

Modelling and Experimental Study of Shape Memory Alloys Coil Spring Actuator

Wei LI^{1,a}, Da-Min CAO¹, Qing-Ying LI¹ and Hui YANG¹

¹School of Air Transportation / Flying, Shanghai University of Engineering Science, No.333, Longteng Street, Shanghai, China

Keywords: Shape memory alloys, Coil spring, Design, Modelling, Experimental study.

Abstract. Most of shape memory alloys (SMAs) are functional intermetallic. They are now practically being used for couplings, actuators, medical guide wires etc. And are hopeful candidates for smart materials, which already exist. Several papers review the latest developments in the modelling of SMAs constitutive behavior. The basic properties of SMAs are including the shape memory effect, pseudoelasticity, as well as other properties such as the acquired and two-way shape memory effect, damping capacity and fatigue life. This paper focus on the modelling of SMAs coil spring actuators, which are used as artificial muscle for its light weight and large deformation. In order to obtain the required force, the shear modulus method has been used in the modelling process. And the parameters of SMAs coil spring can be determined. The theoretical analysis accords well with experiment results.

Basic Properties of Shape Memory Alloys

Shape memory alloys (SMAs) are metallic alloys that can undergo martensitic phase transformations as a result of applied thermomechanical loads and are capable of recovering permanent strains when heated above a certain temperature. At high temperatures the crystal lattice is in a high symmetry, parent austenitic phase. The key characteristic of all SMAs is the occurrence of a martensitic phase transformation between the austenitic phase and the different variants of the low temperature, low symmetry martensitic phase. The martensitic transformation is a shear-dominant diffusionless solid-state phase transformation occurring by nucleation and growth of the martensitic phase from the parent austenitic phase [1]. What make SMAs remarkably different from other materials are primarily the shape memory effect (SME) and pseudoelasticity, which are associated with the specific way the phase transformation occurs.

When a shape memory alloy undergoes a martensitic phase transformation, it transforms from its high-symmetry, usually cubic austenitic phase to a low-symmetry martensitic phase, such as the monoclinic variants of the martensitic phase in a Ni-Ti SMA. In the absence of applied stresses, the variants of the martensitic phase usually arrange themselves in a self-accommodating manner through twinning, resulting in no observable macroscopic shape change. By applying mechanical loading, the martensitic variants are forced to reorient (detwin) into a single variant leading to large macroscopic inelastic strains. After heating above certain temperature, the martensitic phase returns to the austenitic phase, and the inelastic strains are recovered. This behavior is known as the SME. Pseudoelasticity is observed when the martensitic phase transformation is induced by applied thermomechanical loading of the austenitic phase in which case detwinned martensite is directly produced from austenite. The process is associated with large inelastic (transformation) strains which are recovered upon unloading due to the reverse phase transformation [2]. The extensive list of alloys exhibiting SME and pseudoelasticity includes the Ni-Ti alloys, and many copper-, iron-, silver and gold-based alloys [4].

Martensitic transformations are usually divided into two groups—thermoelastic and non-thermoelastic. The non-thermoelastic transformations occur mainly in ferrous alloys and are associated with non-mobile martensite-parent phase interfaces pinned by permanent defects and proceed by successive nucleation and growth. Due to re-nucleation of austenite during the reverse (martensite to austenite) transformation, these transformations are crystallographically non-reversible in the sense that the martensite cannot revert to the parent phase in the original

orientation. The thermoelastic martensitic transformations, on the other hand, are associated with mobile interfaces between the parent and martensitic phases. These interfaces are capable of “backward” movement during the reverse transformation by shrinkage of the martensitic plates rather than nucleation of the parent phase, which leads to a crystallographically reversible transformation [4]. The unique properties of SMAs (i.e., shape memory effect, pseudoelasticity) are the result of thermoelastic martensitic transformation. Summarized below are the main characteristics of martensitic phase transformations that distinguish them among other solid-state transformations:

1. It is associated with an inelastic deformation of the crystal lattice with no diffusive process involved. It results from a cooperative and collective motion of atoms over distances smaller than the lattice parameters. The absence of diffusion makes the martensitic phase transformation almost instantaneous [3].

2. Parent and product phases coexist during the phase transformation, since it is a first order transition, and as a result there exists an invariant plane, which separates the parent and product phases. The lattice vectors of the two phases possess well defined mutual orientation relationships [5], which depend on the nature of the alloy.

3. Transformation of a unit cell element produces a volumetric and a shear strain along well-defined planes. The shear strain is many times larger than the elastic distortion of the unit cell. This transformation is crystallographically reversible [6].

4. Since the crystal lattice of the martensitic phase has lower symmetry than that of the parent austenitic phase, several variants of martensite can be formed from the same parent phase crystal [7].

5. Stress and temperature have a large influence on the martensitic transformation. Transformation takes place when the free energy difference between the two phases reaches a critical value [8].

Modelling of SMAs Coil Spring

Deformation Principles of SMAs Coil Spring

When the power is applied, the temperature of SMAs coil spring rises. And phase transition of SMAs coil spring occurs when the temperature is above T_A s (the temperature which austenite transformation begins), which leads to SMAs coil spring recovering the “memory” shape. As a result, the SMAs coil spring contracts back from $L_0 + \delta$ to L_0 . Conversely, when the power is removed, the temperature of SMAs coil spring decreases to T_M s (the temperature which martensite transformation begins), due to the cooling effect of working medium, Consequently, a SMAs coil spring with two-way shape memory effect lengthens to $L_0 + \delta$, while a SMAs coil spring with one-way shape memory effect needs an external force to lengthen to $L_0 + \delta$. Switching on and off the power alternately can control the SMAs coil spring with expansion deformation, as shown in Figure 1.

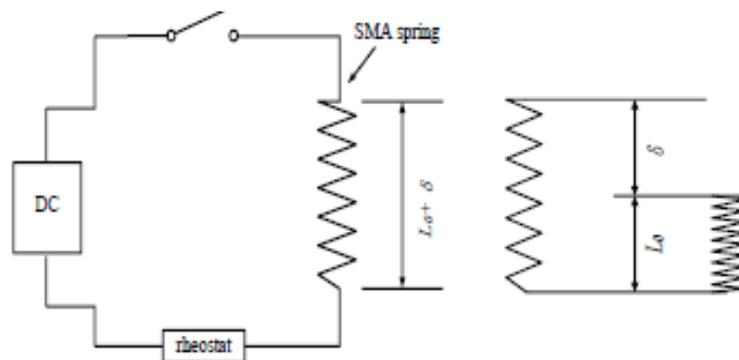


Figure 1. Deformation principles of SMAs coil spring.

Fundamental Equation of States for SMAs Coil Spring

The mechanical properties of SMAs coil spring are different from ordinary coil spring by the reason of shape memory effect (SME) and pseudoelasticity. These differences are as follows:

(1) The stress-strain curve of ordinary coil spring follows linear relationship. But SMAs coil spring follows non-linear relationship.

(2) The mechanical properties of ordinary coil spring have nothing to do with temperature. But the properties of SMAs coil spring are related to the temperature.

(3) For ordinary coil spring, the loading curve coincides with the unloading curve. But the coincidence relationship is inexistence for the SMAs coil spring. Generally, it appears hysteresis of phase transformation or temperature.

The fundamental properties of SMAs include phase transformation recovery force, strain, and temperature. From a physical standpoint, the SMAs coil springs meet the equation:

$$\tau = \tau(\gamma, T) \quad (1)$$

where τ is the shear stress, γ is the shear strain, and T is the temperature.

From a statics standpoint, the SMAs coil springs are following the equation:

$$PD/2 = \int_A \tau(\gamma, T) r dA \quad (2)$$

where P is the load of SMAs coil spring, D is the mean diameter of coil, and r is the radius of the spring wire.

From a geometry standpoint, the SMAs coil springs are following the equation:

$$\delta = D/2 \int_s 2\gamma / ds \quad (3)$$

where δ is the amount of elastic deformation of the SMAs coil spring, d is the diameter of the spring wire, and s is the length of the spring wire.

In a practical application, there are three state and corresponding equation about SMAs coil spring. They are as follows:

(1) Isothermal state and isothermal equation of state

$$\frac{\partial \omega}{\partial \gamma_{\max}} = \frac{\pi n D^3}{d^4} \left(\frac{\partial P}{\partial \delta} \right) \quad (4)$$

where $\omega = PD/d^3$, and n is the number of coils.

(2) Iso-load state and iso-load equation of state

$$\frac{\partial \omega}{\partial T} = \frac{d}{\pi n D^2} \left(\frac{\partial \delta}{\partial T} \right) \quad (5)$$

(3) Iso-strain state and iso-strain equation of state

$$\frac{\partial \omega}{\partial T} = \frac{D}{d^3} \left(\frac{\partial P}{\partial T} \right) \quad (6)$$

Design and Modelling for SMAs Coil Spring

Shear modulus method can be used for SMAs coil spring design in this paper [9]. The shear modulus G of SMAs is related to temperature. But for Nitinol, G is almost steady in low and high temperature. The shear modulus of high temperature G_H takes 25GPa, and shear modulus of low temperature G_L takes 7.5GPa. If working stroke δ , external loads in high temperature F_H and in low temperature F_L are given, parameters of the SMAs coil spring can be defined as follows:

(1) Determine the maximal shear strain γ_{\max} .

γ_{\max} depends on cycle life of SMAs coil spring. The longer the cycle life is, the smaller the γ_{\max} is. If the cycle life is 1 million times, γ_{\max} takes 0.8%, if the cycle life is tens of thousands times, γ_{\max} takes 1.5%. Due to G_L is smaller than G_H , γ_L is larger than γ_H under same external loads. Generally, $\gamma_{\max} = \gamma_L$.

(2) Calculation for the shear strain in high temperature γ_H .

$$\gamma_H = \frac{F_H G_L}{F_L G_H} \gamma_L \quad (7)$$

(3) Calculation for the shear stress in high temperature τ_H .

$$\tau_H = \gamma_H G_H \quad (8)$$

(4) Choose the spring index C , generally $C = 6$. Thereby, stress correction factor k can be given as follows:

$$k = \frac{4C-1}{4C-4} + \frac{0.615}{C} \quad (9)$$

(5) Calculation for the diameter of the spring wire d , and the mean diameter of coil D .

$$d = \sqrt{\frac{8kF_H C}{\pi\tau_H}} \quad (10)$$

$$D = Cd \quad (11)$$

(6) Calculation for the number of coils n .

$$n = \frac{\delta d}{\pi\Delta\gamma D^2} \quad (12)$$

where $\Delta\gamma$ is difference between γ_H and γ_L , and $\Delta\gamma = \gamma_L - \gamma_H$. Therefore, the geometric parameters of SMAs coil spring have been obtained.

A SMAs coil spring has been designed and fabricated in this paper. It is made of NiTiNol wire, and the geometric parameters are as follows: $d=0.5\text{mm}$, $D=3\text{mm}$, $n=14$, $\delta=65\text{mm}$. Furthermore, a setting process of heat treatment is also needed in order to fix original shape of SMAs coil spring.

Experimental study of SMAs Coil Spring

A mechanical experiment has been carried out for the SMAs coil spring, on the conditions of 25 °C room temperature and 65% humidity. One side of SMAs coil spring is fixed in the test bench, and the other side of SMAs coil spring is connected to the force sensor which measuring the phase transformation recovery force. And the temperature of SMAs coil spring is measured by infrared thermometer which is SMART SENSOR AR300, has a measuring range of -32~300 °C, measuring accuracy of ± 2 °C, and resolution ratio of 0.1 °C.

Electro-Thermal Properties of SMAs Coil Spring

Figure 2 shows the experiment for the electro-thermal properties of SMAs coil spring. The relation between exciting current I and temperature T is shown in Figure 3. Experimental result shows that T rises with the increase of I in temperature rise and fall period.



Figure 2. Experiment for the electro-thermal properties of SMAs coil spring.

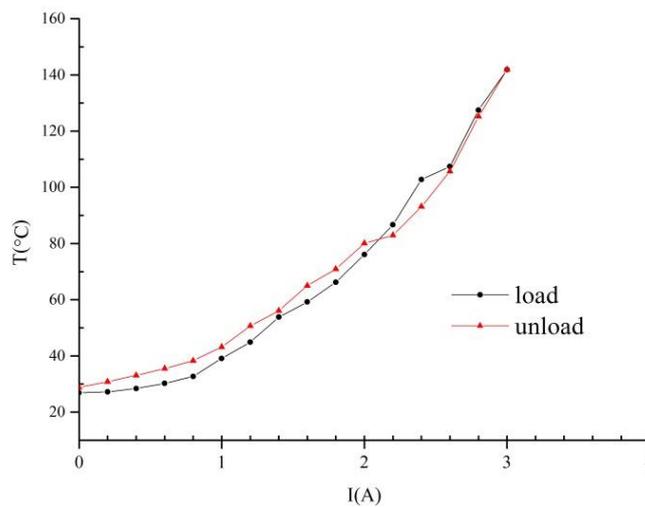


Figure 3. Relation between I and T

Electro-Force Properties of SMAs Coil Spring

Figure 4 shows the experiment for the electro-force properties of SMAs coil spring. The relation between exciting current I and shape recovery force FSME is shown in Figure 5. If I is less than 0.4 A, there is no shape recovery force because of temperature below T_A s. However, FSME of 0.098 N is produced by SMAs coil springs when I reaches 0.5 A. Meanwhile, phase transition occurs and temperature of SMAs coil springs is 30.2 °C. Whereafter, FSME increases gradually with the augmentation of I . The maximum FSME is 5.488 N at 2.4 A, 102.8 °C. In loading process, FSME rises rapidly in the variation of I from 0.8 A to 1.4 A. Subsequently, FSME decreases gradually with the reduction of I . The minimum FSME is 2.352 N at 0 A, 25 °C, rather than 0 N, due to one-way shape memory effect.



Figure 4. Experiment for the electro-force properties of SMAs coil spring.

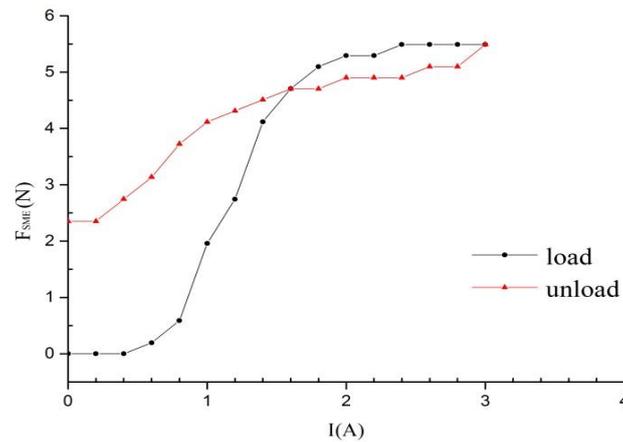


Figure 5. Relation between I and FSME

Conclusions

SMA coil springs are often used as artificial muscle for its light weight and large deformation. This paper focus on the design and modelling of the SMA coils spring actuators. The shear modulus method has been used in the modelling process to obtain the required SME force. According to the modelling process, a SMA coil spring has been designed and fabricated in this paper, which is made of NiTiNol wire, and has 0.5mm of wire diameter, 3mm of mean diameter of coil, 14 of the coil number, as well as 65mm of working stroke.

Experimental study of SMA coil spring has been carried out, which includes electro-thermal and electro-force properties, to prove the validity of the modelling. The experimental result shows that the maximum SME force of SMA coil spring is 5.488 N at 2.4 A, 102.8 °C.

Acknowledgement

This paper is funded by Shanghai Municipal Education Commission Research Foundation (No.ZZGCD15048) and Scientific Research Foundation of Shanghai University of Engineering Science (No. E3-0501-16-01095)

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