DESIGN DIAGRAM FOR LINEAR SMA ACTUATORS INTEGRATED IN A MORPHING WING STRUCTURE

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ABSTRACT

Shape memory alloy (SMA) actuators can be used effectively as active elements coupled with the passive elastic structure of a morphing wing, given their exceptional power density characteristics. Upon heating, SMA deforms the elastic envelope of the wing, while during cooling, the wing restores the energy accumulated during the actuation period, thus ensuring the SMA actuators are reset. The shape-changing behavior of the morphing structure depends on a series of parameters which can be grouped as follows: SMA characteristics, elastic structure properties and the assembly conditions between the SMA and the elastic structure. For an SMA of a given composition, its recovery stress-strain characteristics are determined by the alloy’s thermomechanical history. This paper focuses on the development of a design methodology leading to an optimum selection of a thermomechanical SMA treatment and assembly conditions according to the requirements imposed by the application in terms of the required force-displacement characteristic and number of cycles of operation. A minimum-weight optimization case study is presented.

Keywords: SMA actuator, elastic structure, thermomechanical treatment, assembly conditions, fatigue, optimization

INTRODUCTION

Generally, an actuator is a system that transforms thermal, electrical, fluidic or chemical energy into mechanical work. Actuators can be grouped into two main classes: conventional, such as electric and hydraulic, and non-conventional, such as shape memory, piezoelectric, magnetostrictive or electrostrictive. Conventional actuators are limited in the amount of force they can generate when their size and weight are scaled down, and non-conventional actuators present a good alternative in this case. In that regard, Shape Memory Alloy (SMA) actuators produce the highest work density, and are therefore interesting candidates for robotic, automotive, spatial and aeronautic applications, including active elements for adaptable wing structures [1-3].

SMA, which are classified as smart materials, are sensitive to temperature and stress. After initial deformation at low temperatures, an SMA will return to its original configuration upon heat being supplied. This phenomenon is due to a thermoelastic martensitic transformation. Since the discovery by Bühler of the nickel-titanium SMA in the 60s, serious investigations have been undertaken in a bid to understand the mechanisms of the shape memory effect, and to apply it in industrial, and mainly actuator, applications [4].

This paper focuses on the development of the design methodology adapted to SMA actuators intended for use in specific industrial applications, such as in adaptive wing structures. Indeed, connecting SMA active elements to the flexible structure of the wing extrados should allow modification to be made to the wing’s profile in order to improve laminar flow conditions, and therefore decrease overall fuel consumption.
ADAPTIVE WING

The main goal of this project is to adapt a wing profile to different flight conditions. To that end, airfoil profile modifications will be made by deflecting a part of the extrados. Figure 1 presents an adaptive wing prototype combining 3 main subsystems: flexible extrados, rigid intrados and actuators. The leading edge of the flexible extrados is firmly attached to the rigid intrados and its other edge is connected to a compensation spring that accommodates extrados shaping and maintains aerodynamic continuity between the flexible and rigid parts of the wing. A numerical model of the flexible extrados (skin) was built for the purposes of this project [5]. For a given flexible structure and given flight conditions, this model is able to determine the forces the actuators must provide in order to fit an optimized wing profile.

**Figure 1: Adaptive wing prototype**

**ACTUATOR GROUP**

The actuator group, illustrated schematically in Figure 2, can be divided into 3 elements: linear SMA element, transmission system and flexible skin (bias element). The SMA element is connected to the flexible skin through a cam transmission system. During heating, the SMA element pulls the cam along the rail and a crank, attached to the latter, transfers the displacement to the flexible skin. The cam design allows an adjustment of the force-stroke characteristics of the actuator to those of the flexible skin. This actuation system can be schematized by an SMA active element connected in series to the flexible structure (bias element), where the latter returns the SMA actuator to its initial state and compensate aerodynamic loading associated with the presence of the flow over the wing.

**Figure 2: Actuator group (SMA + transmission) and flexible wing structure (skin)**
The following are the main parameters affecting the behavior of SMA actuators [6]:

- **SMA active element**: stress needed to deform the material in cold (martensitic) state and recovery stress generated by this element upon heating in constraint conditions; these characteristics are dependent on the chemical composition and thermomechanical history of the material, including cold-work, post-deformation annealing and prior thermal, mechanical or thermomechanical cycling.

- **Bias element** (flexible structure of the morphing wing in our case), which ensures a repetitive actuation and can be defined by a specific force-displacement characteristic.

- **Actuator’s assembly conditions**, which determine the initial strain induced in the SMA active element upon its connection with the bias element in the cold (martensitic) state.

**CONSTRAINT RECOVERY SMA TESTING: MATERIALS AND EQUIPMENT**

To evaluate the material capacity of the SMA to generate recovery forces, constraint recovery testing is performed. The material used is a \( \varnothing 1 \) mm wire (Ti-50.26at%Ni) supplied by Special Metals Corp. (NY, USA), subjected to 30% cold-work and post-deformation annealing (PDA) in the 250 to 400°C temperature range (1 hour). After the cold-work (rolling), the cross-section of the SMA is reduced and becomes equal to \( A_0 = 0.7 \) mm². The transformation temperatures after different PDAs are measured using the Perkin Elmer Differential Scanning Calorimeter following the ASTM F2004-05 procedure.

The experimental set-up for the constraint recovery stress experiments is shown in Figure 3. The SMA specimens (initial length \( l_0 = 70 \) mm) are thermally cycled between ambient temperature (25°C) and 120°C (30°C higher than austenite finish temperature to complete martensite-to-austenite transformation) by resistive heating. To that end, a programming power supply (Sorensen DML 40-15) is used to inject electrical current into the specimen, and the heating is controlled using the temperature signal as a feedback. The temperature is measured using a K-thermocouple placed directly on the surface of the specimen and electrically isolated from it by an adequate compound (Wakefield thermal compound). The force generated by the actuator is measured by a load cell (Omega LC 101-500); the displacement, by a Linear Variable Displacement Transducer (Trans Tek series 240), and the electrical resistance, by a Keithley 2010 multimeter. The data acquisition and the control are performed using a PC programmed for this application using LabView software.

The testing bench has three functional testing modes, and the diagrams obtained with them are presented in Figure 4 after 200 cycles of repetitive actuation:

(a) **Constant-stress mode (Figure 4a)**

This figure presents the constant-stress strain/temperature diagrams corresponding to the deadweight bias system. A constant load applied to the actuator determines the initial strain of testing (martensitic state). From this diagram, martensitic (\( \varepsilon_{\text{M}} \)), austenitic (\( \varepsilon_{\text{A}} \)) and recovery (\( \varepsilon_{\text{rec}} = \varepsilon_{\text{M}} - \varepsilon_{\text{A}} \)) strains can be extracted according to the number of heating-cooling cycles.

(b) **Fixed support mode (Figure 4b)**

When a fixed support is used, the stiffness of the bias system is close to infinity. From the stress-temperature diagram obtained, recovery stress increments generated upon heating can be defined as \( \sigma_{\text{rec}} = \sigma_{\text{A}} - \sigma_{\text{M}} \), where \( \sigma_{\text{M}} \) is martensitic and \( \sigma_{\text{A}} \), austenitic stresses.

(c) **Elastic bias mode (Figure 4c)**

Representing an intermediate loading case, the diagrams shown are associated with the stress-strain behavior of an active SMA element connected to an elastic bias spring. This kind of diagram is more akin to an application behavior, when an SMA actuator is coupled with a flexible structure, for example.
Figure 3: Experimental testing bench

Figure 4: Examples of (a) constant-stress, (b) fixed support and (c) elastic bias mode strain-stress diagrams
CONSTRAINT RECOVERY SMA TESTING: SELECTION OF THE PDA AND ASSEMBLY CONDITIONS

To select adequate PDA and assembly conditions for a given SMA material, two performance characteristics of an active element should be taken into account: (a) work density provided by an active element, and (b) the stability of the active element behavior. In fact, it was shown that thermomechanical processing combining cold work and post-deformation annealing (PDA) makes it possible to improve the performance and the lifespan of SMA devices [7]. To select the best-suited PDA conditions and an adequate initial strain, the results of the constant-stress 200-cycle testing are presented in Figure 5, where the recovery ε_{rec} and austenite ε_{A} strains are plotted according to the number of cycles under two constant-stress loads (90 and 300 MPa) and for different PDA conditions.

It can easily be calculated that for a given PDA, the higher the applied stress, the greater the mechanical work produced. For a PDA of 300°C for example, the mechanical work density at the 200th cycle, which is a product of recovery strain and applied stress values, is 7.35 MJ/m³ for a constant stress of 300 MPa, and 0.9 MJ/m³ for a constant stress of 90 MPa. However, this increase in mechanical work is obtained at the expense of actuation stability. For a 90 MPa loading, the recovery and austenite strains remain relatively stable, except after a PDA of 400°C, while for a 300 MPa loading, a drift in the austenite strain becomes much more significant. In fact, its value goes from 0.8 to 2.6% for a PDA of 300°C and from 3.6 to 5.9% for a PDA of 400°C. Therefore, to make an adequate selection of the PDA and the assembly (initial strain) conditions, it becomes important to find the best trade-off between the mechanical work and the actuation stability.

Two performance criteria can be introduced in this respect: (a) the maximum work density provided by an active element during one heating-cooling cycle, and (b) the actuation stability.
factor. For a given force, the work generated by the actuator is proportional to the recovery strain, while the actuation stability depends on the austenite strain constancy.

For a linear SMA element subjected to a constant load, work density can be calculated as follows:

\[ W = \varepsilon_{\text{rec}} \sigma_{\text{const}} \left[ J / m^3 \right], \]

where \( \varepsilon_{\text{rec}} = \Delta l / l \) and \( \sigma_{\text{const}} = F_A A \), \( \Delta l \) is the SMA recovery stroke under the constant force of \( F_A \), and \( l \) and \( A \) are the initial length and cross-sectional area of the SMA active element, respectively.

The actuation stability factor can be expressed as follows:

\[ S = \frac{\varepsilon_A^{(1)}}{\varepsilon_A^{(N)}}, \]

where \( \varepsilon_A^{(1)} \) is the austenite strain at the 1st cycle and \( \varepsilon_A^{(N)} \) is the austenite strain at the Nth cycle.

To establish the best trade-off between these two performance criteria, a simple additive weighting method (SAW) for solving multiple criteria decision making problems [8] is used. The two criteria are normalized between 0 and 1, and are included in the optimization function, which is a sum the two normalized functions:

\[ f(X_{\text{op}})_N = \max \left[ k_1 \frac{W_i - W_{\text{min}}}{W_{\text{max}} - W_{\text{min}}} + k_2 \frac{S_i - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \right], \]

where \( k_1 + k_2 = 1 \) are weight factors, \( W(S)_i \), \( W(S)_{\text{max}} \) and \( W(S)_{\text{min}} \) represent current, maximum, and minimum work density (actuation stability) values, respectively.

In figure 6, the value of the optimization function and of the initial strain is plotted as a function of the applied constant stress and PDA conditions on the base of the 200-cycle testing. It can be observed that the highest value of the optimization function is reached for a PDA of 300°C under an applied stress of 230 MPa, the latter corresponding to 3% of the initial cold (martensitic) strain.

**Figure 6: Selection of the PDA and the initial strain (200th actuation cycle)**
Now, if PDA = 300°C and an initial strain of 3% provide the best PDA and assembly conditions, the SMA alloy thus pre-treated and installed, is subjected to constraint recovery testing under three characterization modes (constant stress, fixed support and elastic bias), as shown as a function of temperature in Figure 4. When thermomechanical cycling is repeated, an evolution of the material behavior is observed. Taking the behavior at the 200th cycle as the stabilized behavior, the results of this testing are plotted in the strain-stress space in figure 7, where two envelope curves are added to delimit the working space for a given active element: (a) the “actuator hot curve” which determines the SMA element equilibrium position in austenitic state, and (b) the “actuator cold curve”, which determines the SMA element equilibrium position in martensitic state, for variable bias conditions.

![Figure 7: Results of SMA active element three-mode testing (after 200-cycle testing)](image)

**DESIGN DIAGRAM AND EXAMPLE OF APPLICATION**

To select an adequate geometry (cross-section and length) for a linear SMA active element connected in series with an elastic bias element (see design schematics in Figure 2), it is necessary to build a so-called design diagram.

First, the SMA testing results presented in the strain-stress space ($\Delta \varepsilon$, $\Delta \sigma$) (figure 7) are converted to force-displacement units using the known geometry of the SMA samples (length, 70 mm, cross-section, 0.7 mm$^2$).

Secondly, we consider that the flexible skin of the morphing wing made of a 5-ply composite laminate requires a force of 2000 N to produce a displacement of 5 mm. The use of the cam-based transmission system shown in Figure 2 (friction losses are neglected), decreases the force required from an actuator by a factor of 3, while multiplying its stroke by the same factor of 3, which yields a force of 667 N be applied at the end of a 15 mm stroke. Given that an active element having a length of 70 mm and a cross-section of 0.7 mm$^2$, and connected with such a flexible structure should deliver $\Delta F_{\text{act}} = 65$ N to produce a displacement of $\Delta l_{\text{act}} = 1.8$ mm (see equilibrium point, Figure 8a), its cross-section and length should be scaled-up approximately tenfold in order to meet the application requirements (Figure 8b).
Figure 8: SMA actuator design diagram (a) and its scaling up (b)

CONCLUSION

The work presented in this paper focuses on the design of SMA actuators for use in a morphing wing structure. First the post-deformation annealing and assembly conditions of an active SMA element are optimized taking into account the density of mechanical work produced and the stability of actuation behavior. Secondly, the constraint recovery testing of an active SMA element is performed using (a) a constant-stress, (b) a fixed support and (c) an elastic bias testing modes. Third, to build a design diagram, the stress-strain diagrams representing the SMA active element behavior of the bias element (flexible skin) are combined on a single graph. Finally, to illustrate the design approach adopted, we select an adequate geometry of the SMA active element (cross-sectional area and length) connected to a specific morphing wing structure.

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REFERENCES