Static aeroelastic deformation of flexible skin for continuous variable trailing-edge camber wing

Libo Liu[a], Weilong Yin[a], Fuhong Dai[a], Yanju Liu[b] and Jinsong Leng[a*]

[a] Centre for Composite Materials and Structures, Harbin Institute of Technology, P. R. China
[b] Department of Astronautic Science and Mechanics, Harbin Institute of Technology, P. R. China

ABSTRACT

The method for analyzing the static aeroelastic deformation of flexible skin under the air loads was developed. The effect of static aeroelastic deformation of flexible skin on the aerodynamic characteristics of aerofoil and the design parameters of skin was discussed. Numerical results show that the flexible skin on the upper surface of trailing-edge will bubble under the air loads and the bubble has a powerful effect on the aerodynamic pressure near the surface of local deformation. The static aeroelastic deformation of flexible skin significantly affects the aerodynamic characteristics of aerofoil. At small angle of attack, the drag coefficient increases and the lift coefficient decreases. With the increasing angle of attack, the effect of flexible skin on the aerodynamic characteristics of aerofoil is smaller and smaller. The deformation of flexible skin becomes larger and larger with the free-stream velocity increasing. When the free-stream velocity is greater than a value, both of the deformation of flexible skin and the drag coefficient of aerofoil increase rapidly. The maximum tensile strain of flexible skin is increased with consideration of the static aeroelastic deformation.

1. INTRODUCTION

For morphing aircraft, morphing skin is one of the key technologies[1-3]. As known, the skins of most aircrafts are rigid which are made of aluminum and composite materials. The out-of-plane deformation is very small. The aerodynamic effect of the out-of-plane deformation is tiny. However, in order to change its wing shape, the morphing wing is always made of flexible materials and structures. The skin of "sliding wing" morphing aircraft developed by Nextgen Aeronautics Company of USA was of an elastomeric silicone material. As the fall of the stiffness, the morphing skin will suffer obvious deformation under aerodynamic loads. Besides, there is big blindness in the design of morphing structures. For the reasons, there is no standard to comply in design; besides, the acquaintanceship is absent that the effect of aeroelasticity to morphing wings is great.

So, the effect of the skin deformation must be considered when the study on structure and aeroelastic of morphing wings is carried on. For one, the effect of skin deformation to the aerodynamic characteristics is studied. For another, the standard of designing morphing skin is built up.

The study about the effect of morphing skin to the air profile and aerodynamic characteristics is few. In Gandhi's study about the requirement of skin stiffness, the relationship of skin deformation and stiffness is not considered[4]. Yin studied the relationship of skin deformation and stiffness[5]. But the study is confined that the angle of trailing-edge is fixed. Besides, the pre-strain is not considered and the analysis is based on inviscid theory.

In this paper, a continuous variable trailing-edge camber wing was studied. Focus on standing up the relationship of flexible skin and stiffness by analysis of aeroelastic deformation of flexible skin, guiding the structure design of flexible skin.

* lengjs@hit.edu.cn; phone/fax: +86-451-86402328

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2. CONTINUOUS VARIABLE TRAILING-EDGE CAMBER WING

Shown in Figure 1, compared with traditional control surface, the continuous variable trailing-edge camber wing (flexible trailing-edge for short) can change the trailing-edge camber continuously, seamlessly and smoothly. Therefore, It can change the pressure distribution on the surface and put off the airflow separation. The lift-drag characteristics and roll control efficiency of an aircraft will be improved with fewer oil consumption and smaller radar reflection cross-sectional area.

The advantage of flexible trailing-edge on improving the wing aerodynamic performance is obviously. But it is difficult to carry out the structure of flexible trailing-edge. The most studies nowadays are carried out with the combine of inner structure like honeycomb structure and flexible skin outside, shown in Figure 2.

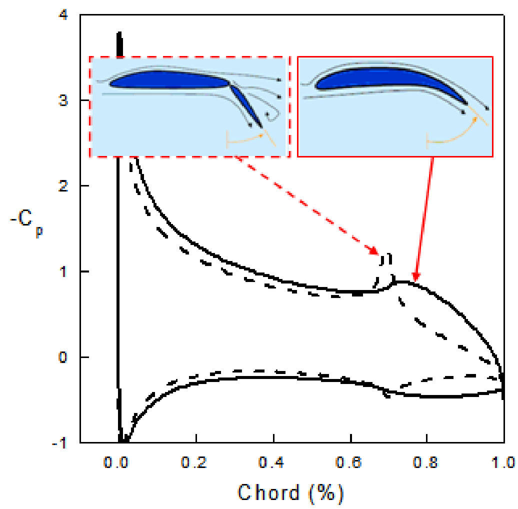


Figure 1 Pressure distribution of the traditional flexible trailing-edge

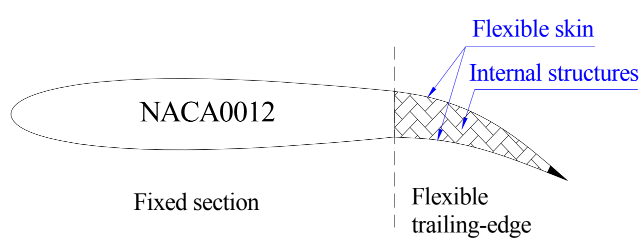


Figure 2 Schematic diagram of flexible trailing-edge wing

For flexible trailing-edge, first, define trailing-edge deflection angle and the arc deflection path. Ordinarily, the define trailing-edge deflection angle is defined as the arc sine of trailing-edge point vertical displacement and the trailing-edge length[4]. Only the location of the hinge and the deflection angle can fix the position of the traditional deflection rudder. But for flexible trailing-edge, even that the trailing-edge length and trailing-edge point vertical displacement are fixed, there are also many possible arc deflection path[6-8]. There is only one straight line between two points but endless curve. The curve of second degree is chosen as the arc deflection path of trailing-edge in our study.

3. AROELASTIC DEFORMATION ANALYSIS

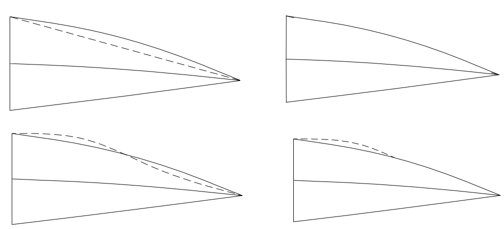
The trailing-edge flexible skin will produce deformation under air aerodynamic load. As reaction, the deformation will cause the change of flow fields and then change the pressure distribution characteristics of wings. Further more, the changed pressure distribution react to the flexible skin and cause deformation. It's a coupling process. Therefore, the analysis of static aeroelastic deformation of flexible skin for continuous variable trailing-edge camber wing is a typical fluid-solid coupling problem.

For fluid-solid coupling problem, strong-coupling and week-coupling are two kinds of analysis methods. The paper use week-coupling method. The deformation of the flexible skin self is considered but ignores the whole deformation of the trailing-edge structure. The deformation is assumed to be a quasi-static deformation process. First, the aerodynamic analysis of rigid air profile is performed, and the converged aerodynamic loads are interpolated into the finite element model to calculate the deformation of the structure. Subsequently, a new grid is rebuilt for the aerodynamic analysis of the deformed air profile. The above mentioned process is duplicated until the deformation of the flexible skin is convergent.

The data of aerodynamic computation and structure analysis needs to be transported between each other in week-coupling method. In this transportation mentioned above, the aerodynamic load data and the structure load must be interpolated. The aerodynamic load data is interpolated into the nodes of the finite element model by spline interpolation.

The aerodynamics analysis is carried on by panel method based on inviscid theory. The structure analysis is by finite element method. Xfoil program is used to calculate the aerodynamic characteristics of subsonic airfoil[6]. Ansys is used to analyze the FE model of skin structure. Matlab language is used to call Xfoil program and Ansys solver. Suppose the flexible skin is made of the isotropic material and the membrane element is chosen as the element type.

The flexible skin is coved on the morphing structure. Due to the support of internal structure, the skin can only suffer bubbled deformation except for sunken deformation. Therefore, the sunken deformation needs to be revised. Shown in Figure 3, in order to obey to the actual situation, the sunken deformation is revised to coincide to the airfoil. In the process of the program, the deformation is revised by judging that if the flexible skin deformation is negative or not. When the displacement of a point is negative, the corresponding deformation is sunken deformation. Then the displacement will be revised to zero artificially to go on the iteration.



(a) Before (b) After

Figure 3 Rule of the skin deformation

4. RESULTS AND DISCUSSION

4.1 Bubbled deformation simulation

Simulate the Static aeroelastic deformation of the flexible skin with the thickness of 2mm and elastic modulus of 200MPa. The coming flow velocity is 100m/s and the angle of attack is 0°. The baseline airfoil is assumed to have an

NACA0012 profile and a chord of 500mm. The length of flexible trailing-edge is 20% of wing chord. The flap angle of flexible trailing-edge is 5° with the Reynolds number of $3x10^6$.

The most important step in studying the effect of the bubbled deformation to aerodynamic characteristics is how to get the correct bubbled deformation. There are two major factors that decide the deformation of flexible skin: the effect of aerodynamic load and the structure of flexible skin (mainly refers to the curvature and the pre-stress). One reason is that the flexible skin will be bubbled under aerodynamic load. Another reason is that the bubbled deformation will increase the curvature and the pre-stress of the skin which block the deformation of the skin.

Figure 4 shows the iteration history of the displacement of flexible skin and the wing surface pressure of the three given points. The given points are located in A, B and C (85%, 90% and 95% of the chord from the leading edge). The deformations get bigger gradually under aerodynamic loads. With the increase of skin deformation, the suction of the A point gets bigger and the bubbled deformation come into being. The curvature and the pre-stress of the skin also get bigger. With the adjustment of the curvature and the pre-stress, there will be a balance of the flexible skin between the deformation and the wing surface pressure at last. Figure 5 shows the balanced deformation of the flexible skin and the pressure distribution of trailing-edge.

It can be seen that only a part of flexible skin produces bubbled deformation, which is about half of the length of trailing-edge. At the same time, the bubbled deformation changes the pressure distribution of the wing largely. The wing pressure decreases before the bubble and increases again after the bubble when air flow along the bubble. There is a big cusp of pressure on the location of the bubble. The air flow suffers bigger adverse pressure gradient when flows along the bubble, so that the possibility of flow separation is bigger.

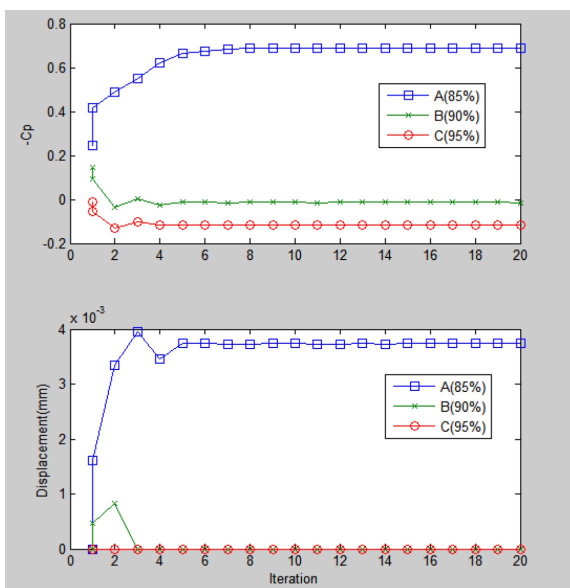


Figure 4 History of the displacement of flexible skin and the wing surface pressure

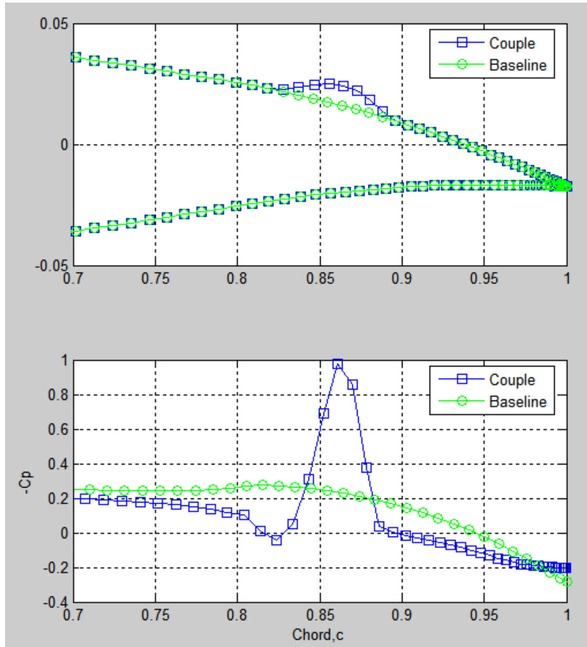


Figure 5 Deformation and surface pressure of flexible skin

4.2 The effect of aeroelasticity to skin deformation

The effect of skin deformation to the load mentioned above won't be considered in the aerodynamic characteristics analysis and wing load calculations of ordinary airfoil. Though the effect of aeroelasticity must be considered in the analysis of wing deformation under aerodynamic load, the aeroelasticity proposed here is mainly the interaction of wing structure and aerodynamic force.

In order to carry out the deformation of morphing wing smoothly continuously, flexible skin must be used. Considered the dual functions of morphing and load supporting, the Modulus of flexible skin is low ordinarily that will cause deformation easily under aerodynamic load. The deformation of flexible skin under aerodynamic load is shown in figure 6. Without the consideration of aeroelasticity, the aerodynamic loads are described as the pressure data on the rigid wing.

Without the consideration of aeroelasticity, the maximum height of bubbled skin deformation is 0.38% of the chord. With the consideration of aeroelasticity, the maximum height of bubbled skin deformation is 0.82% of the chord. It can be seen that the effect of the aeroelasticity to flexible skin can't be ignored. The aeroelasticity of flexible skin must be considered in designing of flexible trailing-edge.

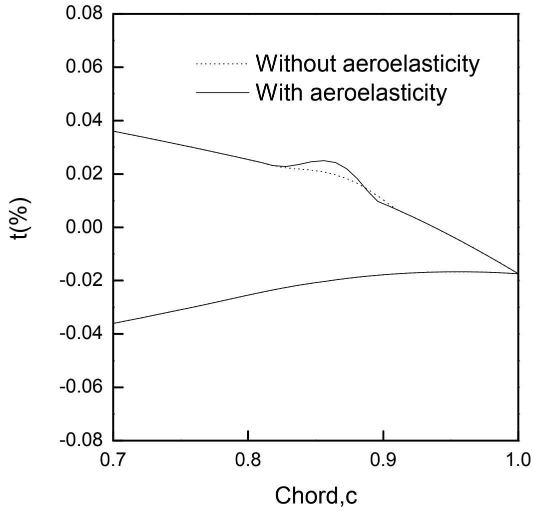


Figure 6 Deformation of flexible skin

4.3 The effect of aeroelasticity to aerodynamic characteristics of aerofoil

From the analysis above, the flexible skin bubbled deformation under aerodynamic load can change the wing pressure distribution and then affect the aerodynamic characteristics. Figure 7 shows the curve of the maximum height (h) of bubbled skin deformation and attack angle which is from 0°to 13°. It can be seen that the bubbled deformation decreases with attack angle's increasing. It can be explained that the air flow along the trailing-edge will separate with attack angle's increasing so that the trailing-edge's suction gets smaller. When the attack angle gets to 13°, the deformation of flexible skin disappears.

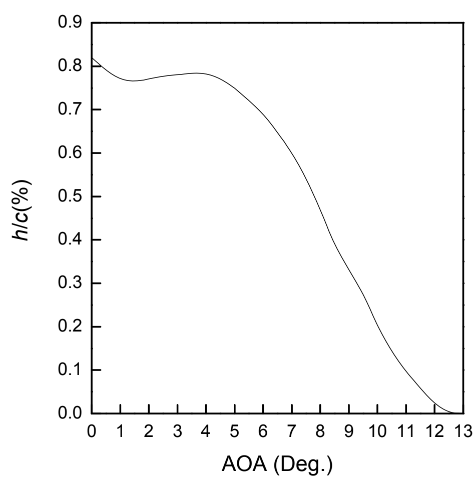
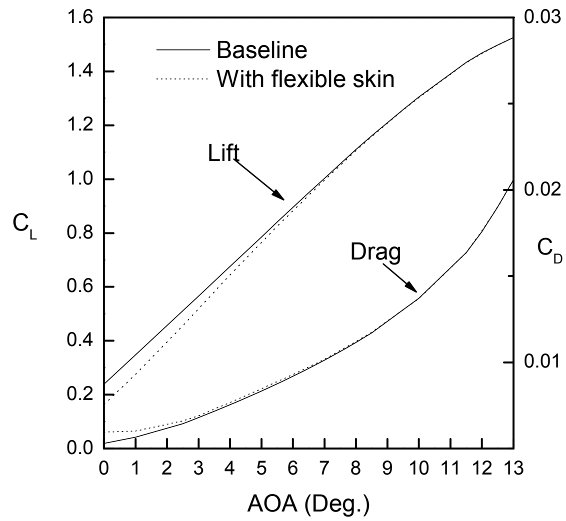
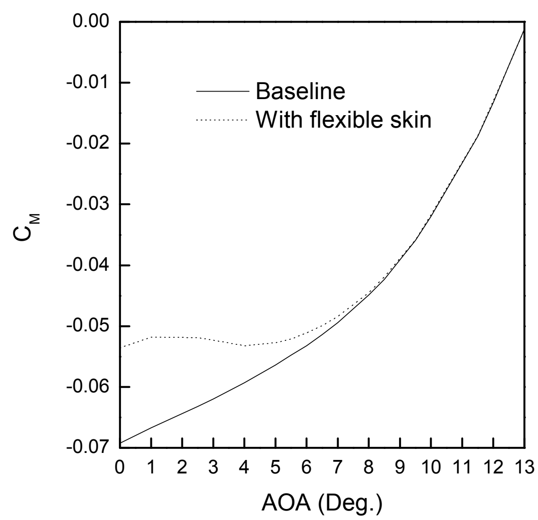


Figure 7 Maximum displacement of flexible skin

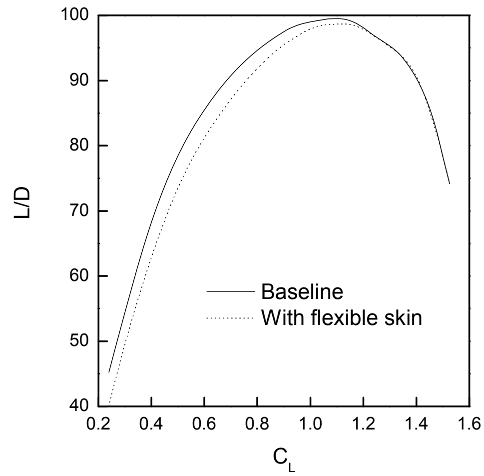
Figure 8 (a) and (b) show the curve of flexible skin's lift and drag coefficient, pitching moment and attack angle. When the attack angle is 0°, the bubbled deformation decreases the airfoil lift by 23% and increases the drag by 13% and decreases the pitching moment by 23%. With the bubble becoming smaller and smaller, the effect of bubbled deformation to the aerodynamic characteristics becomes weaker and weaker. Figure 8 (c) shows the drag polarization curve, of the airfoil with flexible skin. It can be seen that the bubbled deformation has a great effect to lift-drag characteristic of the airfoil when the attack angles are small and the effect gets weak in the big attack angles.



(a) Lift and drag



(b) Pitching moment



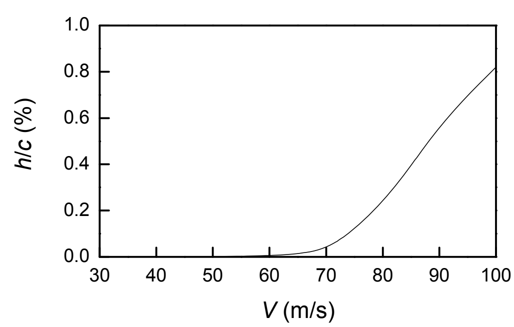
(c) Drag polarization curve

Figure 8 Aerodynamic characteristics of the aerofoil with flexible skin

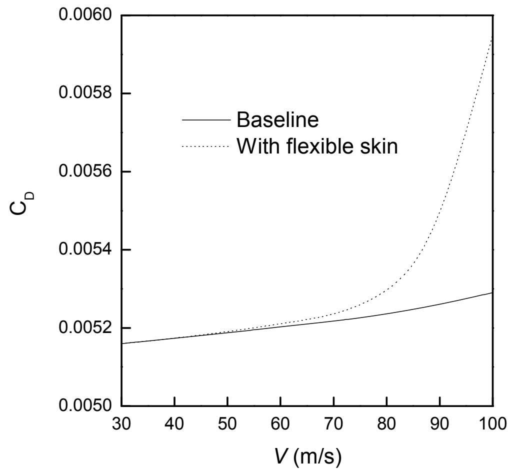
4.4 The variation of bubbled deformation with airflow speed

When the parameters of the skin structure are fixed, the deformation will vary with the airflow condition. Figure 9 shows the curve of the maximum height of the bubble and airflow speed. It can be seen that the bubble isn't evident when the airflow speed is slow; the bubble becomes bigger with the increase of airflow speed. When the airflow speed is over 65m/s, the bubbled deformation gets a sharp increase. The bubbled deformation causes the increase of drag coefficient, shown in figure 9 (b). When the speed gets to 100m/s, the airfoil drag with flexible skin is 13% bigger than the airfoil drag without the bubble (the dotted line). The increase of airfoil drag will decreases the speed of an aircraft.

Therefore, the bubbled deformation of flexible skin is sensitive to the airflow speed and the bubble will limit the flying speed of the aircraft.



(a) Maximum displacement



(b) Drag

Figure 9 Maximum displacement and drag of the aerofoil with flexible skin

4.5 The variation of bubbled deformation with trailing-edge deflection angle

Figure 10 shows the curve of the maximum height of the bubble and trailing-edge deflection angle. The maximum height of the bubble is nonlinear with the variation of trailing-edge deflection angle. When the trailing-edge deflection angle is 0°, the curvature of top surface of trailing-edge is small and the trailing-edge suction also small. So there isn't deformation under aerodynamic load. With the trailing-edge deflection angle increasing, the curvature, suction and prestress of the flexible skin increase. But the curvature and pre-stress of flexible skin increase little. The trailing-edge suction causes bubbled deformation to the skin. The curvature, suction and pre-stress of the flexible skin further increase with the trailing-edge deflection angle's augment, but the curvature and pre-stress become the main factors so that the bubbled deformation gets smaller contrarily.

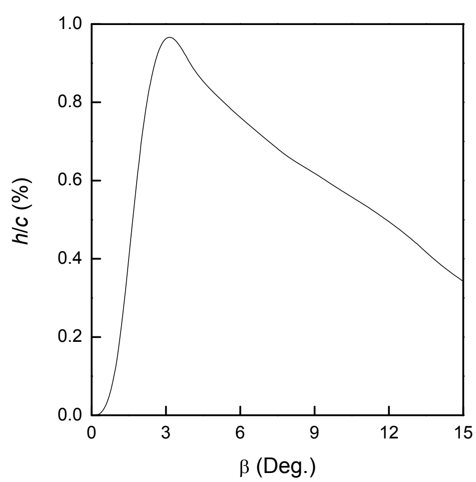


Figure 10 Maximum displacement vs. trailing-edge deflection angle

4.6 The effect of aeroelasticity to the design parameters of flexible skin

The effect of bubbled deformation to the tensile deformation of flexible skin is studied. Figure 11 shows the curve of tensile strain of flexible skin with the trailing-edge deflection angle. It can be seen that the tensile strain of flexible skin increases with the trailing-edge deflection angle's augment. The effect of aeroelastic deformation to the tensile deformation of flexible skin is obvious only in small trailing-edge deflection angle. With the increase of the trailing-edge deflection angle, the effect of aeroelastic deformation to the tensile deformation is gradually decreasing. When the trailing-edge deflection angle gets to 15°, the maximum tensile strain of skin is 1.78% without considering the bubbled deformation. If the bubbled deformation is considered, the maximum tensile strain of skin is 1.88%, which is bigger by 5.6% than it without considering the bubbled deformation.

In order to reduce the bed effect of bubbled deformation to the airfoil aerodynamic characteristics, the bubbled deformation must obey some rules. Unfortunately, there is not yet a deformation rule about the flexible skin of morphing wing. In order to face the bubble of flexible skin, some researchers adopted the skin deformation rule proposed by Jacobs in 1934 called Jacobs' law for short. This rule was also called the pillow constraint or the bubble constraint. The rule is described that the maximum displacement of flexible skin is not greater than 0.1 % of wing chord.

Figure 12 shows the curve of elastic modulus of flexible skin which obeys to the Jacobs' law with the trailing-edge deflection angle. It can be seen that the elastic modulus of flexible skin varies with the trailing-edge deflection angle. Different trailing-edge deflection angles correspond to different skin elastic modulus. The maximum value of elastic modulus of flexible skin is 390*MPa* which appears on a very small trailing-edge deflection angle. The minimum value appearing on the deflection angle of 0°is lower than 10*MPa* which is lower by 2 orders of magnitude.

If the flexible skin is made of traditional materials like silicone rubber, the minimum elastic modulus should be 390*MPa*. But its optimum point only is at the deflection angle of 3°. So the best selection of flexible skin should be the variable stiffness materials or structures, which can change the elastic modulus by different trailing-edge deflection angle. The existing variable stiffness materials[9,10] or structures like shape-memory-polymers (SMP)[11] and morphing skin structures based on variable stiffness tube are appropriate solutions for variable stiffness skin.

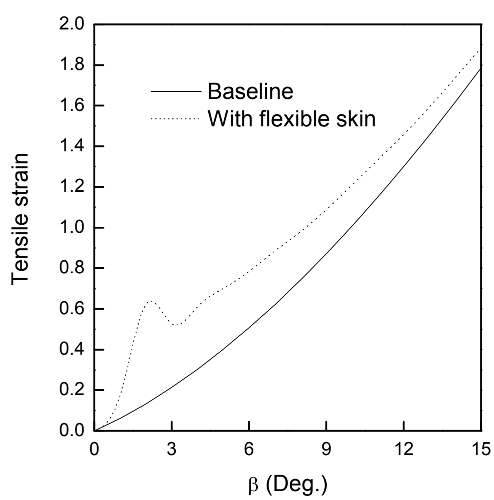


Figure 11 Tensile strain vs. trailing-edge deflection angle

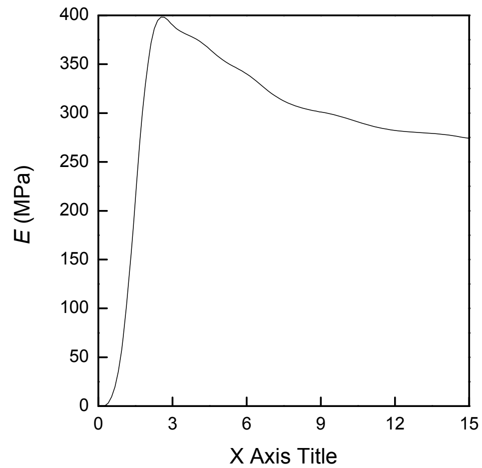


Figure 11 Elastic modulus of flexible skin vs. trailing-edge deflection angle

5. CONCLUSIONS

The method for analyzing the static aeroelastic deformation of flexible skin under aerodynamic loading was developed based on the panel method and finite element method. The effect of the bubbled deformation to airfoil aerodynamic characteristics and skin design parameters is studied. Some conclusions can be drawn.

(1) The flexible skin on the upper surface of trailing-edge will bubble under the air loads and the bubble has some effects on the aerodynamic pressure near the surface of local deformation.

(2) The bubbled deformation has a powerful effect on the airfoil aerodynamic characteristics. With the increase of the attack angle, the bubble gets smaller and the effects get weaker gradually.

(3) The bubbled deformation of flexible skin increases with the increase of airflow speed. The bubble gets a sharp increase when the airflow overtakes a velocity. The direct result caused by the bubbled deformation is the increase of drag coefficient. For the aircraft with a trailing-edge, the flying speed is limited by the bubble.

(4) The aeroelastic deformation of flexible skin also has some effects on the maximum tensile strain. At the same time, flexible skin should be made of variable stiffness materials or structures.

In summary, the effect of the deformation of flexible skin to the airfoil aerodynamic characteristics and the structure design parameters must be considered in the design of the structure and aerodynamics of flexible trailing-edge. In our future works, the wind tunnel test will be carried out to measure the bubbled deformation and investigate its influence on the aerodynamic characteristics of the airfoil.

6. ACKNOWLEDGMENTS

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