Influence of hinge point on flexible flap aerodynamic performance

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Abstract. Large scale wind turbines lead to increasing blade lengths and weights, which presents new challenges for blade design. This paper selects NREL S809 airfoil, uses the parameterized technology to realize the flexible trailing edge deformation, researches the static aerodynamic characteristics of wind turbine blade airfoil with flexible deformation, and the dynamic aerodynamic characteristics in the process of continuous deformation, analyses the influence of hinge point position 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 hinge point moving forward, total aerodynamic performance of flexible flap improves. Positive swing angle can push the transition point backward, thus postpones the occurrence of the transition phenomenon.

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 bending deformation, causing aerodynamic performance change, formed a typical nonlinear fluid-structure interaction problem. Research shows that when the wind turbine blade length reached more than 30m, 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 focus on smart morphing wings in the field of aerospace, in the field of wind turbine blades basically focus 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 being constant [9-12], active flexible flap airfoil research suggests that the appropriate flexible deformation can improve its aerodynamic performance. At the same time, the airfoil thickness and camber change has a certain influence on airfoil stall and transition point, while the flap tail deformation will change the thickness and camber, thus influence the stall and transition point of the airfoil.

In fact, airfoil flexible design still can 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 hinge point 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. The inflow velocity $U_\infty$ direction remains unchanged, then the angle of attack $\alpha_i$ increases when the trailing edge (T) swings down, so define the swing angle $\beta_i$ (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.

\[ \beta_i = \beta_0 + \sin \left( 2\pi t \cdot T^{-1} \right) \beta_{\text{max}} \]  

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

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

\[ \alpha_i = \alpha_0 - \arctan \left( \frac{y_T}{x_T} \right) \]  

where, $x_T$, $y_T$ is the coordinate of the T point.

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

\[ \alpha_i = \alpha_0 + \arctan \left( \frac{(1-k) \cdot \sin \beta_i}{k + (1-k) \cdot \cos \beta_i} \right) \]  

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

3. Meshing and calculation conditions
We used reforming dynamic grid technique; the flow field calculation domain is shown in figure 2, the grid 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 $Re = 8 \times 10^5$.

Boundary conditions: inlet velocity, pressure outlet, airfoil surface used no slip wall condition.

Swinging angle control: the initial angle is 0°, flexible tail swing period is 2s and time step is 0.01s, angular range is $-25^\circ$ to $25^\circ$.  

Figure 1. Sketch of swing angle and deformation of flexible flap.
Flap parameters: NREL S809 airfoil as original airfoil, select 0.625\(c\), 0.750\(c\) and 0.875\(c\) as three hinge point position for flap numerical simulation, as shown in figure 4.

4. Results and analysis

4.1. Static aerodynamic characteristics

Figure 5(a) shows the aerodynamic characteristics of the S809 original airfoil and its three derived airfoil F625, F750, F875 \((k = 0.625, 0.750, 0.875, \beta = 10^\circ)\). Figure 5(b) is the corresponding transition point position with the changing of angle of attack.

As can be seen from figure 5(a), within the scope of the normal angle of attack, the original airfoil lift coefficient increases with the angle of attack increasing. The interval \(-5^\circ \leq \alpha \leq 5^\circ\) is linear region (completely adherent flow), and \(5^\circ \leq \alpha \leq 20^\circ\) range is nonlinear region (transition flow or partly separation flow). The lift coefficient range of three deformation airfoils at \(-5^\circ \leq \alpha \leq 5^\circ\) can completely cover the lift coefficient variation range of original airfoil running at \(0^\circ \leq \alpha \leq 20^\circ\), and within the area lift coefficient keeps linear relationship with angle of attack (completely adherent flow).
While at $5^\circ \leq \alpha \leq 20^\circ$, although in the nonlinear area, the lift coefficient still increases with the angle of attack increasing.

Within the $-5^\circ \leq \alpha \leq 5^\circ$ range, the drag coefficients of deformed airfoils and the original airfoil basically hold the line; while in the $5^\circ \leq \alpha \leq 20^\circ$ range, compared with the original airfoil, the drag coefficient is slightly higher, but little change, combined with lift coefficient rise together, airfoil aerodynamic performance improves as a whole.

As can be seen from figure 5(b), the overall trends of the transition point position change of the four airfoils with the angle of attack differs little, transition point quickly moves forward when the angle of attack reaches $5^\circ$. Compared with the original airfoil, when $\alpha \leq 10^\circ$ the transition point of the deformed airfoils moves backward, which suggests that appropriate angular deformation can delay the boundary layer separation. For the deformed airfoils, when $\alpha \leq 5^\circ$ the transition point of F750 airfoil is backward compared with that of F625 airfoil; while at $\alpha \leq -5^\circ$ transition point of F875 airfoil moves backward compared with the former two but moves forward at $-5^\circ \leq \alpha \leq 5^\circ$.

Comprehensive the above analysis, with the hinge point moves forward, lift coefficient increases, drag coefficient almost remains unchanged, transition point position is leveling off along with the change of angle of attack.

4.2. Dynamic aerodynamic characteristics

Figure 6 shows the dynamic changing process of lift-drag coefficients of flexible flap with swing angle within one cycle. It's easy to see that the periodical change of lift-drag coefficients with swing angle forms a closed circuit, the lift coefficient presents a $\bigcirc$ shape and the drag coefficient presents a $\infty$ shape respectively.

With hinge point moves forward, the maximum value of lift-drag coefficient of flap increases and the minimum value decreases, which means the change of lift-drag coefficients with swing angle intensifies, this may be due to with the same time swing angle, when the hinge point moves forward, the flap tail part increases, and the actual movement distance of trailing edge point increases.

![Figure 6. Comparison of lift-drag characteristics in one cycle](image)

Figure 7 shows the airfoil surface static pressure distribution of several representative swing angles within one swing period. As can be seen from the figure, the airfoil pressure side and suction side show cyclical changes within one swing period. And under the same swing angle, different motion directions of the flap result in different airfoil surface static pressure distributions, even the pressure surface and suction surface inversion.
5. Conclusion

The increase of the length and weight of wind turbine blades caused by large-scale development trend, has become a 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 hinge point position on the static and dynamic aerodynamic characteristics of flexible flap, the results show that:

(1) With the same time swing angle, when the hinge point moves forward, the static lift coefficient increases obviously and drag coefficient is slightly increased, the overall aerodynamic performance is improved.

(2) The flexible deformation of the flap can change its thickness and camber, thus affect the position of the transition point appeared, positive swing angle can make transition point position move backwards, and delay the occurrence of separation phenomenon.

(3) With the hinge point position moves forward, the flap dynamic lift-drag coefficient change along with the change of swing angle intensifies.

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