10^\circ$ almost turn to a reversed $\circ$ type. At $\phi=-5^\circ$ and $\phi=5^\circ$ the shape and position of dynamic drag coefficient closed loop with the angle of attack offsets from that at $\phi = 0^\circ$. At $\phi=10^\circ$ the drag coefficient increases sharply, which is due to the separation of the flow.
Figure 5 shows the dynamic lift-drag characteristics curve along with the changing of swing angle with $\phi = -5^\circ, 0^\circ, 5^\circ, 10^\circ$. As can be seen from the figure, the flap lift-drag coefficients trend are basically the same with that along with the change of angle of attack, but with the change of swing angle the flap dynamic aerodynamic characteristics observation can be more intuitive. At $\phi = 10^\circ$, the flap lift coefficient differs least at little swing angles while differs most at big swing angles, which may be due to at big swing angles the flow separation occurs and up-swing can reduce the effect of separation and down-swing enhances the separation. At $\phi = 10^\circ$, the flap drag coefficient differs least when it passes the same swing angle back and forth, which may be due to the flow separation and the deformation effect on drag coefficient decreases.

![Figure 5](image)

**Figure 5.** Periodical change of dynamic lift-drag characteristics with swing angle.

Figure 6 shows the dynamic lift-drag characteristics curve along with the changing of flow time with $\phi = -5^\circ, 0^\circ, 5^\circ, 10^\circ$. As can be seen from figure 6 (a), with the increase of inflow angle from $-5^\circ$ to $10^\circ$, the overall lift coefficient increases in a period. The maximum values at $\phi = 0^\circ, 5^\circ, 10^\circ$ are basically the same, but the minimum value increases in a row, which leads the average value of lift coefficient to increase, while the amplitude decreases at the same time. As can be seen from figure 6 (b), it’s different from lift coefficient that drag coefficient has two maximums in a period. The bigger maximum value of drag coefficient occurs in the former semi-period with positive inflow angles, while the bigger maximum value of drag coefficient occurs in the latter semi-period with negative inflow angles. This may because the swing angle in the former semi-period makes the angle of attack increase positively with positive inflow angles, while the swing angle in the latter semi-period makes the angle of attack increase negatively with negative inflow angles. And bigger angle of attack causes bigger drag coefficient in both cases.
Figure 6. Periodical change of dynamic lift-drag characteristics with flow time.

Figure 7 is pressure contour and flow chart around the flap under different inflow angles with $\beta_t = 25^\circ$. As can be seen from figure 7(a), although the inflow angle is -5°, the flap still has its lower side surface as the pressure side and the upper side surface as the suction side, that is because the flap swing angle is 25°, resulting a positive actual angle of attack for the flap, combining figure 4(a) we can intuitively see the actual angle of attack is about 1.2°. Inflow angle increases from -5° to 5°, the pressure difference between upper and lower surface of flap gradually increases, when inflow angle increases to 10° the pressure difference is reduced, this is because the flow has been in a serious separation. Figure 4 (a) shows that S809 original airfoil is completely attached flow at $-5^\circ \leq \alpha \leq 6^\circ$, while flow in figure 7(c) has separated, the flap may cause flow early separation at the same time while increasing the lift coefficient.
5. Conclusion
The increase of the length and weight of wind turbine blades caused by large-scale development trend, has become key and hot issue of wind turbine safety and economic operation. The active control of flexible trailing edge flap, can affect the aerodynamic layout around the airfoil. Analysed the influence of inflow angle on the static and dynamic aerodynamic characteristics of flexible flap, the results show that:

1) With the increase of inflow angle, the hysteresis loop of dynamic lift coefficient and drag coefficient shape deviation occurs, even turns into different shapes.

2) Lift coefficient change over time only has one maximum in a period, and drag coefficient change over time has two maximums, and the drag coefficient wave is more irregular than lift coefficient.

3) Appropriate swing angle can improve the flap lift coefficient, but may cause flow early separation. To improve the overall performance of wind turbine blades, different angular control should be used at different cross sections, in order to achieve the best performance.

4) The flexible trailing edge deformation of the flap has great influence on aerodynamic characteristics, which can provide theoretical reference for active flow control.

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