Design and experimental verification of smart aileron structure based on Shape Memory Alloy

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Abstract. In traditional smart aileron structures, a pair of Shape Memory Alloy (SMA) wire is arranged on one side of the rib. Although large deformation angle could be achieved, the overall driving speed is relatively slow because of the long cooling time of SMA. To improve the speed, we designed the structure with multiple SMA wires being arranged on both sides of the rib. Theoretical analysis showed that this structure could improve the driving speed by reducing the cooling time during each deformation cycle. After measuring the parameters of SMA, we processed ANSYS simulation to analyze the deformation angle. Results showed that in the new structure, the upward angle was 92% of the existing structure and the downward angle was 67% of the existing structure. These losses were acceptable as the deformation angle has already been large enough. Finally, experiments were processed to determine the required driving time as well as verify the simulation results. In the new structure, the speed was increased by about 44%. Besides, the upward and downward deformation angles of the new structure were 90% and 65% of the existing one, which were close to the simulation results.

1. Introduction

Elevators, rudders and ailerons have traditionally been utilized to provide the control torque for aircrafts. Among them, the difference in the deflection angles of the left and right aileron causes the rolling moment. Traditional aileron is connected to the wing by hinges, which results in the separation of airflow and therefore the increase of the aerodynamic resistance on the aircraft due to the gap on the wing [1,2]. Therefore, we consider the aileron driven by smart materials to solve this problem.

The concept of smart materials with both driving and sensing capabilities was first introduced in the mid-1980s [3,4]. Composed of smart materials, smart structure is lighter, higher in energy density and larger in deformation compared with mechanical ones. As the materials could conveniently been arranged inside the wing, the structure with smart materials could ensure the continuity of wing surface.

The internal driving of the wing needs to divide the trailing edge of the rib into several components, and then use the relative rotation between two adjacent components to produce an overall camber change. There are some studies which designed the variable-camber aileron or wing that used SMA wires to differentially drive the relative motion between two parts, thereby bending the aileron or wing [5-9]. As the primary material to drive such structures, Shape Memory Alloy (SMA) can produce large strain, efficient work output as well as direct displacement, and can be easily combined with the existing mechanical structures. The two ends of SMA wire are usually fixed on the adjacent two parts of the rib to produce an angular output. However, the biggest problem of this structure lies in that the cooling time of SMA is very long [10]. To solve this problem, the current method mainly includes...
setting a heat sink or a cooling fin to assist heat dissipation, designing new controller of SMA wire to improve the dynamic response speed or combining it with other materials that respond faster \[11,12\]. This paper attempts to improve the response speed of the driving structure from another angle, that is to change the layout of SMA wires on the ribs

2. Properties and Parameters of Shape Memory Alloy

2.1. Properties of Shape Memory Alloy

As the smart material, SMA can be used as both a sensor and an actuator. When temperature is changed, it would transit between martensite phase and austenite phase with the output of deformation and stress. Usually, the temperature of SMA is controlled by the current flowing through it. During the phase transition, the temperature has four nodes, these are the starting and ending temperature of martensite phase transition \(M_s\) and \(M_f\) in the temperature reduction process, and the starting and ending temperature of austenite phase transition \(A_s\) and \(A_f\) in the temperature increasing process.

When it is higher than \(A_f\), SMA is under austenite phase and could memorize its shape. When the temperature drops, martensite transition occurs. SMA is totally under martensite phase and the shape could be artificially changed with an external force when it drops below \(M_f\). It could then be heated again to produce an austenite phase transition. When it achieves \(A_t\), the phase transition is completed. Without external stress, the wire would automatically return to its original shape. This property of SMA is called Shape Memory Effect (SME) and can be easily applied to the internal control of smart aileron. Since the rib is divided into several parts, the two ends of the alloy wire can be respectively fixed on two adjacent parts, and the wire would shrink when heated by the current. The ribs then rotate relatively to each other and the overall angle is generated.

2.2. Parameters of Shape Memory Alloy

To determine the parameters of SMA, we studied the constitutive model proposed by Liang-Roger to clarify the parameters of the material. The model was shown in equation (1) to (5).

\[
\sigma - \sigma_0 = E(\epsilon - \epsilon_0) + \Omega(\xi - \xi_0) + \theta(T - T_0) \tag{1}
\]
\[
\Omega(\xi) = -E \cdot E(\xi) \quad \theta(\xi) = -\alpha E(\xi) \tag{2}
\]
\[
E(\xi) = E_s + \xi (E_m - E_s) \tag{3}
\]
\[
\xi = \frac{\xi_m}{2} \{\cos[\alpha_s (T - A_s) + b_s \sigma] + 1\} \tag{4}
\]
\[
\alpha_s = \frac{\pi}{A_f - A_t} \quad b_s = -\frac{\alpha_s}{c_s} \tag{5}
\]

From the constitutive model of SMA, the stress is determined by strain, martensite volume fraction and temperature, while the martensite volume fraction is related to temperature and stress. By integrating the above equations, we obtained the relationship between stress, temperature and strain of SMA which was shown in equation (6).

\[
\sigma - \sigma_0 = \frac{1}{2} \{\cos \frac{\pi (T - A_f - \sigma / c_s)}{A_f - A_t} \} (E_m - E_s) \tag{6}
\]

Therefore, to establish the model of SMA, we needed to determine the phase transition temperature, elastic modulus under two states, the maximum recoverable strain and the stress required to increase the phase transition temperature by one degree.

The SMA used is the NiTi alloy produced by Suzhou Rongqian Rare Metal Co. Ltd., which has the diameter as 0.5 mm and the ratio of Ni and Ti as 55.6% and 44.39% respectively. Since other parameters were not provided, experiments needed to be performed.

First, since the resistance of SMA would abruptly change at the point of phase transition, the resistance and temperature of SMA were simultaneously measured, and the relationship between them was obtained. As shown in Table 1, four phase transition temperatures of SMA were measured.
Table 1. Phase transition temperature of SMA.

|          | Ms  | As  | At  |
|----------|-----|-----|-----|
|           | 46° | 68° | 34° | 58° |

After measuring the phase transition temperatures, the elastic modulus of it at normal temperature and 58 degrees were measured by the INSTRON electronic universal material testing machine and the result was 11.5GPa and 31.7GPa respectively. Then the wire was stretched to a certain length at room temperature and then heated to observe whether it could restore the original length or not. The result showed that the maximum recoverable strain of the wire is 7%. Finally, in the case where a certain stress was applied to the wire, the phase transition temperature was measured and the stress required to increase the transition temperature by one degree was calculated to be about 158kPa.

3. The designed structure and the analysis of driving speed

3.1. The designed structure

The research of this paper was based on the existing structure with the structural comparison being shown in Figure 1 and Figure 2. In Figure 1, only one pair of SMA wires was arranged on one side of the rib, with one wire on the upper side and another on the lower side. In Figure 2, another pair of wires was added to the back side and the original single wire was replaced by multiple wires.

In the actual process, SMA wire should be pretreated at high temperature to remember its initial length. Then it is stretched under a lower temperature and fixed to the side of the rib. If the upper wire is heated, it would generate stress and tend to shrink. The wire in the lower side would be stretched and the second segment of the rib would rotate upward. As a result, the aileron has an upward camber. On the other hand, if the lower wire is heated, the upper wire would be stretched and the aileron has a downward camber. Therefore, by controlling the current flowing through the wires, it is possible to produce the desired deformation which could in turn drive the change in the camber of aileron.

The advantages of the designed structure over the existing one could be reflected in two aspects. Firstly, the designed structure could increase the response speed by adding a pair of SMA wires and then making the driving process more flexible. Besides, the utilize of multiple SMA wires could produce greater stress to withstand the aerodynamic force experienced during flight.

3.2. The analysis of driving speed

3.2.1. The existing structure. The driving process of the aileron in the existing structure was shown in Figure 3. It can be seen that in each cycle, two cooling processes were required. The time taken by the austenite transition of the wire was set as \( t_h \), and that taken by martensite phase was set as \( t_c \), then the time for the wire to finish each cyclic process was shown in equation (7).

\[
t_f = t_h + 2t_c
\]  

(7)

Since the cooling time of the wire is relatively long, it takes a high proportion in the overall cycle and affects the deformation speed of the aileron to a large extent.
3.2.2. The designed structure. In the designed structure, the driving process becomes complicated as the number of SMA wires was increased. As shown in Figure 2, aileron could be bent upward by heating SMA1 or SMA3 on the upper side and then be bent downward by simultaneously heating SMA2 and SMA4 without the cooling of heated wires. Then all the heated wires were cooled so that the aileron could restore to the horizontal state. The next cycle could therefore be performed. This driving process was shown in Figure 4.

It can be seen from Figure 4 that only one cooling process was required in each cycle. Then the time needed for each cycle was shown as equation (8).

\[ t_2 = 2t_c + t_h \]  

(8)

By reducing the proportion of cooling time in each cycle, we could spend more time in the driving process. In this way, the response speed during flight could be improved.

4. Finite element simulation of deformation angle

The modelling and simulation of the rib were carried out based on the obtained parameters. The aerofoil was selected as NACA0012. The length of the aileron was designed as 25cm, two parts were 5cm and 20cm. The thickness was 0.5cm and the length in the vertical direction was 6cm. During the simulation, the wire was designed to be 15mm in height and 10cm in length.

As shown in Figure 5, in the existing structure, the upward and downward result was equal. The wing tip displacement was 6.2107 cm and the angle was 14°. When adopting the designed structure, single SMA wire was firstly arranged. Theoretical analysis showed that when the rib moves upward, the wing tip displacement could be \( \frac{(E_A + E_M)}{(E_A + 2E_M)} = 0.79 \) of the existing structure. When it moves downward, the proportion would be \( \frac{2(E_A + E_M)}{(3E_A + E_M)} = 0.81 \). As shown in Figure 6 and Figure 7, the simulated displacements were 0.79 and 0.81 of the existing structure respectively, which were in agreement with the theoretical results.

Since multiple SMA wires could withstand higher aerodynamic forces, simulation analysis was performed in condition of multiple SMA wires. It was finally determined that three wires were arranged on the upper side and two wires were arranged on the lower side. In this case, the deformations were 0.92 and 0.67 of the existing structure.
5. Experimental verification

5.1. Deformation angle
To verify the simulation results, the rib model was designed and processed, as shown in Figure 8. The height of the rib was 12cm and the length was 50cm, of which the first section was 10cm. Two rib sections could rotate with each other and their thickness was 1cm. The rib material was 45# steel. The length of the wire was 13cm and the height was 4cm. Besides, the assembly to fix these wires could rotate in the rib plane freely and ensure that the change of the wire direction during the driving process would not be affected. First, the finite element model of the rib was established based on the size of prototype. The case that the wire was distributed on one side was studied and the simulation result was shown in Figure 9. The wing tip displacement was 4.3cm and the deformation angle was 4.9°.

Then the experimental verification was performed. The DC power was used to drive the deformation of the wire. During the heating process, the temperature of the wire was measured using a thermocouple with the help of the insulating tape. As shown in Figure 10 and Figure 11, the wire on the upper and lower side were respectively heated and the wing tip displacement was 3.1cm. Thus, the deformation angle was 3.44°. The results were reduced by about 30% compared with the simulation.

In the same way, the designed structure was also verified. When three wires were arranged on the upper side and two were arranged on the lower side, the maximum upward displacement of the wing tip was 2.8cm and the downward displacement was 2 cm. The ratios of these displacements to the displacements of the existing structure were respectively 0.90 and 0.65, which were close to the 0.92 and 0.67 obtained by simulation. In this way, the rationality of the simulation results could be verified.

5.2. Deformation speed
The deformation speed of the aileron needs to be experimentally verified. During the heating of the wire, a DC voltage source was used to supply a 3V voltage to the wire. It was obtained that the heating time required was 3s and the cooling time was 10s, so the total time required to complete a cycle in the existing structure was tested to be 23s.

After improving the structure, the two sets of SMA wires on the lower side could be simultaneously heated after heating the upper wire, so two driving processes could be continuously
performed. Therefore, the time to complete one cycle was tested to be 16s. It was obtained that the new structure could increase the deformation speed of the aileron by about 44%.

6. Conclusion
To improve the driving speed of smart aileron, we designed the new structure with multiple SMA wires being arranged on both sides of the rib. ANSYS simulation was processed to analyze the deformation angle. Results showed that in the new structure, the upward angle was 92% of the existing structure and the downward angle was 67% of the existing structure. These losses were acceptable as the deformation angle has already been large enough. Then the experiments were processed to determine the required driving time and verify the simulation results. In the new structure, the speed was increased by about 44%. Besides, the upward and downward deformation angles of the new structure were 90% and 65% of the existing one, which were close to the simulation results.

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