Research on Variable Sweepback Angle of Winglet Driven by Shape Memory Alloy

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Abstract. Because of its shape memory effect, shape memory alloy (SMA), as a driver, provides more possibilities for the design and optimization of winglets of variable sweepback angle. In view of three different flight states of a large civil aircraft, i.e., take-off, cruise and landing, the effects of different winglets of variable sweepback angle on the aerodynamic performance of the aircraft are analyzed by computational fluid dynamics (CFD), and then the optimal sweepback angles are 35°, 45° and 50° respectively. Based on the change of the sweepback angle of winglets in different flight states, a variable sweepback winglet structure based on SMA wire is designed. Combined with SMA constitutive relation, SMA driving mechanism is designed by the coupling method of force, heat and strain. The mechanism can automatically adjust the swept angle of winglets according to different flight conditions, so as to improve the lift drag ratio of wings.

1. Introduction

With the increasing shortage of oil resources in the world, it has become more and more important to improve the aerodynamic efficiency of aircraft to reduce fuel consumption, and drag reduction technology is an effective way to improve the aerodynamic efficiency. For large aircraft, the induced resistance accounts for about 40% of the total resistance in cruise state and 60% in low-speed and high angle of attack flight such as take-off or landing [1-2]. According to Breguet relationship, the reduction of induced drag can improve lift drag ratio, reduce fuel consumption rate and reduce the quality of the aircraft, thus increasing the range of the aircraft and reducing the flight cost. However, the current design of the winglet is only based on the cruise condition [3], and the drag reduction effect is not obvious for the take-off and landing conditions with larger proportion of induced drag.

In order to optimize the aerodynamic performance of winglets under various flight conditions, the design of variable sweepback angle winglets came into being. The design can change the shape of winglets under different flight conditions, so as to obtain better drag reduction effect. Airbus and the University of Bristol have jointly developed a winglet based on a motor-driven variable tilt angle. This winglet can increase the lift-drag ratio by about 3% during take-off [4]. At present, there are few researches on variant winglets in China. Si L of Northwest Polytechnic University put forward a kind of variant winglet design scheme of the steerable trailing edge rudder. The numerical simulation...
shows that the aerodynamic performance can be improved by deflecting the trailing edge [5]. Li W and others from Nanjing University of Aeronautics and Astronautics proposed a research scheme of variable tilt angle winglet with SMA spring actuator [6]. This solution can automatically adjust the tilt angle of the winglet according to different flight conditions, and optimize the aircraft’s drag characteristics in real time.

This paper takes a large civil aircraft as the research object. The influence of leading-edge sweepback angle of winglet on the aerodynamic performance of aircraft in different flight stages is analyzed by computational fluid dynamics (CFD). On this basis, a small wing with variable leading-edge sweepback angle driven by SMA wire is proposed. Combining with the constitutive theory of SMA, the SMA driving mechanism is designed by the coupling method of force, heat and strain. The research work of this paper can provide some reference for the research of variant winglets and the corresponding driving technology in the future.

2. Aerodynamic performance analysis of winglet

2.1. Research model
In this paper, the wing of a large civil aircraft with winglets is taken as the research object, and the simplified model is shown in figure 1.

![Figure 1. Research model.](image)

2.2. Aerodynamic performance analysis
In this paper, it is assumed that that during the take-off state, the angle of attack is 13°, the velocity of free flow is 0.4 Ma, and the temperature of free flow is 300 K; In the cruise state, the angle of attack is 4°, the free flow velocity is 0.8 Ma, and the free flow temperature is 250 K; in the landing state, the angle of attack is 8°, the free flow velocity is 0.4 Ma, and the free flow temperature is 300 K. In this paper, it is assumed that in each flight state, the leading-edge sweepback angle of the winglet changes in the range of 10 ~ 60 degrees with a step of 5 degrees. So, there are 11 different winglets in each flight state.

![Figure 2. The flow field grid diagram of wing](image)  
![Figure 3. The relation curves of lift drag ratio and leading-edge sweepback angle](image)
The numerical calculation was performed by commercial calculation software ANSYS. The numerical simulation calculation only considered the wing and the winglet and ignored the fuselage and other components. The density-based implicit solver is used and the turbulence model is selected from the Spalart-Allmaras model. Numerical calculations are performed on the wing in each state. The wing outflow field grid is shown in figure 2.

In this paper, the lift drag ratio $K$ is taken as the optimization object to analyze the aerodynamic performance of the wing. The relation curves of lift drag ratio $K$ and leading-edge sweepback angle $\alpha$ of winglet in takeoff and landing state are shown in figure 3 and figure 4. The curve of lift drag ratio and leading-edge sweepback angle $\alpha$ of winglet in cruise state is shown in figure 5.

**Figure 4.** The relation curves of lift drag ratio and leading-edge sweepback angle

As can be seen from figure 3, with the increase of leading-edge sweepback angle of winglet, the overall trend of lift drag ratio of wing increases first and then decreases in take-off and landing flight. The same is true of figure 4. Because in the high angle of attack flight, such as take-off and landing, the pressure difference resistance and induced resistance are the main parts of aircraft resistance, and the winglet can effectively reduce the induced drag of the aircraft. With the increase of the leading-edge sweepback angle, the wingtip fossa of the winglet and the wingtip fossa of the wing are getting closer and closer, which can further reduce the overall strength of the tail socket, and then increase the lift-to-drag ratio. It can be seen from figure 5 that the lift-to-drag ratio of the wing also increases and then decreases during cruise. Because in the initial stage, changing the sweepback angle of the winglet can effectively reduce the energy loss and improve the lift drag ratio of the wing. However, when the sweepback angle is too large, it will cause stall and reduce the lift drag ratio of the wing.

In summary, the change of the lift drag ratio with the sweepback angle of the leading edge of the winglet is generally similar under different flight conditions. However, the sweepback angles corresponding to the maximum lift drag ratios in different states are not consistent. It can be seen from figure 3, figure 4 and figure 5 that the optimal sweepback angles corresponding to the maximum lift drag ratios of take-off, cruise and landing states are $35^\circ$, $45^\circ$ and $50^\circ$ respectively.

### 3. Design of driving mechanism of variable angle of sweepback of winglet

#### 3.1. SMA drive mechanism requirements

The design of the variable sweepback angle winglet drive mechanism focuses on how to reasonably arrange the drive mechanism in the small space of the winglet. Moreover, because the surface of winglet has a large aerodynamic load, the driving mechanism should produce enough driving force to overcome the aerodynamic load. The driving method of the traditional hydraulic mechanical system is more complicated, and the weight and volume are relatively large. Therefore, a drive system represented by a new type of smart material must be selected as the drive actuator of the variable
sweepback angle winglet. Current research on SMA shows that SMA materials have unique shape memory effects and super elasticity, and they can be very effectively used as fast-response, lightweight, and high-force actuators. Therefore, it is very suitable for the application of variable sweepback angle winglets [7-9].

3.2. The Selection of actuator for SMA driving mechanism

SMA actuator can be activated through temperature change by using SMA wires, SMA belts, SMA torque tubes and other forms, therefore, the selection of SMA actuator needs to be considered according to the specific situation. The variable sweepback angle winglet scheme proposed in this paper only requires deformation in a single direction, and considering the control complexity, SMA wire is selected as the actuator. Such an actuator has the advantages of smaller volume, simple control and larger displacement. It can be designed to be installed on the winglet and will not affect the normal flight of the aircraft.

3.3. The design of SMA drive mechanism

In this paper, the variable sweepback angle winglet driving mechanism is composed of winglet matrix and SMA actuator, the simplified model is shown in figure 6. SMA actuators can be connected to the point inside the winglet after cooling below the martensite temperature. When the wires are heated above the initial temperature of austenite, they begin to shrink to their memory length. In this process, the transformation recovery force is generated and the matrix of winglets is deformed, thus changing the sweepback angle of winglets. When the temperature is below the completion temperature of martensite, the SMA actuator returns to the original state, so that the winglet sweepback angle returns to the original shape.

The deformation of winglets can be divided into two stages. In the first stage, from take-off stage to cruise stage, as shown in figure 6(a), the winglet sweepback $\alpha_1$ increases from 35° to 45°. In this stage, SMA actuator 1 was used for heat treatment and training. And finally its memory length $l_1$ is trained to 510 mm, then it is pretensioned to $l_1+\delta_1=536$ mm and installed in the driving mechanism. In the second stage, from cruise stage to landing stage, as shown in figure 6(b), the winglet sweepback $\alpha_2$ increases from 45° to 50°. In this stage, SMA actuator 2 was used for heat treatment and training. And finally its memory length $l_2$ was trained to 480 mm, then it was pretensioned to $l_2+\delta_2=510$ mm and installed in the driving mechanism. Electric heating is used to control the SMA drive mechanism. First, wrap the resistance wire around the surface of the SMA wire. Then, the outermost layer is covered with an elastic insulating skin, so that it is not affected by the external environment during the flight. By controlling the on-off button installed on the control panel, the SMA drive mechanism is turned on and off to control the sweepback angle of the leading edge of the winglet.

![Figure 6. The geometry model of Winglet](image)
4. The realization of variable sweepback winglet driving mechanism

4.1. SMA Constitutive Model

The SMA material model selected in this paper is only subjected to axial tensile force, and the model has a larger axial dimension than a radial dimension, so only the axial deformation is considered. For the one-dimensional case, the constitutive relationship of the SMA can be finally obtained.

$$
\varepsilon = \varepsilon^e + \varepsilon^t = \sigma S + \alpha (T - T_0) + H \zeta
$$

$$
\varepsilon^t = \begin{cases} 
\frac{1}{2} \cos \left( A^M (T - M^f) \right) - \frac{A^M}{C^M H} \left( \sigma H + \frac{\sigma^2 (S^M - S^A)}{2} + \sigma (\alpha^M - \alpha^A) (T - T_0) \right) + 1, & \zeta > 0 \\
\frac{1}{2} \cos \left( A^A (T - A^f) \right) - \frac{A^A}{C^M H} \left( \sigma H + \frac{\sigma^2 (S^M - S^A)}{2} + \sigma (\alpha^M - \alpha^A) (T - T_0) \right) + 1, & \zeta < 0
\end{cases}
$$

In the formula, $\sigma$ is the axial tensile stress, $H$ is the maximum transformation strain, $\zeta$ is the martensite volume fraction. $S=1/E$ is the elastic compliance, $E=E^A+\zeta(E^M-E^A)$ is the elastic modulus, and $E^A$ is the elastic modulus of austenite, $E^M$ is the elastic modulus of martensite, $\alpha = \alpha^A+\zeta(\alpha^M-\alpha^A)$ is the coefficient of thermal expansion, $\alpha^A$ is the coefficient of thermal expansion of austenite, and $\alpha^M$ is the coefficient of thermal expansion of martensite, $T$ is the temperature, and $T_0$ is the initial temperature, $C^M$ is martensite stress influence coefficient.

4.2. Numerical calculation

In this paper, a summary of the material properties of simulated SMA is shown in table 1 [10].

| $M^f$  | $M^x$  | $A^x$  | $A^f$  | $E^A$  | $E^M$  | $\alpha^A$ | $H$       | $C^M$ |
|--------|--------|--------|--------|--------|--------|------------|----------|-------|
| -88°C  | -55°C  | 0.2°C  | 28.4°C | 70.6Gpa| 32Gpa  | 3.5×10^{-5}/°C| 0.045   | 0.593 |

According to the SMA theoretical model (1) and the material parameters in table 1, the stress-strain curve at 30°C is calculated, as shown in figure 7. It can be seen from the figure that with the increase of stress, the strain will increase correspondingly. When the stress reaches 800MPa, the maximum deformation of SMA wire is 6.7%.

**Figure 7.** The curve of relationship between stress and strain

**Figure 8.** The temperature-strain curves under different stress

Based on the stress-strain relationship in figure 7, the temperature-strain relationship of the SMA...
wire was calculated under the pre-stress of 400MPa, 600MPa, and 800MPa under the thermal cycling condition of 0 ℃ to 200 ℃. The numerical calculation results are shown in figure 8. The temperature control interval and achievable strain of the SMA wire under different stresses can be obtained from figure 8, and the numerical calculation results are shown in table 2.

Table 2. Temperature control interval and achievable strain of SMA wire under different stresses.

| Strain (MPa) | 400   | 600   | 800   |
|-------------|-------|-------|-------|
| Temperature (℃) | 0~120 | 55~165 | 80~194 |
| Stress (%)   | 5.2   | 5.5   | 5.8   |

It can be seen from table 2 that the deformation of the SMA wire gradually increases with increasing stress. It is known from Section 3.3 that during the first stage of winglet deformation, the SMA wire deformation amount is $\delta_1/l_1 = 5.1\%$, so under 400MPa stress, the control temperature range is 0 ~ 120 ℃, which can meet the design requirements. In the second stage of winglet deformation, the amount of SMA wire deformation is $\delta_2/l_2 = 5.8\%$, so under 800MPa stress, the control temperature range is 80 ~ 194℃, which can meet the design requirements.

5. Conclusion
In this paper, the influence of different sweepback angle winglets on the aerodynamic performance of the aircraft are analyzed through computational fluid dynamics (CFD), and the optimal sweepback angle under different flight conditions is determined. Based on this, a new type of sweepback angle winglet structure scheme based on shape memory alloy drive is proposed. The scheme can automatically adjust the sweepback angle of winglet according to different flight conditions, so as to optimize the lift drag ratio of wings. The optimization theory and design can be extended to more wings, which lays a foundation for further optimization of aerodynamic efficiency of wings.

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