Numerical study on the aerodynamic characteristics of both static and flapping wing with attachments

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Abstract. The purpose of this paper is to investigate the aerodynamic mechanism of airfoils under different icing situations which are different icing type, different icing time, and different icing position. Numerical simulation is carried out by using the finite volume method for both static and flapping airfoils, when Reynolds number is kept at 135000. The difference of aerodynamic performance between the airfoil with attachments and without attachments are be investigated by comparing the force coefficients, lift-to-drag ratios and flow field contour. The present simulations reveal that some influences of attachment are similar in the static airfoil and the flapping airfoil. Specifically, the airfoil with the attachment derived from glaze ice type causes the worse aerodynamic performance than that derived from rime ice type. The longer the icing time, the greater influence of aerodynamic performance the attachment causes. The attachments on the leading-edge have the greater influence of aerodynamic performance than other positions. Moreover, there are little differences between the static airfoil and the flapping airfoil. Compared with the static airfoil, the flapping airfoil which attachment located on the trailing edge causes a worse aerodynamic performance. Both attachments derived from rime ice type and glaze ice type all will deteriorate the aerodynamic performance of the asymmetrical airfoils. Present work provides the systematic and comprehensive study about icing blade which is conducive to the development of the wind power generation technology.

1. Introduction

An increasing demand for renewable energy in countries all over the word has stimulated a growing number of studies on wind energy. The use of wind energy has had a remarkable progression in the past decades. However, to make full use of the wind energy, some challenges should be further investigated. For example, the blades of wind turbines often freeze because of the cold weather when it is used in the high latitude area (Zhang and Ren, 2007). The ice forms attachments on the surface of blades and has a great influence about the performance and safety of wind turbines. This mechanism still is not fully understood. Many researchers have been devoted to the aerodynamic analysis of blade icing problem, both experimentally and theoretically. Bose (1992) carried out the experiment of icing blade in the natural situation. He found that the ice mainly located in the leading edge and the trailing edge, and was little in the suction surface. Jasinski et al. (1998) made an experimental measurement on the special airfoil NREL-S809 in an icing wind tunnel. Their results revealed that the ice on the airfoil surface made the airfoil’s aerodynamic characteristics become worse and significantly changed the
performance of the wind turbines. Clement Hochart (2007) did an experiment to investigate the ice shape of airfoil. He got some ice shapes by changing the liquid water content and temperature. After the aerodynamic analysis of these icing airfoils, he found that the lift decreased and drag increased when glaze or rime accreted on the blade profile. Deng et al (2010) simulated the ice accretion process on the airfoil by solution the Navier-Stokes equations. They found that the attachment formed by icing can advance the stalling angle of attack. Zhu (2011) used the Lagrange solution to calculate the ice accretion. Their results show that the glaze ice could enlarge the drag coefficient and aggravated the separation of flow. However, most above study focus on just one situation. The systematic and comprehensive study on both static and flapping airfoils with many kinds of attachment formed by icing process is infrequent. Accordingly, we aim to increase our understanding on the aerodynamic mechanism of airfoils under different icing situations. The attachments on the surface of airfoils are formed by three conditions which are different icing type, different icing time, and different icing position. A finite volume method is used to simulate the flow characteristics around both static airfoil and flapping airfoils. The difference of the aerodynamic forces among the series of flow field is examined and how difference attachments affect the fluid field is discussed in detail.

2. Description of the Problem

Current works propose to investigate the attachments on the aerodynamic mechanisms of airfoil in a general-purpose numerical method. Both NACA4412 and NACA0012 airfoils with the same thickness and infinite span are used as the smooth models. The attachments on the surface were formed in three situations which are different icing type, different icing time and different icing position. The geometric shapes of surface attachments on the leading-edge of airfoil are derived from two icing types. One is the glaze ice, the other one is the rime ice, as shown in Figure 1. It is seen that the attachments formed by the two icing condition is very different. In the glaze ice condition, the ice grows mainly along longitudinal direction and the chord length of airfoil is almost no increased. In contrast, rime ice grows along transverse direction and its geometric shapes are more smooth and regular in the rime ice condition. Thereout, some modeled airfoils on base of NACA4412 and NACA0012 when icing time is 10min are respectively shown in Figure 2(a) and (b). Moreover, the change of the attachment shapes at different icing times is depicted in Figure 3.

(a) The glaze ice’s geometric shapes in 2min, 6min, 10min
(b) The rime ice’s geometric shapes in 2min, 6min, 10min

Figure 1. The glaze ice and the rime ice’s geometric shapes in different icing time [7]

(a) The glaze ice airfoil of ice 10min
(b) The rime ice airfoil of ice 10min

Figure 2. NACA4412, NACA0012 airfoil with surface attachments derived from different icing types

(a) The rime ice airfoil and the glaze ice airfoil of icing 2min
(b) The rime ice airfoil of icing 6min
(c) The glaze ice airfoil of icing 6min

Figure 3. The modeled airfoils in different icing time
Figure 4 show the experimental measurement of an airfoil in a real icing situation. It can be seen that icing attachments mainly locates at the leading edge, the trailing edge, upper and lower surfaces where are near the leading edge. Accordingly, to further investigate the aerodynamic characteristics of these icing attachments at different positions, the modeled airfoils are built, as shown in Figure 5. Four cases which the icing attachments distribute on leading edge, trailing edge, upper surface and lower surface’s, are respectively analyzed in this paper.

Figure 4. The airfoil’s complete icing graph [8]

(a) The airfoil’s ice on the upper surface 
(b) The airfoil’s ice on the lower surface 
(c) The airfoil’s ice on the trailing edge

Figure 5. The modeled airfoils in different icing position

3. Method of the Solution

The two-dimensional, unsteady, incompressible Reynolds-averaged Navier-Stokes equations are expressed as follows:

\[
\begin{align*}
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} &= - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \left[ u_j \frac{\partial u_i}{\partial x_j} - u_i \frac{\partial u_j}{\partial x_j} + \frac{2}{3} k \delta_{ij} - v \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right], \\
\rho \frac{\partial \rho}{\partial t} &= 0,
\end{align*}
\]

Where \( u \) is the velocity vector, the pressure \( p \) is normalized by \( \rho U^2 \), \( \rho u_i u_j \) is the Reynolds stress, \( \delta_{ij} \) is the Kronecker Delta number. \( v \) is eddy viscosity determined by the turbulence model, \( k \) is the turbulent kinetic energy. \( k - \omega \) Standard turbulence model is used in the present work. The Reynolds number is 135000. The equations are solved in the finite volume method in the inertial frame. The first order time integrations are used. The SIMPLEC algorithm is employed to deal with the coupling between the pressure and velocity. The convective flux and diffusive flux terms are evaluated using the second-order accurate central difference scheme, respectively. The computational domain which is 19c×16c in two directions is shown in Fig 6(a). After a grid independent test, the total number of triangular meshes in the computational domain is about 60000, as shown in Figure 6(b).

Figure 6. The compute domain and the grid partition
The inlet boundary located at 7c upstream of the leading-edge point of airfoils, an uniform flow is prescribed

\[ u_1=10, u_2=0, u_3=0 \]  \hspace{1cm} (2)

The outlet boundary located at 11c downstream of the rear of airfoils, the outflow boundary conditions is given, i.e.

\[ \frac{\partial u_1}{\partial x} = \frac{\partial x_2}{\partial x} = 0 \]  \hspace{1cm} (3)

The upper and down boundaries is 8c far away from the surface of the airfoils. A symmetry boundary conditions is given as follows

\[ u_z = 0\, \frac{dx_1}{dy} = 0, \frac{dp}{dy} = 0 \]  \hspace{1cm} (4)

The no-slip boundary conditions are prescribed at the wall. The influence of these conditions have been investigated and found to be sufficiently adaptive. The simulation starts assuming the fluids is initially at rest.

The lift and drag are scaled here by velocity, so that the lift and drag coefficients are computed from:

\[ C_L = \frac{2F_L}{\rho U_m^2c}, \quad C_D = \frac{2F_D}{\rho U_m^2c} \]  \hspace{1cm} (5)

Where FL and FD are lift and drag forces, respectively.

For the dynamic cases, a harmonic motion \( h = A \sin 2\pi ft \) is employed by the airfoils in this study. The value of \( A \) is 0.1c and \( f \) is 1.59 rad/s, respectively. Then, the period-averaged lift and drag coefficients of the flapping airfoils are calculated as follows:

\[ \overline{C_L} = \frac{1}{T} \int_0^T C_L dt, \quad \overline{C_D} = \frac{1}{T} \int_0^T C_D dt \]  \hspace{1cm} (6)

This study uses the airfoil NACA0012 to validate the numerical algorithm when Reynolds number is kept at 135000. The comparison between our calculated values and the experimental values (Lee and Greontakos, 2004) of a static airfoil is shown in Figure 7. It can be seen that the present calculation is in a good agreement before stalling. Although the stalling angle of attack advances 2° and the peak value is smaller, which the general difference can be consider very small. The validation of the numerical algorithm for the flapping cases has been done in our previous work (Zhang and Zhou, et al, 2013). That numerical code is reliable for qualitatively analyzing flow characteristics around static and flapping airfoils.
4. Result and Discussion

4.1. The effect of attachments on the flow characteristics of static airfoils

Different attachment models formed in different icing conditions are implemented in current study. For the static cases, simulations are carried out for the attack angle from 0° to 18°. The force coefficients and flow field structures as observed in this study are presented here systematically.

Figure 8 gives the force coefficients and lift-to-drag coefficients of airfoil with surface attachments deriving from different icing types. It is seen that the stall attack angle of smooth NACA4412 airfoil is about 10° and the maximum lift coefficient is about 1.06. The lift to drag ratio reach a peak and then reduce as the attack angle increases. The attachments derived from both glaze ice and rime ice conditions, enhance the drag, and the lift to drag ratios are all smaller than those of no attachment airfoils. Further, current results show that the attachments derived from glaze ice condition have a more dramatic influence on the aerodynamic characteristics of the airfoil. The forces and lift-to-drag coefficients of airfoil with attachments deriving from glaze ice condition change more significant than those driving form rime ice condition. Take the results of attack angle at 4° as example, the lift to drag ratio of airfoil with attachments deriving from glaze ice condition is reduced about 53.8% than that of rime ice result. Attachments deriving from glaze ice condition make aerodynamic characteristics of airfoil become much worse and the stall angle of attack become smaller. This is likely due to the attachments effectively changes the vortex shedding mechanism at the separation point of airfoil. Figure 9 gives the flow field contour of airfoil with attachments deriving from different icing types. It can be seen that a significant difference between the three conditions appears at higher attack angles. The attachments induce the flow field separation more intense than those of no attachments. Moreover, current results also show that the flow around the airfoil the attachments deriving from glaze ice condition, are more complex at the trailing-edge than that of rime ice condition.
Figure 8. The force coefficients and lift-to-drag ratios of static NACA4412 airfoil with attachments derived from different icing type.

Figure 9. The comparison velocity contour of NACA4412 airfoil with different attachments when attack angle is kept at 0°, 8°, 12°, 16°, respectively.

Figure 10 and Figure 11 show the force coefficients and lift-to-drag radio of static airfoil with attachments increasing with icing times. When the icing time increased, the attachments driving from rime ice and glaze ice conditions have a little difference. The attachments driving from rime ice is mainly changed in length, while the ones driving from glaze ice is mainly changed in thickness. As shown in Figure 10(b) and Figure 11(b), the drag coefficient is monotonically increasing with icing time. The lift coefficients and lift to drag ratios reach a peak and then reduce as the icing time. The longer the icing time, the greater the attachments affect the aerodynamic performance of airfoils. It is also seen that the aerodynamic performance of airfoil with attachments driving from glaze ice condition become much worse that the others. Especially, the lift to drag ratios reduce to the smaller values as icing time increase as shown in Figure 10(c) and Figure 11(c).
Figure 10. The force coefficients and lift-to-drag ratios of airfoil with attachments derived from rime ice at different icing times.

Figure 11. The force coefficients and lift-to-drag ratios of airfoil with attachments derived from glaze ice at different icing times.
Figure 12 respectively shows the force coefficients and lift-to-drag ratios of the static NACA4412 airfoil with attachments at different icing positions. The icing position on the surface of airfoil include leading-edge, trailing-edge, upper surface and lower surface. Among, the attachment located at the leading-edge is used the glaze ice type. Current results show that the positions of attachments indeed significantly change the aerodynamic performance of the airfoil. Wherever attachments positions locate, the lift to drag ratios is reduced as shown in figure 12(c). It is also found that the attachment on the leading-edge has the greater effect than others. When the attachments deriving from glaze ice condition locate at the leading-edge of airfoil, the lift to drag radios become the most small at every attack angle, and the stalling appear at a little smaller attack angle than other conditions. Furthermore, when attachment located on the upper surface of airfoil, the stalling attack angle appeared in advance. In contrast, when attachment located on the lower surface, the stalling attack angle is delayed. The phenomenon is more obviously at high attack angles. Figure 13 shows the pressure contour when attachments located at trailing-edge and lower surface of airfoil at 8°attack angle. It can be seen that attachments on lower surface of airfoil can create a bigger high pressure zone near the lower surface and significantly affect the distribution of the pressure gradient, as shown in figure 13(a) and (b). As a result, the lift is enhanced and the stalling is delayed. When the attachments is on the trailing-edge of the airfoil, the high pressure zones near the lower surface is smaller than that of no attachment case, as shown in figure 13(a) and (c). The lift and lift-to-drag ratios are all reduced, and the aerodynamic performance becomes worse.

![Figure 12](image)

Figure 12. The force coefficients and lift-to-drag ratios of static NACA4412 airfoil with attachments on different icing positions.
To investigate the effect of the airfoil’s basic shape, the numerical calculation on the aerodynamic forces of two types of airfoils with the same attachments, are carried out. A symmetrical NACA0012 airfoil and an asymmetrical NACA4412 airfoil are respectively selected as airfoil’s basic shape. The results are compared in detail and systematically analyzed. Figure 14 gives the lift to drag ratios of NACA0012 and NACA4412 airfoils with the same attachments. The lift to drag ratios of both NACA4412 and NACA0012 airfoils are all reduced by the attachments. Nonetheless, the extent of influence on two airfoils is not the same. For example, the largest reductions of lift to drag ratio between NACA4412 and NACA0012 airfoils with the same attachment derived from rime ice condition, is respectively 24.5% and 7.8%. Similarly, the largest reductions of lift to drag ratio between the two airfoils with the same attachment derived from glaze ice condition, is respectively 72.4% and 90.2%. These results reveal that the airfoil’s basic shape is one of key impact factors on the aerodynamic characteristics of airfoil with icing attachments. More specifically, it is seen that the symmetrical airfoil is more easily influenced by the attachment of glaze ice type and the asymmetrical airfoil is more easily influenced by the attachment of rime ice type.

Figure 13. The pressure contour when attach angle is 8°

Figure 14. Lift to drag ratios of NACA0012 and NACA4412 airfoils with the same attachments

4.2. The effect of attachments on the flow characteristics of flapping airfoils

For the flapping cases, simulations are carried out for the attack angle from 0° to 20°. The period-averaged force coefficients and flow field structures are systematically presented. Figure 15 shows the period-averaged lift coefficient, drag coefficient and lift to drag ratio of a flapping NACA4412 airfoil with surface attachments deriving from different icing types. All the attachments deriving from either rime ice or glaze ice condition raise the period-averaged drag coefficients and reduced period-averaged lift to drag ratios of the airfoil as shown in figure 15(b) and (c). The vorticity snapshot around the flapping airfoil with attachments deriving from different icing types are illustrated in figure 16. It is seen that the vortex separation mechanism of flapping airfoils is significantly changed by the surface attachments. Moreover, similar to results of static airfoil, the attachment deriving from glaze
ice condition provides the lowest period-averaged lift to drag ratio and causes the worst aerodynamic performance than others. This is mainly due to the surface attachments derived from glaze ice condition, give rise to the larger vortexes at both leading-edge and trailing-edge of the airfoil, and cause the worse aerodynamic performance.

![Graphs showing period-averaged lift and drag coefficients](image)

**Figure 15.** The period-averaged lift coefficient, drag coefficient and lift to drag ratio of a flapping NACA4412 airfoil with attachments deriving from different icing types.

![Vorticity contours](image)

**Figure 16.** The vorticity contour of a NACA4412 airfoil with attachments deriving from different icing types, when attack angle is kept at 8°.

Figure 17 and Figure 18 give the period-averaged force coefficients and lift-to-drag radio of the flapping airfoil with attachments increasing with icing times. The period-averaged drag coefficient is monotonically increasing with icing time. The lift to drag ratios reaches a peak and then reduces as the icing time. The longer the icing time, the greater the attachments affect the aerodynamic characteristics of the flapping airfoil. This observation is similar to the static airfoil.
(a) Period-averaged lift coefficient                  (b) Period-averaged drag coefficient

(c) Period-averaged lift to drag ratio

**Figure 17.** Period-averaged force coefficients and lift-to-drag ratio of the flapping airfoil with attachments derived from rime ice at different icing times
Figure 18. Period-averaged force coefficients and lift-to-drag radio of the flapping airfoil with attachments derived from glaze ice at different icing times

Figure 19 shows the period-averaged force coefficients and lift-to-drag ratios of the flapping NACA4412 airfoil with attachments at different icing positions. When attachment located on the trailing edge of airfoil, the period-averaged force coefficients and lift-to-drag ratios are both small. Compared with the static airfoil, it is seen that attachment located on the trailing edge cause the worse aerodynamic performance in the flapping airfoil. In addition, it is similar to the results of static airfoil that the attachments on the leading-edge have the greater effect of aerodynamic performance than others. Figure 20 shows the vorticity snapshot when attachments located on different positions at 10°attack angle. It can be seen that the direction of vortex shedding is more horizontal when attachment is located on the trailing edge of airfoil, as shown in figure 20(b). It is the possible reason that why the period-averaged force coefficients and lift-to-drag ratios are both small. The airfoil with attachment at the upper surface has the larger leading-edge’s vortexes than the airfoil with attachment at the lower surface, as shown in figure 20(c) and (d). So, the aerodynamic performance of airfoil which attachment located on the upper surface is worse.
Figure 19. The period-averaged lift coefficient, drag coefficient and lift to drag ratio of a flapping NACA4412 airfoil with attachments on different positions

Figure 20. The vorticity contrast map of different icing position in the 10° angle of attack

Figure 21 shows the period-averaged lift-to-drag ratios of flapping NACA4412 airfoil and flapping NACA0012 airfoil with the same attachments. Similar to the results of static airfoils, the basic shapes of airfoil have a significant influence. The largest reductions of period-averaged lift to drag ratio between NACA4412 and NACA0012 airfoils with the same attachment derived from rime ice condition, is respectively 56.82% and 35.88%. Similarly, the largest reductions of lift to drag ratio between the two airfoils with the same attachment derived from glaze ice condition, is respectively 86.6% and 79.4%. It seems that the asymmetrical airfoil has the greater effect of aerodynamic performance in both icing types of attachment. Figure 22 shows the vorticity snapshot of different airfoil with the same attachments. In general, flapping NACA4412 airfoil gives rise to the larger vortexes at both leading-edge and trailing-edge of the airfoil. That is probably reason that why flapping NACA4412 airfoil has the worse aerodynamic performance than that of NACA0012 airfoil.
Figure 21. Period-averaged lift to drag ratios of NACA0012 and NACA4412 airfoils with the same attachments

Figure 22. The vortices contrast map of different icing airfoil in the 12° angle of attack

5. Conclusion
In this paper, how aerodynamic characteristics affected by the attachment on the surface of airfoil, is systematically investigated. In the situation of static airfoil, according to the different icing situations, there are some conclusions can be draw in follows. First, the airfoil with the attachment of glaze ice type causes the worse aerodynamic performance than the airfoil with the attachment of rime ice type. Second, the longer the icing time, the greater influence of aerodynamic performance the attachment causes. Third, the attachments on the leading-edge have the greater effect of aerodynamic performance than other positions. Fourth, the symmetrical airfoil is more easily influenced by the attachment of glaze ice type and the asymmetrical airfoil is more easily influenced by the attachment of rime ice type.
Among, the first three conclusions are also in accordance with the flapping airfoil. However, there are some differences between the flapping and static airfoils. Specifically, the attachments located on the trailing edge of flapping airfoil cause aerodynamic performance become worse. The asymmetrical airfoil with the attachments derived from either rime ice type or glaze ice type all has a worse aerodynamic performance. In general, the attachments formed in various icing conditions deteriorate the aerodynamic performance of airfoil in most of situation. Hence, it is very essential to further develop the effective deicing technology to improve the operation life and performance of the wind machinery in the next work.

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