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A computational and experimental study of shape memory alloy spring actuator

Abstract*. The paper presents the combined experimental and computational study of the shape memory alloy (SMA) spring actuator. The design strategy for a system composed of two springs: a SMA spring and a steel spring has been presented. The force versus stroke characteristics of designed system at high and low temperature condition have been calculated and measured. The electro-thermo-mechanical characterization of SMA spring has been carried out. The selected results of calculation and laboratory tests of the designed spring system have been given.*

Streszczenie. *W pracy przedstawiono wyniki obliczeń i badań eksperymentalnych siłownika sprężynowego wykonanego ze stopu z pamięcią kształtu. Omówiono zaproponowaną strategię projektowania systemu składającego się z dwóch sprężyn: sprężyny SMA i sprężyny stalowej. Wyznaczono i zmierzono charakterystykę siły w funkcji przesunięcia dla stanu wysoko i niskotemperaturowego. Zaprojektowano specjalne stanowisko pomiarowe do badań elektro-cieplno-mechanicznych sprężyny SMA i układu złożonego ze sprężyny SMA i sprężyny stalowej. Przedstawiono wybrane wyniki obliczeń i badań laboratoryjnych zaprojektowanego układu sprężyn (**Modelowanie i eksperymentalne badania siłownika sprężynowego wykonanego ze stopu z pamięcią kształtu**).*

Keywords: shape memory alloys (SMA), spring actuator, extension/compression spring.
Słowa kluczowe: stopy z pamięcią kształtu (SMA), siłownik sprężynowy, sprężyna naciągowa/naciskowa.

Introduction

Shape memory alloys (SMA), according to their ability to revert to their programmed shape through thermal activation have a great potential for a wide range of actuator application [1, 2, 3, 4]. The SMA have two stable phases: the high-temperature phase, called austenite and the low-temperature phase, called martensite. In addition, the martensite phase can be in one of two forms: twinned and detwinned [1, 2]. The phase transformation taking place between austenite phase and martensite phase during heating or cooling is the basis of the special properties of SMA. The primary effects of SMA related to the phase transformation are pseudoelasticity and shape memory effects [1]. The pseudoelasticity occurs when the low-temperature phase transformation is caused by stresses at a constant temperature. This effect applies for most of nowadays shape memory applications in the field of medical devices [3]. The shape memory effects are related to the material's ability, initially deformed in the low-temperature phase, to regain its original shape when heated to the high temperature phase. The shape memory effects may be one-way or two-way effects [1, 2]. Two methods can be used to ensure the necessary reversible shape memory effect i.e. intrinsic and extrinsic. Intrinsic methods rely on the modification of the material's microstructure, so that some orientations of martensitic variations are preferably nucleated after cooling. The intrinsic methods are also called training processes [2]. Extrinsic methods rely on adding an additional external component to the SMA material that provides the necessary stress to induce stress-oriented variants [2]. The overview of SMA effects has been presented in Fig. 1.

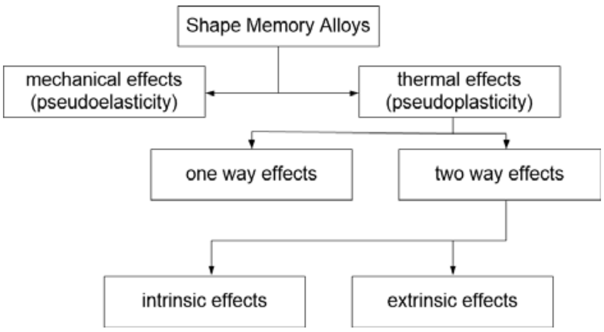


Fig.1. Overview of shape memory alloy effects

The shape memory effects of SMA allow it to be used as actuators. Due to reproducible reversible deformation the extrinsic two-way effects are in special interest for actuator applications. The actuation of the SMA actuators can be achieved by methods such as Joule heating, fluidic actuation, electromagnetic heating, RF electromagnetic actuation, and laser actuation [1, 2].

The SMA based actuators can be easily formed into various shapes. The most popular shapes are spring, wire, ribbon and sheet [1, 3, 5]. The SMA springs have a much higher recoverable strain compared to the others SMA shapes. In the paper the electro-thermo-mechanical characteristics of the reversible shape memory effect SMA spring have been investigated. The SMA springs have been actuated by passing electric current through them. A prototype of linear actuator with SMA spring and a biasing steel spring has been demonstrated.

SMA spring actuator design

- **Manual fabrication of SMA springs**

The SMA springs can be used for both compression and extension. The SMA spring behaviour depends on the temperature of the spring. As illustrated in Fig. 2a, the extension spring at low temperature is extended, but at high temperature is compressed providing a pulling force. A tightly coiled extension spring it means that the shape has been remembered at high-temperature phase. The compression spring at low temperature is compressed, but at high temperature extends providing a pushing force (Fig. 2b).

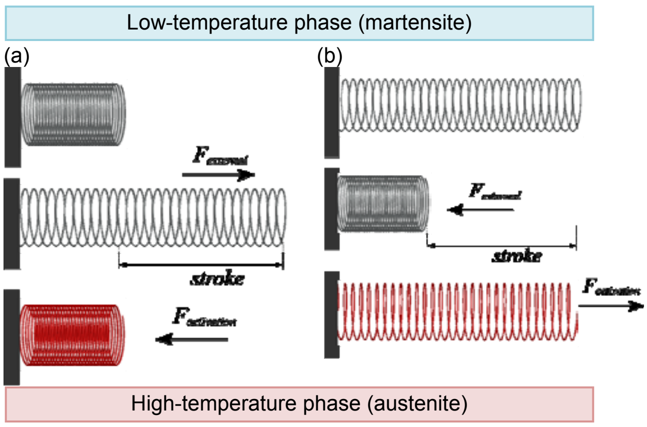


Fig.2. The SMA spring: a) extension spring, b) compression spring

In the design procedure of the SMA spring, the aim is to arrive at the spring wire diameter (d) the mean diameter of the coil (D) and the number of coils (n) for a spring that will provide the required force (F) and a stroke (s) in a complete actuation cycle. The proper values of shear modulus (G_A) in the austenite phase and (G_M) in the martensite phase, the maximum shear stress (τ), shear stress in the austenite phase (τ_A), and shear stress in the martensite phase (τ_M) are the input parameters in this design procedure. The force generated by the spring in austenite phase can be expressed as follows [1, 2]:

$$F_A = \frac{d^4 G_A}{8nD^3}\delta_A \tag{1}$$

where δ_A is the linear deflection of the spring in the austenite phase.

The detailed design procedure of SMA spring has been described in previous work [6]. The in house software for designing calculation of SMA spring has been elaborated. Manual fabrication is a good way to produce many prototypes of the SMA springs in a relatively short time and at low cost. A several sample SMA springs have been designed and fabricated using commercially available Ni-Ti wire. To memorize the desired shape, the springs have been maintained at 500°C for 30 minutes inside industrial oven. After this time, the springs have been quenched with water. Finally, good quality SMA springs have been obtained with repeatable and stable properties.

- **The mathematical model for the stroke – temperature hysteresis of a SMA spring**

The analysis, design and optimization of the SMA spring are significantly dependent on the knowledge of the thermal hysteresis loop. There are many approaches to develop a mathematical model describing the thermo-mechanical hysteresis [7, 8, 9, 10]. In the paper we focus on the model adapted from the limiting loop proximity (L2P) hysteresis. The L2P model was originally developed for magnetic hysteresis [9]. The stroke – temperature hysteresis can be described as follows:

$$s(T) = \frac{H_h}{\pi}\left[\arctan\left(\beta\left(\delta\frac{H_w}{2} + T_c - T\right)\right) + \frac{\pi}{2}\right] \tag{2}$$

where: H_h is the hysteresis loop height, H_w is the hysteresis loop width, β is related with $\mathrm{d}s/\mathrm{d}T$ at T_c, T_c is the critical temperature at the centre of the hysteresis curve, T is the SMA spring temperature, δ is operator defined as 1 or -1.

The combination of the curves s (T, $\delta = +1$) and s (T, $\delta = -1$) refer to the hysteresis loop in the s - T plane.

The hysteresis model can be described by in the form of an algebraic equation, which is easy to implement. The hysteresis model (2) has been simulated in MATLAB/Simulink environment. The more details have been presented in a previous work [10]. The parameters of this model have been determined using an experimental set-up specially built for this test.

If the temperature of the SMA spring cannot be measured directly, then the temperature of the SMA spring can be determined on the basis of the static equation of thermal equilibrium. Assuming that the ambient temperature is constant, the problem is one-dimensional, the load applied to the spring is constant and the volume and surface changes are negligible, the static equation of thermal equilibrium can be expressed as follows:

$$m_s c_p \frac{\mathrm{d}T}{\mathrm{d}t} = \frac{U^2}{R} - h_c A_s (T - T_a) \tag{3}$$

where: m_s is the SMA spring mass, c_p is the specific heat, T is the equivalent SMA spring temperature, U is the voltage, R is the SMA spring resistance, h_c is the equivalent heat convection coefficient. A_s is the convective surface area of the spring, T_a is the ambient temperature. In order to improve the heat transfer model the coefficient h_c can be approximated by a second order polynomial of the temperature, $h_c = h_0 + h_2 T^2$ [10].

The tested SMA springs have been surrounded by air, therefore the heat transfer has been dominated by convection and the radiation can be omitted.

This model allows to determine the curve of heating and cooling of the SMA springs for given value of supply voltage and heat transfer conditions. The temperature of the springs is controlled indirectly by varying the value of electric current passing through them.

The system composed of a SMA spring and a biasing steel spring

Usually a SMA actuator has been composed of actuation element and reversal element. The reversal element can be either a dead-weight or a bias spring or another SMA (antagonist configuration), etc. [1, 2]. In the paper a SMA-spring actuators using as active element electrically driven SMA spring working against to a steel spring have been considered. Figure 3 shows the system composed of a SMA spring and a biasing steel spring.

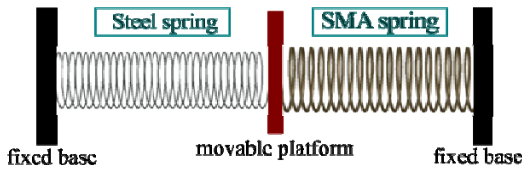


Fig.3. The system composed of a SMA spring and a steel spring

First, both the SMA springs and steel springs are pre-loaded so that the system is pre stressed. In the low-temperature phase, the steel spring can completely compress the SMA spring to its locked length. The heated SMA spring increases stiffness and generates enough force (F_A) to compress the steel spring – see Fig.4. Then, during cooling, the steel spring reacts to a change in the shape of the SMA spring and compresses it. In the low-temperature phase the forces of the steel spring and the SMA spring are balanced (F_{s1}=F_M). During the cooling and heating cycle between the springs there is the two-way motion. In the Fig. 4 the displacement of the movable platform between springs at the high- and the low-temperature phase has been denoted as working stroke Δs. Whereas the difference between the force generated by the SMA spring in austenite phase F_A and force exerted by the biasing spring F_{s2} has been denoted as usable force F_u.

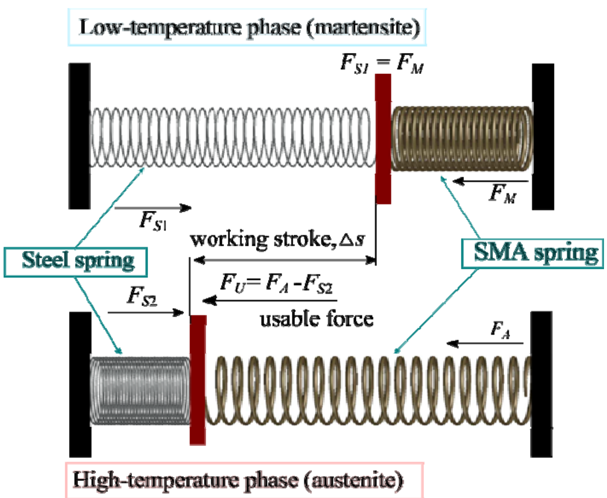


Fig.4. The two-way motion of the two springs system

The software for determining the distribution of forces in a system composed of two springs has been developed in *Microsoft Visual Studio C#*. The main task of this software is designing of a SMA spring actuator operating in a series with a steel spring. In the design model the friction effect is neglected and a linear stress-strain behaviour is assumed. The software user can enter the data (e.g. from a file) describing the parameters of the springs required to calculate the forces acting in the system. The software user can find the calculated values of forces as well as the force vs. stroke characteristics of designed system at high and low temperature condition. The calculated and measured forces have been presented in Fig. 5.

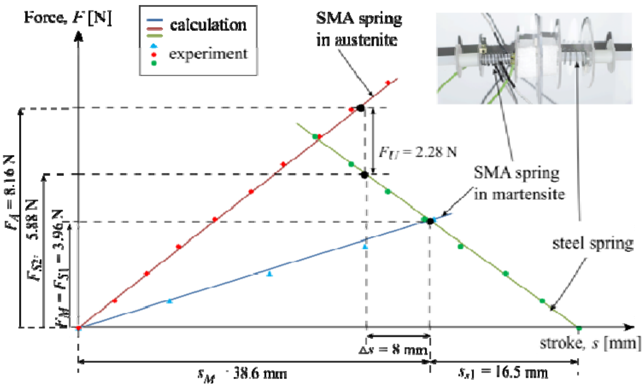


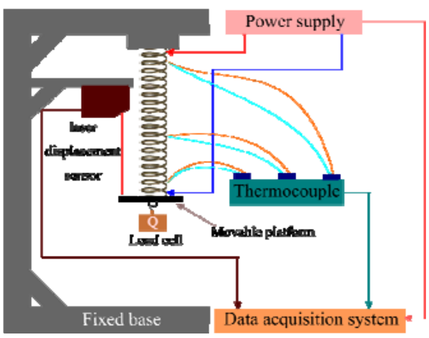
Fig. 5. Force vs. stroke characteristics of two spring system

It can be found that the values calculated by using in house software and obtained by measurements are in satisfactory agreement. Two characteristics (force vs. stroke) can be distinguished for the SMA spring: one for the high-temperature phase and the other for the low-temperature phase. The characteristics of the steel spring has an opposite slope in relation to these characteristics. The intersection of the characteristics of the SMA spring and the steel spring inform about the force and stroke in the equilibrium state of the actuator.

Experimental setup and selected results

In order to verify proposed model for the *s-T* hysteresis loop the SMA extension and compression spring have been investigated. The both type of SMA springs have been fabricated by using Ni-Ti wire. The springs with the following parameters have been tested: (a) extension spring: the wire diameter $d = 0.5$ mm, the mean diameter of the coil $D = 5$ mm, the number of coils $n = 28$, the initial length $l_{SMA} = 52$ mm, (b) compression spring: the wire diameter $d = 1$ mm, the mean diameter of the coil D=10 mm, the number of coils $n = 11$, the initial length $l_{SMA} = 57$ mm. The parameters of hysteresis model needed for calculation can be easily measured through a simple experiment, specially designed for the extension spring and another one for the compression spring. The view of the elaborated laboratory stands have been shown in Fig. 6.

(a)



(b)

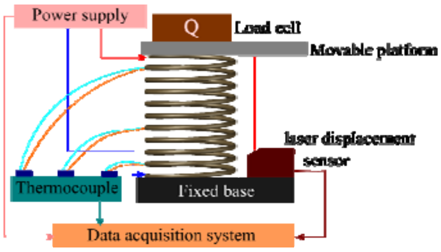


Fig. 6. The experimental setup: a) extension spring, b) compression spring

The SMA spring during the measurements has been heated by a slow-increasing direct electric current. On the other hand the current has been reduced slowly in the cooling cycle and SMA spring has been cooled with natural air convection.The temperature rise in the SMA spring has been monitored using three K type thermocouples as well as thermal camera. The SMA spring has been heated from 25°C to 100°C and again cooled to 25°C and the corresponding stroke values have been noted using the laser displacement sensor. Figure 7 shows the stroke *vs.* temperature hysteresis loops of extension spring at two values of the load as well as selected field distributions obtained from the thermal camera. The stroke *vs.* temperature hysteresis loops of compression spring during the heating and cooling cycle have been presented in Figure 8.

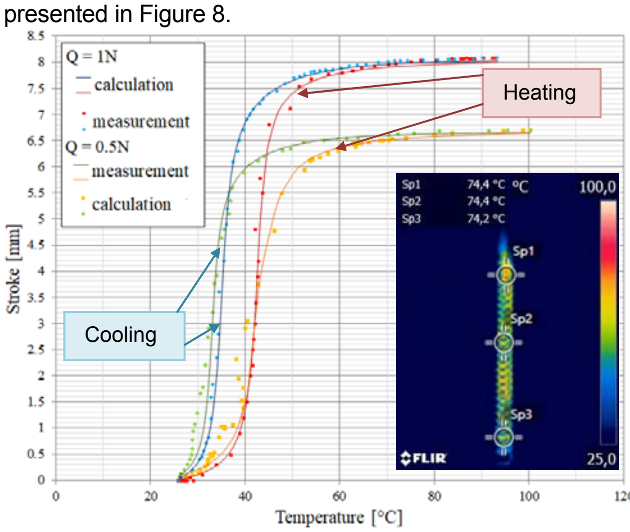


Fig. 7. The stroke - temperature hysteresis and test of the SMA extension spring using thermal camera

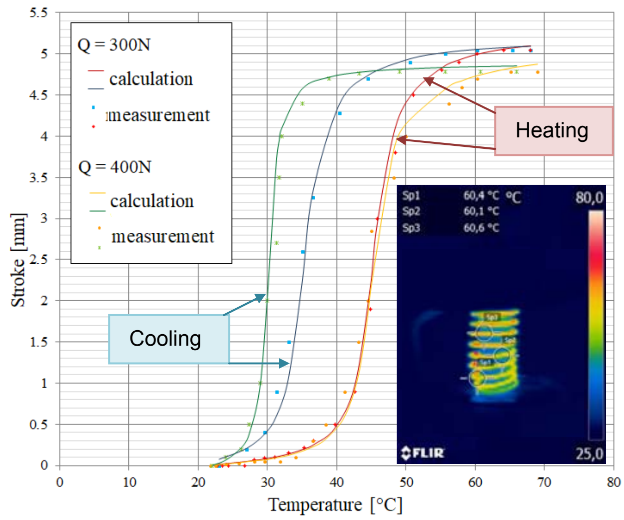


Fig. 8. The stroke - temperature hysteresis and test of the SMA compression spring using thermal camera

It can be noticed that by increasing the applied load the width of the hysteresis loop has been increased. This phenomenon is typical of the SMA's actuators and corresponds to an increase of transformation temperatures as a function of the mechanical loading.

In order to verify proposed model and developed software, the authors designed and built the dedicated experimental setup to study the system composed of a SMA compression spring and a biasing steel spring. The steel spring with the wire diameter of 0.8 mm, the mean diameter of the coil 15 mm, the number of coils 7 and the initial length of 46 mm has been investigated. Figure 9 shows the view of the dedicated experimental setup. To supply the SMA actuator, the QPX600DP power supply (80 V, 50 A) was selected, which enables stabilization of the voltage (U) and the current (I). Both values of U and I are measurable in real-time using digital multimeters. Three K-type thermocouples have been used to measure the spring temperature. The working stroke has been measured by the laser displacement sensor.

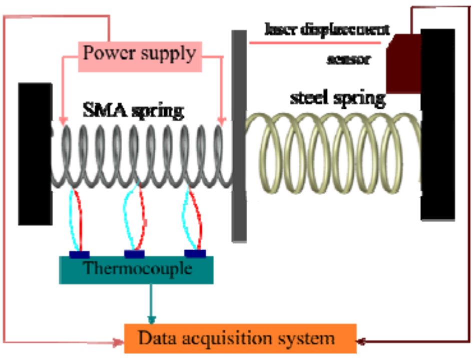


Fig. 9. The experimental setup

The selected dynamic characteristics of the designed spring system determined at the experimental setup have been shown in Fig. 10 and 11.

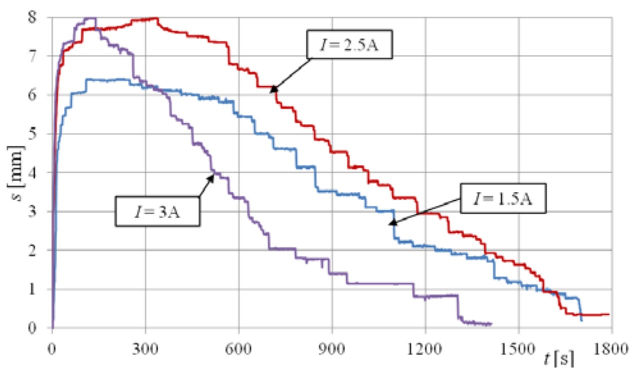


Fig. 10. The stroke waveforms for different values of current

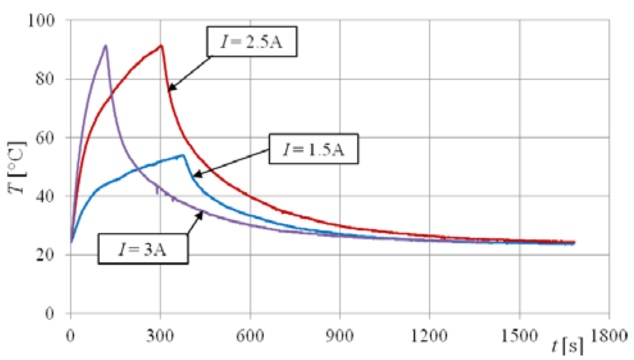


Fig. 11. The waveforms of the temperature for different values of current

The dynamic characteristics have been presented, taking into account changes in the length of the SMA spring and temperature as a function of time with a linearly increasing load and at stepping on and off the current. It has been observed that the response time and maximum stroke considerably depend on the magnitude of the electric current. The response time was longer for a small electric current (I = 1.5 A) and shorter for a larger electric current (I = 3 A). The maximum value of stroke was the same like calculated value of working stroke ($\Delta s = 8$ mm) by using in house software.

Conclusions

The results of the investigation of the electro-thermo-mechanical characterization of SMA spring have been presented and discussed. The mathematical model for the stroke–temperature hysteresis of the SMA spring has been proposed and successfully implemented.

The dedicated software for designing SMA springs and bias spring SMA actuators was elaborated and tested. The validation of in house software was realized using experiment. The force vs. stroke characteristics of designed actuator (SMA spring–steel spring) have been calculated and compared with measurements. The simulation and measurements results are in satisfactory agreement.

The dedicated experimental setups have been designed and built to study the SMA spring actuator performance. The knowledge of dynamics characteristics of the springs system is necessary when designing SMA actuators that will be used to generate vibrations e.g. in energy harvesting system.

The number of different SMA actuators have been fabricated according to the design concept by using proposed approach. It has been found that SMA spring can successfully be employed to provide a linear displacement.

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