Analysis on the Aerodynamic Characteristics of a Continuous Whole Variable Camber Airfoil

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Abstract. In this paper, based on the genetic algorithm, a 4-section optimization airfoil structure is designed, which can change entire camber of the airfoil. For this new type of integral changeable camber airfoil, its first structure can be deflected downward by 30 degrees, the second section is fixed, the third stage be capable of deflect downward by 30 degrees, and the fourth section be able to bend up and down by 30 degrees. In addition, the computational fluid dynamics method is adopted to numerically simulate the aerodynamic performance of variable camber airfoils. The numerical results observe that the used of varying camber airfoil has better been stalling characteristics and larger lift coefficient comparison with the Clark Y airfoil and NACA114 airfoil.

1. Introduction

In terms of basic aerodynamics and practical flight application, variable-camber UAV (Unmanned Aerial Vehicle) has great potential [1-3]. In the field of aerodynamics, variable camber wings can improve the flight performance of UAV and adapt to a variety of missions; in the field of bionic science, it can help understand the complex mechanisms of animal flight. Besides, it can effectively delay the flow separation and improve stall characteristics for UAV with low Reynolds number [4-6]. For low-velocity vehicles, the control methods of the leading edge and trailing edge flaps are not only difficult to satisfy the multi-task requirements of the aircraft, but also the complex hinges on the system greatly increase the structural weight, which easily leads to configurational noise, vibration and fatigue damage [7]. Therefore, it is particularly important to design a wing that can maintain an optimal aerodynamic shape under various missions and environments.

Since the 1980s, the flexible technology of variable camber wing had been studied [8], which was listed as one of the key technologies of future aircraft. Based on research and analysis results, it was shown that in the implementation of adaptive deformation of the wing, from the traditional rigid structure to the compliant mechanism, there is a certain amount of research from the conventional materials and structures to the new smart materials and structures [2, 9-14]. Among them, the wing camber change was reached by using of compliant mechanisms, new intelligent material and structures. However, due to the fact that the study of functional materials, structures, and compliant mechanisms is still in an immature stage, and the drive system based functional materials have a relatively low efficiency in practical applications, which are difficult to meet the needs of current feasible engineering.

In order to overcome the problem, a novel entire variable camber wing was achieved by authors. In this paper, it is worth noting that the airfoil is optimized designed by genetic algorithm. The new
2. Optimize airfoil design

In order to be available to define the deflection angle of the variable camber airfoil, a symmetrical airfoil, NACA 0012, is selected. Figure 1 shows the maximum bending angle range of the airfoil.

![Figure 1. The maximum range of the variable camber airfoil](image)

Based on the XFOIL software for aerodynamics calculation, genetic algorithm and the corresponding objective function, a set of aerodynamic shape optimization method for the overall change camber airfoil is established. Shown in Figure 2-a, in the process of the change of airfoil camber, the four-typical state of airfoil was chosen to research. To verify the aerodynamic performance advantages of variable camber airfoil profile of 2D, Clark Y airfoil and NACA114 airfoil was selected, which were used as analysis of the results, as shown in figure 2-b.

![Figure 2. Schematic diagram of 2D airfoil: (2-a) 4-variable camber airfoil profiles, (2-b) the Clark Y airfoil and NACA114 airfoil](image)

3. Numerical simulation

3.1 CFD validation

A two-dimensional airfoil, NACA4412, is selected to validate the accuracy of the computational simulation. In order to obtain the precise simulation of the flow around variable camber airfoil, a C-type structured grid is adopted in the ICEM CFD 15.0[15], as shown schematically in Figure 3. The total number of mesh cells of computation field around the airfoil profile is 108500, the flow field is 20L away from the far-field boundary condition, and the quality of grid is 0.86~0.93. The reference length L is equal to 330mm, which corresponds to the airfoil chord length.

The boundary layer of normal velocity is very large in the adjacent airfoil region, which decreases from a relatively high value to the wall velocity. Therefore, it is necessary for boundary grid Y spacing value set to calculate the flow field of the near wall region. In this study, NACA Y+ wall distance estimation online is adopted, and the height of the first layer grid is calculated to be 0.001mm. The Spalart-Allmaras (SA) solver is adopted in this study.
Figure 3. Schematic of computation mesh.

The far-field boundary conditions are described as follows: Mach number is equal to 0.215, Reynold number is equal to $3 \times 10^6$, and the angle of attack is range from $0^\circ$ to $10^\circ$, with the far-field constant velocity. The simulation results are displayed in Figure 4.
Figure 4. Calculation and experimental characteristic coefficient versus AOA (Angle of attack) for NACA4412.

Figure 4-a show the effect of angle of attack on the lift coefficient distribution. The lift curve agrees well with experimental data within the range of the angle of attack. Figure 4-b and 4-c illustrates the airfoil drag coefficients and lift-to-drag ratios. It can be seen that the results of numerical computations are within the measured data range of the M.R.Ahmed[16] and Abbott et al[17] wind tunnels test. In general, the simulation results before stalling are considered to be believable.

3.2 Aerodynamic characteristics of the optimize variable camber airfoil (VCA)

3.2.1 Grid independence. In order to verify grid independence, three types of mesh with the increase grid density are employed to investigate lift and drag coefficients based on Clark Y airfoil in Figure 2 and \( \alpha = 0^\circ \sim 14^\circ \). The far-field flow is 18m/s and other parameters are the same as in section 3.1. The calculation results in Table 1 and Figure 5 show that the deviation of calculation of differences grid density are lower than 1.5% before lower than 8°. When the angle of attack become larger than 8°, the compute results deviate, which might have due to stalling of airfoil or unsteady vortex cause the flow separation. To reduce the costs and obtain a relatively high accuracy, the normal grid density is chosen in present research.
Figure 5. Lift and drag coefficient distribution of Clark Y airfoil with different grid density.

Table 1 Mesh independence study for variable camber airfoil at Re=406508 and angle of attack of 0° to 10°.

| Type     | Grid cells | α  | Cl  | Cd  |
|----------|------------|----|-----|-----|
| Sparse   | 45600      | 0  | 0.353 | 0.0145 |
|          |            | 4  | 0.805 | 0.0157 |
|          |            | 8  | 1.202 | 0.0204 |
| Normal   | 123400     | 0  | 0.359 | 0.0144 |
|          |            | 4  | 0.786 | 0.0158 |
|          |            | 8  | 1.196 | 0.0221 |
| Dense    | 384000     | 0  | 0.373 | 0.0148 |
|          |            | 4  | 0.813 | 0.0170 |
|          |            | 8  | 1.178 | 0.0222 |

3.2.2 2D characteristics of the optimization VCA. A calculation numerical simulation is performed to evaluate the aerodynamic characteristics of the optimization VCA. The normal grid is selected, and the boundary conditions are set adopting the same as conditions in section 3.2.
Figure 6. Aerodynamic coefficient versus AOA. 6-a lift coefficient versus angle of attack, 6-b drag coefficient versus angle of attack, and 6-c lift-to-drag versus angle of attack.

Figure 6-a shows that the lift coefficient increases at first and then turns to descending with the AOA increasing. The numerical results indicate that the variable camber airfoil has a larger stalling angle and a greater maximum lift coefficient than the Clark Y airfoil and NACA114 airfoil. The lift coefficient increases with the increase of airfoil camber with the same angle of attack, and it show an obvious enhances trend toward the camber increase. In addition, the lift coefficient of the Clark Y airfoil and NACA114 airfoil is between $a_1$ airfoil and $a_2$ airfoil, which demonstrate that the optimized airfoil in this paper has high lift and large angle of stall characteristics.

The drag coefficient distribution with different airfoil camber is shown in Figure 6-b. According to this result, the resistance coefficient increases when the AOA of the far-field air increase. As it is is shown in Figure 6-b, the drag coefficient increases obviously when the airfoil camber is greater than $a_1$ airfoil. Besides, the drag coefficients of the $a_1$ airfoil and NACA114 airfoil are almost identical, which also indicates that the optimally designed airfoil has a similar resistance characteristic of the conventional airfoil. It is worth noting that when the angle of attack is in the range of 12° to 14°, the drag coefficient increases significantly and it as well corresponds to the airfoil stall characteristics.

Figure 6-c shows that for variable camber airfoil, decambering can increase the lift-to-drag ratio; for the camber increases even further, the situation reversed. In addition, the lift-to-drag ratio of $a_2$ airfoil is approximately identical with NACA114 airfoil. The above shows that the optimized design of variable camber airfoil has excellent aerodynamic performance.
4. Conclusions
In this paper, an optimal design variable camber airfoil based on genetic algorithm is proposed. Besides, two-dimensional numerical simulation methods are applied to variable camber airfoil to investigate the effect of varying camber airfoil on the aerodynamic performance of UAV. The following conclusions can be drawn as

1) As compared with Clark Y airfoil and NACA114 airfoil, adjustable camber airfoils have better aerodynamic performance and stalled characteristics.
2) For variable camber airfoil, decambering can increase the lift-to-drag ratio; for the camber increases even further, the situation reversed.

Further study is necessary to explore the appropriate number of wing rib sections and investigates the effects of the relative rotation angle between different sections on aerodynamic performance of the whole AVCW UAV. The developed complete AVCW UAV is a potential future candidate for UAV field.

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