Numerical evaluations of the effect of leading-edge protuberances on the static and dynamic stall characteristics of an airfoil

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Abstract. Wavy leading edge modifications of airfoils through imitating humpback whale flippers has been considered as a viable passive way to control flow separation. In this paper, flows around a baseline 634-021 airfoil and one with leading-edge sinusoidal protuberances were simulated using S-A turbulence model. When studying the static stall characteristics, it is found that the modified airfoil does not stall in the traditional manner, with increasing poststall lift coefficients. At high angles of attack, the flows past the wavy leading edge stayed attached for a distance, while the baseline foil is in a totally separated flow condition. On this basis, the simulations of pitch characteristic were carried out for both foils. At high angles of attack mild variations in lift and drag coefficients of the modified foil can be found, leading to a smaller area of hysteresis loop. The special structure of wavy leading edge can help maintain high consistency of the flow field in dynamic pitching station within a particular range of angles of attack.

1. Introduction

Wind turbine working in high-speed wind conditions suffer from flow separations, thus leading to a decline of the performance and efficiency. As a result, measures for flow separation control are very important and necessary. As a typical application of passive control method, wavy modification of the leading edge was inspired from biomimetic. It has been reported that, in spite of its large size and heavy body, the humpback whales are extremely agile and maneuverable when hunting prey. According to the research of Fish et al. [1], the wavy protrusions on the leading edge of the whale flippers play an important part in flow separation control, thus leading to its flexibility and mobility. Besides, it is found that the cross section of the flipper has a profile similar to a NACA634-021 airfoil, and the wavy leading edge along spanwise direction is similar to a sinusoidal curve [2].

Experimental studies have been carried out on the aerodynamic characteristics of the modified airfoil with wavy leading edge, and it is proved that the wavy leading edge can improve the stall characteristics [3-5]. Numerical simulations have also been used to explore and analyze the effects of the specific airfoil modifications. Among them, Yoon [6] found that at high angles of attack spiral limit streamlines would appear near the valleys of the protuberances due to the locally low pressures, which changed the distribution of the separation line around the leading edge, leading to a larger region of attached flow and a higher lift coefficient. ARAI [7] found that in post-stall region the longitudinal vortex generated by the wavy leading edge extended the attached area on the suction side of the airfoil, thus avoiding a sharp decline of the lift coefficient. In Favier's study [8], a Kelvin—
Helmholtz-like instability driven by the spanwise modulation of the streamwise velocity profile induced by the wavy leading edge, is proposed to be at the origin of the generation of the streamwise vortices which control the boundary layer separation.

In general, wavy leading edge modifications of airfoils are believed to be a viable way to improve static stall characteristic. However, since the blades of wind turbine are always working in a complex dynamic condition as a result of atmosphere turbulence, ground boundary layer effect, yawing run and etc., the dynamic characteristics of the airfoils are also very important. As far as the authors are aware of, no research has been published on this issue.

In this paper, NACA634-021 was chosen as the baseline airfoil. Wavy modifications were made on its leading edge for comparison. The static and dynamic aerodynamic characteristic of the airfoils as well as the details of the flow fields were numerically investigated.

2. Computational model and method

The geometric data of the original NACA634-021 and the modified airfoil are set according to the experimental model in Ref. [4]. The chord of the baseline airfoil is 100mm, as shown in Fig. 1(a). The modified airfoil has a sinusoidal leading-edge profile along the spanwise with wavelength 0.25c and amplitude 0.12c. The wingspans of both airfoils are set as 0.25c, which equals to a single period of the modified airfoil (Fig. 1(b)).

The computational field was divided into two parts, a rotational cylinder region containing the airfoil inside (1000mm in diameter) and the outer flow field, where the outer boundary conditions were defined. The mesh of the inner and outer part were constructed respectively and connected by a cylindrical interface. The grid numbers of the inner and outer part are 2,106,428 and 1,254,160 respectively. The grid around the airfoil was refined in the boundary layer, and the values of wall $y^+$ are below 5.

The computations were carried out in FLUENT software for study of both static and dynamic stall characteristics. In static cases the airfoils were fixed at a series of angles of attack, while in the dynamic cases the airfoils were set to oscillate with respect to pitch. The axis of rotation is 0.6c away from the trailing edge, and the angle of attack oscillates as follows:

$$\alpha = \alpha_0 + \Delta \alpha \times \sin(2Kt^*)$$

where $\alpha_0$ is the mean angle of attack; $\Delta \alpha$ is the oscillation amplitude in angle of attack; $K$ is the reduced frequency; the dimensionless time $t^* = t \times U_{\infty}/c$, where $U_{\infty}$ is the absolute speed at infinity, and $c$ is the chord of the baseline airfoil. In this paper $\Delta \alpha$ was fixed to 5° and $K$ equalled to 0.1. $\alpha_0$ was set as 10°, 15° and 20° respectively.
The working fluid was air with Reynolds number $2.0 \times 10^5$ according to the experimental counterpart of the baseline airfoil. The flows were simplified as incompressible due to the low Mach numbers. The turbulence model was chosen as the Spalart-Allmaras model, which has been proved to be suitable for wall-bounded flow in aero-space applications. The pressure-velocity coupling was set as SIMPLEC scheme and the spatial discretization is second order upwind. Velocity and pressure conditions were specified at inlet and outlet respectively. Periodic conditions were applied on the two sides of the flow fields. Transient method was applied for both static and dynamic cases.

3. Results and discussions

3.1. Static characteristics

The lift and drag coefficients were averaged for each case of computations of static stall study and compared with experiments in Ref. [4], as shown in Fig. 3. It can be seen that reasonable agreements have been achieved. The lift coefficient of the baseline airfoil grows linearly with the angle of attack $\alpha$ increasing from $0^\circ$ to $12^\circ$. After that comes the mild stall region and the growth of lift coefficient slows down. At around $20^\circ$ the deep stall flow occurs, with a sudden drop in the lift coefficient. Comparing with experimental observations, the simulations successfully captured the stall angle and the sharp decline in the lift coefficient, but the deviation increases around the stall angle.

As to the modified airfoil, the computational lift coefficient also has a consistent trend with the experimental data. It can be seen that when the angle of attack is bigger than $9^\circ$ the increase of the lift coefficient slows down, which is lower than the baseline airfoil. However, in the range of the angles of attack studied, the modified airfoil does not stall in the traditional manner. The lift coefficient keeps at around 0.8 when $\alpha > 10^\circ$ without an obvious decline, and becomes higher than the baseline airfoil in deep stall condition.

The computed drag coefficient is also generally consistent with the experiment, while the deviation is larger than the lift coefficient. The computed values are general small than experiments. The reason may be the larger error in predicting frictional drag than the pressure drag. It can be seen that the drag of the modified airfoil is greater than the baseline airfoil, but it changes more gently without a sudden rise around the stall angle.

![Lift coefficient curve](image1.png)  
(a) Lift coefficient curve

![Drag coefficient curve](image2.png)  
(b) Drag coefficient curve

Figure 2. The static aerodynamic characteristic of the two airfoils.

Four different cross sections named Section I, II, III and IV were intercepted (Fig. 1) for the analysis of the flow fields around the two airfoils. Among them, Section II represent convex section of the modified airfoil, Section IV represents the concave section and Section III represent the midsection which is identical with Section I. The streamlines around different sections are as follows.

At $5^\circ$ (Fig.3) flow separation appears on the suction side of the modified airfoil around Section IV, while the flow stays attached all along the baseline foil. It turns out that the lift coefficient of the modified foil is a bit lower than the baseline one.
At 15° (Fig.4) a backflow eddy is formed on the back of the baseline foil, and the separation point is at about half the chord. As to the modified foil, few vortices can be observed around the convex section and the midsection, but the streamlines are twisted due to the influence of the spanwise flow. Flow separations become more apparent around the concave section with complicated vortices, leading to a lower lift coefficient compared to the baseline foil.

At 25° (Fig.5) the baseline airfoil is in deep stall condition. A main vortex attaches to the vast majority of the suction side with a secondary vortex behind. The separation point is close to the stagnation point and the length scale of the main vortex is as large as the airfoil chord. However, on the convex section of the modified foil the flow stays attached along more than half of the suction surface. Around the concave section, the area of the recirculation zones is similar to the baseline foil, which is smaller on the other sections. It can be concluded that the wavy leading edge can help increasing the area of attached flow at high angles of attack, leading to a larger lift coefficient and a better stall characteristic. The conclusion is consistent with Ref[4].

3.2. Dynamic characteristics

A time independence verification on the baseline airfoil is carried out, in which $\alpha_0 = 20^\circ$, $\Delta\alpha = 5^\circ$ and $K = 0.1$, as shown in Fig.6 where the variations of lift coefficient with time are periodic. It is also found that using different physical time steps $dt = 0.0002s$ and 0.0005s the lift coefficient curves are exactly consistent, while a bit difference appears when $dt = 0.001s$. The time step is chosen as 0.0005s in the simulations below.
The dynamic results are shown as follows compared to the static characteristics. For the lift coefficient of the baseline foil (Fig. 7(a)), the hysteresis loop is close to the static result when $\alpha_0 = 10^\circ$. As $\alpha_0$ increases, the area of the hysteresis loop curves expands. The maximum lift coefficient is higher than the static value and the minimum lift coefficient is lower. When $\alpha_0$ comes to 20°, the area of hysteresis loop becomes much larger ranging from 0.6 to 1.2. The sharp decline of lift coefficient is delayed from 20° to about 25°. The lift coefficient stays as low as 0.6 when $\alpha$ descend from 25° to 20°, and then rises back slowly. If a wind turbine is working in a dynamic condition around the pitching angle, the performance will be unsteady, causing negative impact to the efficiency and service life of the blade and the unit.

For the modified foil (Fig. 7(b)), the variation of lift coefficient in a hysteresis loop is a bit greater than the baseline case when $\alpha_0 = 10^\circ$ and 15°. When the foil is pitching up from 15° to 20°, an approximate stall occurs with a decline of lift coefficient. When $\alpha_0$ comes to 20°, the lift coefficient turns out to be stable, ranging narrowly from 0.75 to 0.9. The hysteresis loop varies gently without any remarkable changes. From the point of stability the modified foil is much better than the baseline at high angles of attack.

The drag coefficient (Fig. 8) has a similar trend. When $\alpha_0 = 10^\circ$ and 15°, the variation of drag coefficient of modified foil is slightly larger and more irregular than that of baseline foil. When $\alpha_0 = 20^\circ$, the hysteresis loop of baseline foil has a sharp rise and drop, while the modified foil varies more gently.

**Figure 6.** Time independent verification for the baseline case $\alpha_0 = 20^\circ$.

**Figure 7.** The dynamic lift coefficient curve at different balance angles of attack.

**Figure 8.** The dynamic drag coefficient curve at different balance angles of attack.
The flow field was analysed for the typical case $\alpha_0 = 20^\circ$. Four feature points of time listed below are $\alpha = 15^\circ$, $20^\circ$ pitching up, $25^\circ$ and $20^\circ$ pitching down (Fig. 9-12). For the baseline foil, a main vortex and a secondary vortex gradually develops with the angle of attack increasing from $15^\circ$ to $20^\circ$ and then to $25^\circ$. At $25^\circ$ the separation zone has covered most part of the suction surface. When the baseline foil is pitching down back to $20^\circ$, the separation point still stays close to the leading edge and the secondary vortex disappears, which is different from the vortex structure of the case pitching up to $20^\circ$. The flow separation is delayed when pitching up, while the reattachment is also delayed when pitching down, thus leading to a large difference of lift and drag performance.

As to the modified foil, the vortex structure also develops with the angle of attack increasing from $15^\circ$ to $25^\circ$. However, when the baseline foil is pitching down to $20^\circ$, the flows of all the three section are very similar to the case $20^\circ$ pitching up. For these two cases, the streamlines are both mostly attached around Section II and twisted forming some incomplete vortex structures around the Section III. No obvious delay of separation or reattachment is observed during the cycle. It can be concluded that the special structure of wavy leading edge can help maintaining high consistency of flow in dynamic station within a particular range of angle of attack.
4. Conclusions
In this paper, the static and dynamic stall characteristics of a modified foil with wavy lead edge and the original baseline foil are explored numerically. The conclusions are summarized as follows:

1) The modified foil has a better static stall characteristic at high angle of attack without an obvious decline of lift coefficient. It is verified that the special structure of wavy leading edge can help suppressing flow separation.

2) In dynamic stall condition, the aerodynamic force of the baseline foil turns out to be extremely unsteady at high angle of attack, while the stability of the modified foil is much better.

3) Wavy leading edge can help maintain high consistency of flow in dynamic stall condition within a particular range of angle of attack, avoiding the delay of separation and reattachment. Further studies on the aerodynamic mechanism of the effects of the wavy leading edge are needed.

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