THEORETICAL AND EXPERIMENTAL STUDY ON SHAPE MEMORY ALLOY TORSION ACTUATOR

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Abstract

Shape memory alloy (SMA) torsion actuator is one of the key issues in actuator technologies for adaptive wings. Nickel-Titanium alloy wire is sort of SMA in common use, and it possesses special mechanical property. SMA torsion actuator has been made up of NiTi wires and a thin-walled tube, and it can yield torsion deformation and moment, thus can manage the wing spanwise torsion.

In this paper, the primary mechanical model of SMA torsion actuator is established, the relationship between torsion angle of the tube and the temperature is analyzed theoretically and verified by experiments, and optimum parameters for SMA actuators are discussed. In an experimental system, the AOA of a wing model connected with SMA torsion actuator can be changed continuously up to 15°, and good agreement is obtained between analytical and experimental data. The research is important for adaptive wing design, adaptive airfoil control and structural analysis in the future.

1 Introduction

New developments in smart materials and structures have made adaptive wing possible in near future. The camber and angle of attack (AOA) of adaptive wing can be continuously changed by strain actuators [1], this may promise a significant improvement in aerodynamic performance in flight conditions.

The key of adaptive wings depends on actuating technologies, in which SMA torsion actuator is an important research content. SMA wires with plastically elongated, characterized by: (a) the shape memory effect, in which SMA can be plastically deformed in its martensite phase, then restored to the original shape by heating them above the austenite phase transformation temperature, (b) large and variety of deformation available, (c) great recovery force if they are restrained during phase transformation, once bound on tubular structure, can form SMA torsion actuator. Heating SMA and making use of the recovery strain during phase transformation can produce torsion deformation in a tubular structure, and finally cause a wing model connected to a torsion actuator to deform. Therefore, it is of vital importance to establish the mechanical model of SMA torsion actuator under the excited state and analyze the structural deformation pattern in order to achieve the adaptive control of a wing figure.

2 The Mechanical Model of SMA Torsion Actuator

SMA torsion actuator has been made up of NiTi SMA wires and a thin-walled tube, in which the same diameter NiTi wires are unwounded and bounded on the surface of the thin-walled tube angled α to its generatrix and with constant spaces. As the NiTi wires are symmetrically arranged, no bending deformation but compression and torsion deformation will occur to the torsion actuator.

Assumptions in analysis are following:

(1) considering a SMA wire strain along its axis, neglecting the bending effect;

(2) uniform distribution of stress and shear stress in a cross-section of a thin-walled tube;

(3) no relative slide between NiTi wires and tube wall.

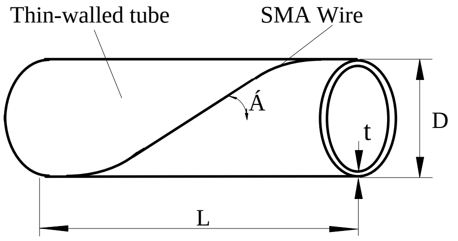

Figure 1. SMA torsion actuator diagram

Geometric parameters of the thin-walled tube include *t* thickness of the tube, *D* outside diameter, and *L* tube length. SMA wires are evenly spaced on surface of the thin-walled tube, d_s is the diameter of SMA wires, *N* the number of wires, and α the angle included between a SMA wire and a generatrix of the tube. The equilibrium equations of the SMA torsion actuator in a cross-section can be expressed as:

$$N\frac{\pi d_s^2}{4}\sigma_s\cos\alpha-\pi Dt\sigma=0 \tag{1}$$

$$\pi Dt\tau\frac{D}{2}-N\frac{\pi d_s^2}{4}\sigma_s\sin\alpha\frac{D}{2}=0 \tag{2}$$

where σ and τ correspond to stress and shear stress in a cross-section of the thin-walled tube respectively, σ_s is stress in a SMA wire cross-section.

The constitutive relationship of the thin-walled tube is given by:

$$\sigma=E\varepsilon \tag{3}$$

$$\tau=G\gamma \tag{4}$$

where E and G represent elastic modulus and shear elastic modulus of the thin-walled tube respectively, ε and γ are strain and shear strain.

The constitutive equation of a SMA wire is as follows[2]:

$$d\sigma_s=E_s d\varepsilon_s+\Theta dT+\Omega d\xi \tag{5}$$

where

$$d\xi=\frac{\partial\xi}{\partial T}dT+\frac{\partial\xi}{\partial\sigma_s}d\sigma_s \tag{6}$$

Substituting Eq.(6) into Eq.(5) results in:

$$E_s d\varepsilon_s=\left(1-\Omega\frac{\partial\xi}{\partial\sigma_s}\right)d\sigma_s-\left(\Theta+\Omega\frac{\partial\xi}{\partial T}\right)dT \tag{7}$$

where E_s is SMA elastic modulus, Ω phase transformation coefficient, Θ thermoelastic coefficient, ξ martensite volume fraction, T temperature.

The deformation coordinate relationship between the thin-walled tube and SMA wires can be described by:

$$\varepsilon_s=\varepsilon_\alpha=\frac{\mu-1}{2}\varepsilon-\frac{1+\mu}{2}\varepsilon\cos2\alpha+\frac{\gamma}{2}\sin2\alpha \tag{8}$$

Eq.(8) shows that the SMA strain ε_s should conform to the thin-walled tube strain ε_α in the direction of α. The tube torsion angle φ is expressed as:

$$\varphi=\frac{2L}{D}\gamma \tag{9}$$

Utilizing Eq.(9) and differentiating Eq.(8) bring about:

$$d\varepsilon_s=d\varepsilon_\alpha=\left(\frac{\mu-1}{2}-\frac{1+\mu}{2}\cos2\alpha\right)d\varepsilon+\frac{D}{4L}\sin2\alpha d\varphi \tag{10}$$

Substituting Eq. (3) and Eq. (4) into Eq. (1) and Eq. (2), and differentiating, $d\sigma_s$ and $d\varepsilon$ are solved as:

$$d\sigma_s=\frac{2GD^2t}{Nd_s^2L\sin\alpha}d\varphi \tag{11}$$

$$d\varepsilon=\frac{GD\cos\alpha}{2EL\sin\alpha}d\varphi \tag{12}$$

Substituting Eq. (10), Eq. (11) and Eq. (12) into Eq. (7) can yield:

$$\left(\Theta+\Omega\frac{\partial\xi}{\partial T}\right)dT=\left(1-\Omega\frac{\partial\xi}{\partial\sigma_s}\right)\frac{2GD^2t}{Nd_s^2L\sin\alpha}d\varphi-\frac{E_sD}{4L}\left[2(\mu\sin^2\alpha-\cos^2\alpha)\frac{G\cos\alpha}{E\sin\alpha}\right]d\varphi+\sin2\alpha d\varphi \tag{13}$$

Eq.(13) displays the relationship between temperature increment and torsion angle increment, and during heating or cooling, the relative change of torsion angle between two ends of the SMA torsion actuator can be determined by it.

NiTi SMA phase transformation possesses three stages [3]:

The first stage, before the phase transformation, the martensite fraction is not changed under the condition of determinate temperature and stress:

$$\frac{\partial \xi}{\partial T} = \frac{\partial \xi}{\partial \sigma_s} = 0 \qquad (14)$$

The second stage, during the phase transformation, temperature and stress cause the change of martensite fraction :

$$\frac{\partial \xi}{\partial T} = -\frac{\xi_0}{A_f - A_s} \qquad (15)$$

$$\frac{\partial \xi}{\partial \sigma_s} = \frac{\xi_0}{C_A(A_f - A_s)} \qquad (16)$$

where A_f is austenite phase finish temperature, A_s austenite phase start temperature, C_A stress influence coefficient related to stress induced transformation, ξ_0 initial martensite fraction of SMA.

The third stage, phase transformation finishes:

$$\xi = 0 \qquad (17)$$

Substituting $\frac{\partial \xi}{\partial T}$ and $\frac{\partial \xi}{\partial \sigma_s}$ in three stages into Eq.(13) leads to following relations:

$$AdT = Bd\varphi \qquad (18)$$

where A is the parameters related to NiTi wire property, B parameters related to the sizes and property about the thin-walled tube and NiTi wire.

In first and third stages (before and after phase transformation), A and B are derived as follows :

$$A = \frac{\Theta}{E_s} \qquad (19)$$

$$B = \frac{2GD^2 t}{Nd_s^2 L \sin\alpha} - \frac{D}{4L}\left[2(\mu \sin^2\alpha - \cos^2\alpha)\frac{G\cos\alpha}{E\sin\alpha} + \sin 2\alpha\right] \qquad (20)$$

In second stage (during phase transformation): A and B can be described:

$$A = \frac{1}{E_s}\left(\Theta - \frac{\Omega\xi_0}{A_f - A_s}\right) \qquad (21)$$

$$B = \left[1 - \frac{\Omega\xi_0}{C_A(A_f - A_s)}\right]\frac{2GD^2 t}{Nd_s^2 L \sin\alpha} - \frac{D}{4L}\left[2(\mu \sin^2\alpha - \cos^2\alpha)\frac{G\cos\alpha}{E\sin\alpha} + \sin 2\alpha\right] \qquad (22)$$

The number of SMA wires is a function of α:

$$N = \frac{\pi D \cdot \cos\alpha}{d_s} \qquad (23)$$

in calculation, N is chosen integer, just even.

From Eq.(18) to Eq.(23), the relationship between torsion and temperature of SMA torsion actuator can be determined during the heating process.

3 The Experimental Results of SMA Torsion Actuator

In experiment, one end of SMA torsion actuator is restrained, the other is free and with a reflected mirror. Torsion angle of the actuator is measured with deflexion of laser beam when the actuator is heated. The experimental and calculation results are shown as Figure 2 and 3. In the experiments and analyses, the thin-walled tube parameters are: E=120 GPa, G=45 GPa, L=500mm, D = 20mm, t =0.1mm, N=60, α=45°. NiTi SMA parameters include: d_s=0.2mm, E_s=26.3MPa, A_s=38°C, A_f=63°C, Ω= -490 MPa, Θ= -0.1MPa, C_A=2.5 MPa, ξ_0=0.6.

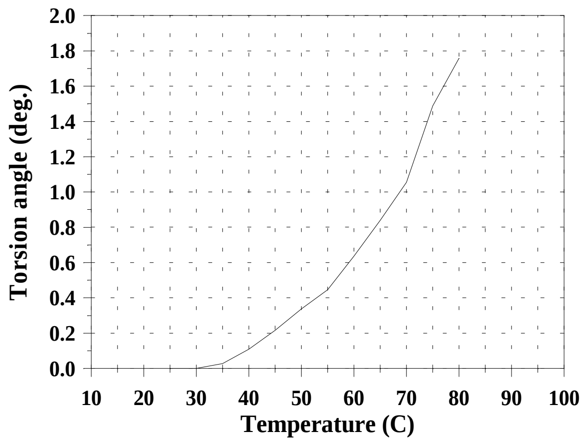

Figure 2. The experimental results about torsion angle and temperature

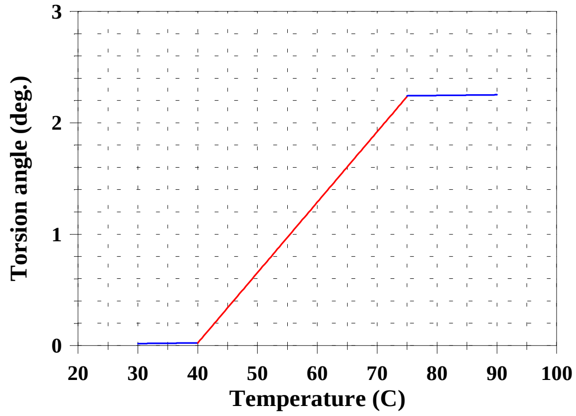

Figure 3. The theoretical relationship between torsion angle and temperature

The experiment of SMA torsion actuator can be easily repeated. Compared the experimental results with theoretical analyses, it is found that the torsion angle of the torsion actuator changes in non-linear way with the rise in temperature. Both conforming in numerical value, with a maximum of 1.6 degrees, but there is bigger deviation in the intermediate stage (namely in the phase transformation process of NiTi wires). The main reason is that in numerical value simulation, there exists the difference between constitutive relationships and reality of NiTi wires; several physical parameters of the NiTi wires are not accurate enough; and changes of E_s and torsion stiffness (including adhere layer) of the torsion actuator are not taken into consideration.

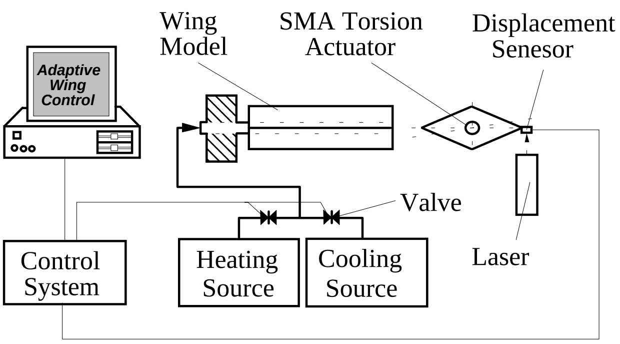

Figure 4. Adaptive wing model experimental system with a SMA torsion actuator

Figure 4 shows an adaptive wing model experimental system with a SMA torsion actuator. When the actuator is heated, the deflexion of the aluminum-skinned wing model will occur, and its AOA can be continuously changed. When the actuator cooled by liquid nitrogen, the model AOA returns to its original position. The experimental system is computer-controlled, the AOA change of the wing model can reach 15 degrees, and the duration of one action cycle is about 10 seconds.

4 Conclusions

This paper is to show that it is possible to achieve torsion deformation of driving structures by using the physical properties of NiTi SMA wires. The deformation degree of the torsion tube can be increased by more SMA wires and optimizing its structural parameters. However, in order to predict the driving property of SMA torsion actuator accurately, there is much work to be done of which modification of constitutive relationships of NiTi SMA wires and accurate measurements of physical parameters of NiTi wires are to be given priority to.

Acknowledgements

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