Experimental measurements of shape memory alloys wires

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Abstract: Paper deals with examinations of properties of shape memory alloy actuators. Authors describe design of own laboratory stand for obtaining electro-thermo-mechanical characteristics of SMA wires (maximum length 900 mm). The stand allows for semi-automatic measurements of voltage and current (supplying the actuator), temperature of wire and its extension. Data acquisition and control signals are realized by PC computer. All elements of the measuring system are connected by GPIB network (IEEE 488.2 standard). Control program for static measurements was written in G language (LabVIEW environment). Temperature is measured using infrared camera Flir A325. Displacement measurement system contains optical sensor (converting piston movement into series of pulses), pulses counter, PWM signal generator (PWM signal fulfillment is proportional to number of pulses), lowpass filter and buffer conditioning external signal. For dynamic measurements data recording is performed using digital oscilloscope Tektronix MSO 2024 equipped with four separated channels and digital filter. Wide range of examinations of several SMA wires allowed for drawing its exploitative characteristic helpful for practical use. It shows length change of actuator as a function of mechanical load (Fig. 10). Finally some example static as well as dynamic characteristics are presented and short discussion is carried out.

Key words: SMA, martenistic transformation, measuring stand, SMA characteristics

1. Introduction

Shape memory alloys (SMA) belong to modern group of materials called "smart materials". This group of materials becomes more and more popular in recent years. Smart Material is defined as a material for which one or more properties depends on some external parameter. Size and shape of SMA depends on temperature. It seems to be very easy but in fact it is more complicated. According to temperature level SMA can achieve one of two possible crystallographic structures. Low temperature structure is called martensite and high temperature form – Austenite. When temperature changes SMA molecules turn between mertensite and austenite in so called martenistic transformation (direct or reverse trans-

formation). Following the internal, structural change material also changes its macroscopic properties. It can be easily observed as a deformation of shape and size. Thus SMA can generate force or perform mechanical work which means one can use it as an actuator or temperature sensor (it can also act the both roles in the same time). What is particularly important – SMA actuators have powerful force/size (force/mass) factor. It makes them interesting choice in designing of micro machines and robotics actuators.

2. Properties of SMA

SMAs are already well known and described in literature, however controlling of SMA actuators is very difficult because characteristic of martenistic transformation is nonlinear with hysteresis. The transformation starts above some threshold temperature (A_s), which depends additionally on mechanical stress. During reverse transformation (temperature rising) particular molecules transforms into austenite form so material is not homogenous unless temperature reaches next threshold value (A_f) where practically all molecules are transformed to austenite. Direct transformation has different threshold temperatures (M_s and M_f). Thus there is hysteresis seen in the characteristic of transformation (Fig. 1). During transformation not only mechanical properties (length, diameter, toughness) are changing but also electrical resistivity. It makes the precise control of the transformation process very difficult and challenging.
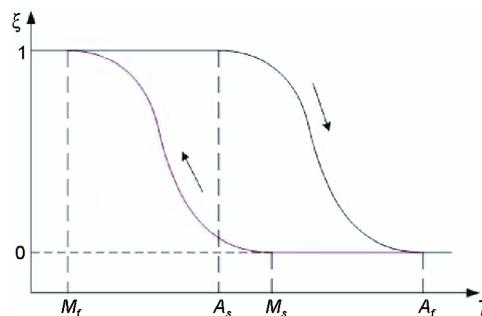

Fig. 1. Thermo-mechanical characteristics of SMA $\xi = f(T)$ [3]

In literature there are a lot of mathematical models for martenistic transformation. Most of them try to describe the physical phenomenon of transformation very precisely and need a lot of material parameters. Some control strategies use those models, however because of their complicity, they need quick processors for complex calculations in real time. Rapid changes of environment (e.g. bias load) generates huge errors of position calculations and different value of calculated and real position. There are also easier strategies – e.g. bi-state control strategy. It does not need complicated calculations but allows only for estimating the maximum deformation for given mechanical load. This strategy uses turn-on/turn-off control but allows only for two-state control of actuator. This method was developed to Segmented Binary Control

(SBC) [4, 5]. Separate group of control systems try to use fuzzy logic and neural networks [6]. There is no easy way for precise positioning of SMA actuator in whole range of movement.

The most important characteristic describing behavior of SMA actuators is thermo-mechanical characteristic. It is describing relative number of molecules transformed to martensite (martensitic fraction – ξ) as a function of temperature (Fig. 1). This leads to another characteristic, describing the deformation of SMA actuator as a function of temperature (for constant load). If heating is realized by flow of electric current we can draw electromechanical characteristic – deformation of SMA as a function of current. All above characteristics are nonlinear and dependent on one more parameter – internal stress in material. Increasing internal stress (e.g. by increasing mechanical load) causes shift of whole characteristic to higher temperatures. This phenomena is shown in Fig. 2. Increasing mechanical load can also influence width of hysteresis in electromechanical characteristic [3].
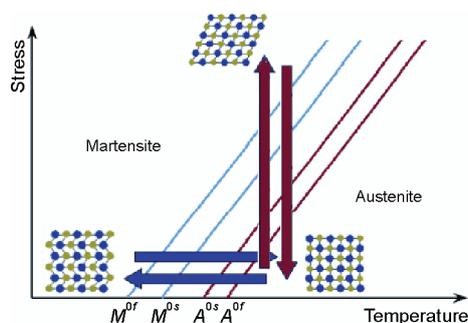

Fig. 2. Dependence of martenistic transformation on internal stress [9]

Above considerations lead to conclusion that precise knowledge of characteristics is necessary for successful control of SMA actuators.

3. Measuring stand

To draw thermo-mechanical characteristic of SMA it is necessary to measure several values in the same time. The most difficult is measurement of temperature of SMA wire (its diameter is 50-350 μm) while length, resistance and load measuring is much easier. To fulfill the requirements the special measuring stand was designed and built. It allows for automated measurement of static and dynamic characteristics of SMA wires of different length and diameter. Static measurement returns parameters of wire when temperature is steady while dynamic measurement allows to observe time changes of parameters after impulse change of heating current. Main assumptions for measuring stand project were:
  – resistive heating of wire with current constraint,
  – changeable mechanical load with constant value (gravitational),
  – using infrared camera for temperature measurement,
  – optical measurement of displacement,

– simultaneous measurement of current, voltage, displacement and temperature,
– maximum wire length – 900 mm,
– minimal mechanical load – 75 g,
– maximum displacement – 80 mm,
– automatic measurement process with data acquisition system.

Design of a stand (Fig. 3) allows to place SMA wire (1) between stiff crosspiece (2) and moving piston (3).

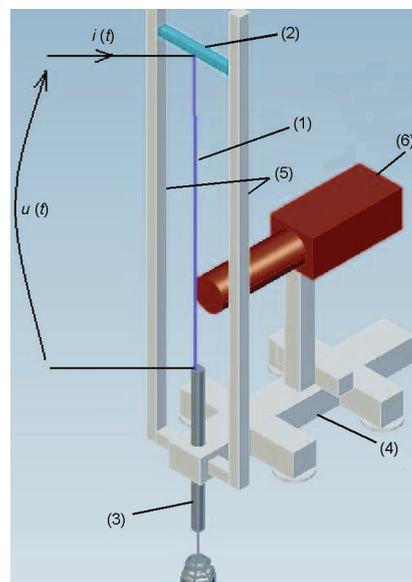Fig. 3a. Measuring stand
– real view

Fig. 3b. Measuring stand
– model

Gravitational mechanical load can be increased by using additional masses and allows for constant load during measurement process. Base (4), frame (5), and the crosspiece (2) are made using aluminum profiles. Infrared camera (6) is mounted to base at the constant level but

it can be shifted horizontally to allow picture sharpness regulation. Electrical circuit is separated from aluminum base by PCV distances. To improve the quality of infrared measurement part of the stand was covered with black cardboard sleeve. In window of Fig. 3a you can see also displacement sensor placed in the bottom part of stand.

According to the Joule-Lenz Law the wire temperature rise is nearly proportional to the square of flowing current. To set the constant temperature in SMA wire the supply system should allow for current stabilization. The power supply PSH-3620 A (36 V, 20 A) was chosen to feed the system. It allows for current as well as for voltage stabilization.

Measurement of electrical parameters is realized using three precise multimeters Rigol DM3052. It allows for simultaneous recording of current and voltage of SMA actuator and voltage signal of optical displacement sensor. Data acquisition and control signals are realized by PC computer. All elements of the measuring system are connected by GPIB network (IEEE 488.2 standard). Control program for static measurements was written in G language (LabVIEW environment). For dynamic measurements data recording is performed using digital oscilloscope Tektronix MSO 2024 equipped with four separated channels and digital filter.

Temperature measurement is realized using infrared camera Flir A325. It has resolution of 320×240 pixels and can record pictures up to 60 Hz. For measuring temperature of very thin wires (50-500 μm) special macroscopic lens (closeup 1×) were used. Its surface resolution is 25 μm. Camera signal is send to PC computer by Ethernet connection with maximum speed of 1GB/s (Gigabit Ethernet). Additionally, ambient temperature is measured all the time by digital thermometer chip DS18B20, however its result is only displayed but not recorded. Figure 4. presents infrared camera view for SMA wire with 308 μm diameter.
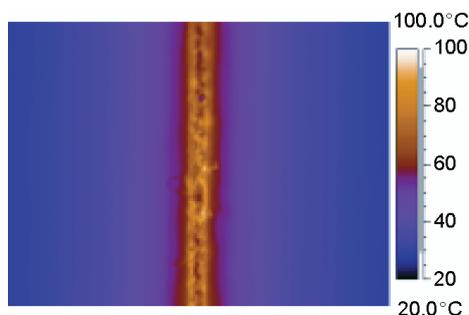

Fig. 4. Infrared camera view for SMA wire with 308 μm diameter

Displacement measurement system consists of optical sensor (converting piston movement into series of pulses), pulses counter, PWM signal generator (PWM signal fulfillment is proportional to number of pulses), lowpass filter and buffer conditioning external signal. Amplitude of converter's external voltage is measured by digital multimeter Rigol DM3052. Movement detection is realized by integrated optical sensor H9720 and measuring tape with 85 μm resolution scale. The sensor has two optical tracks geometrically shifted. Thus two external signals (A and B) are phase shifted what allows for direction detection (by measurement of signals phase difference). Pulse counting and PWM generating is realized by 8-bit microcontroller AVR ATmega88. Microcontroller count pulses from one input while second

input is used only for direction detection. Pulse counting is realized by detection of (both) signal ramps using internal interrupt INT. When ramp is detected both inputs are compared. If their signals have the same value – counter is decreased, if not – it is increased. Block diagram presenting displacement-voltage converter is shown in Fig. 5. while idea of pulse counting (with direction detection) is shown in Fig. 6.
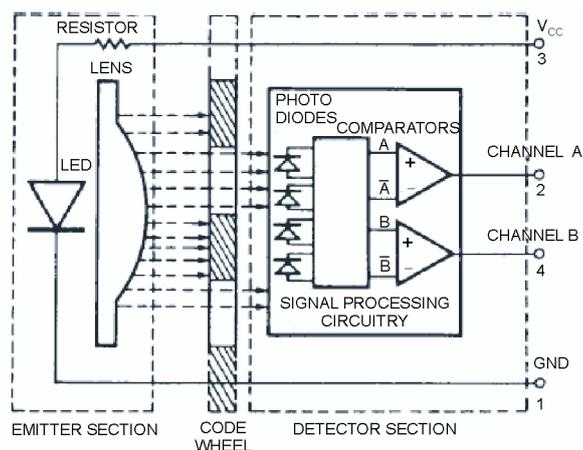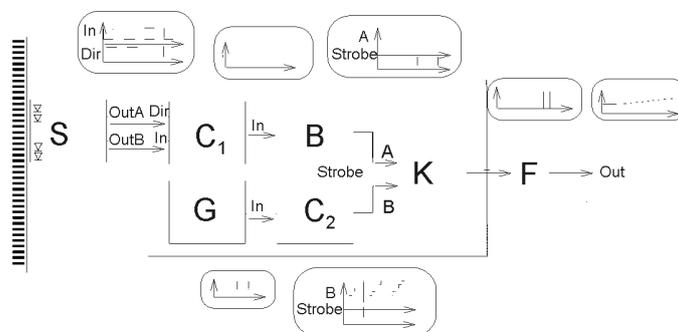

Fig. 5a. Block diagram of Q9720 sensor [1]

S – Sensor   G – Generator   In – Input signal
C – Counter   K – Comparator   Dir – Direction
B – Buffor   F – Filter

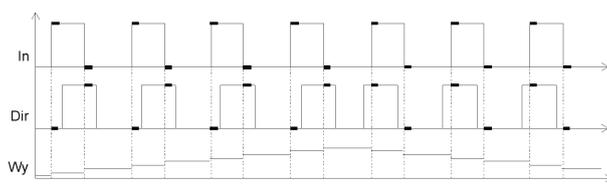Fig. 5b. Block diagram of displacement-voltage converter

Fig. 6. The idea of pulse counting

Sensor (S) generates series of pulses (L_S) which are counted by counter (C_1) and compared in comparator (K) with number of generator (G) pulses (L_G) counted by counter (C_2). Counter (C_2) works in one direction only – the value is increased to overrun the counter. Time needed to overflow this counter determines period of generated PWM signal. PWM signal frequency is 3.5 kHz. Unless $L_G < L_S$ in comparator its output is set to "high" in other case it is "low". Sensor and external microcontroller interrupt are working asynchronously. Output of pulse counter (L_S) is buffered to avoid errors caused by unpredictable changes of counted value.

Changing of number of pulses in buffer is possible only in moment of overflow of counter L_2 (Strobe is the signal controlling this operation). This solution is hardware-implemented in timers built-in to AVR microcontrollers. The role of lowpass RC filter connected to output of PWM generator is to convert digital PWM signal into analog (average) signal. Cutoff frequency of the filter is $C_F = 384$ Hz. Output buffer (operational amplifier with $k = 1$) is conditioning signal and assure high impedance of filter load.

4. Example results of realized measurements

Figure 7 presents two series of static characteristics of length reduction as a function of heating current ($L = f(I)$) for mechanical load $F = 2.075$ kg in SMA actuator type F2000 (length $L = 400$ mm, nominal load $F_N = 2$ kg). This picture illustrates the repeatability of measurements which seems to be very good.
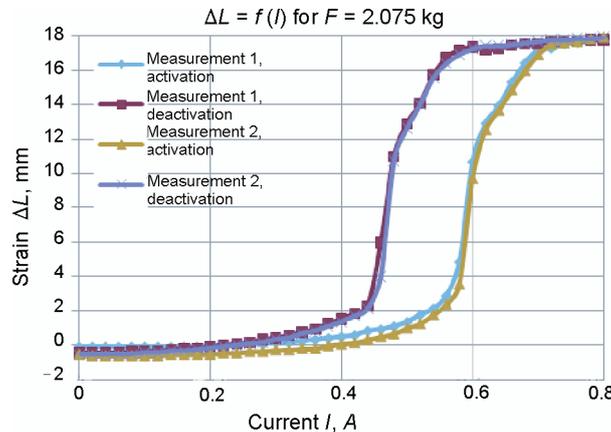

Fig. 7. Repeatability of measurements for SMA actuator type F2000 with load $F = 2.075$ kg

Figure 8. presents two static characteristics of the same actuator and the same load ($F = 2.075$ kg). Curve ΔL shows length reduction ($\Delta L = f(I)$ – the same that in Fig. 7) while curve T shows temperature of the SMA wire ($T = f(I)$).

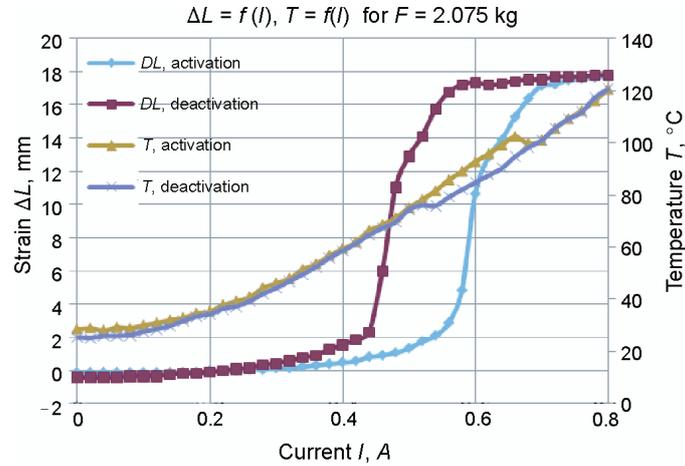$\Delta L = f(I)$, $T = f(I)$ for $F = 2.075$ kg

Fig. 8. Static characteristics of strain and temperature for SMA actuator type F2000 with load $F = 2.075$ kg

Figure 9 presents exemplary dynamic characteristics of length reduction in time for three different constant loads and impulse change of heating current ($\Delta L = f(t)$, for $F = $ const and $i(t) = I_{MAX} \cdot 1(t)$, where $I_{MAX} = 0.8$ A).

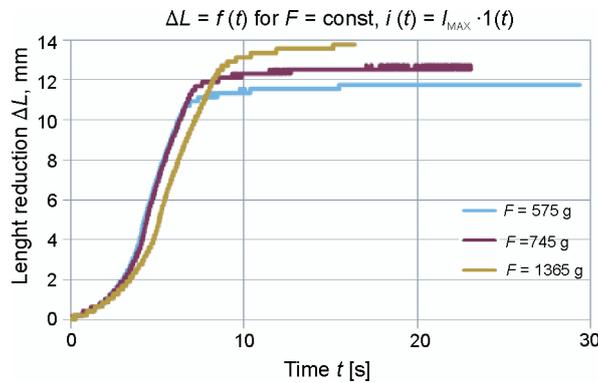$\Delta L = f(t)$ for $F = $ const, $i(t) = I_{MAX} \cdot 1(t)$

Fig. 9. Dynamic characteristics of F2000 actuator

Wide examinations of several SMA wires allowed for drawing its operating characteristics. It shows length change of actuator as a function of mechanical bias (Fig. 10).

L_{0A} – length of activated actuator with no load,

L_A – length of activated actuator with load,

ΔL – length reduction caused by activating of loaded actuator,

L_N – length of nonactivated actuator with load.

Above characteristics describes possible lengths of actuator mechanically biased and supplied with different values. This characteristics shows the behavior of SMA actuators and allows for easier selection of actuator length for particular task. The task is understood as

a movement of specific bias at defined distance or pressing the object with specified force. Figure 10 presents length of activated and nonactivated actuator (with mechanical load) in steady state. One should remember that change of the length of SMA wire (caused by Martenistic transformation) is 5-15% – depending on actuator type. It is also important to remember that working with maximum displacements causes very quick wear fatigue of actuator.
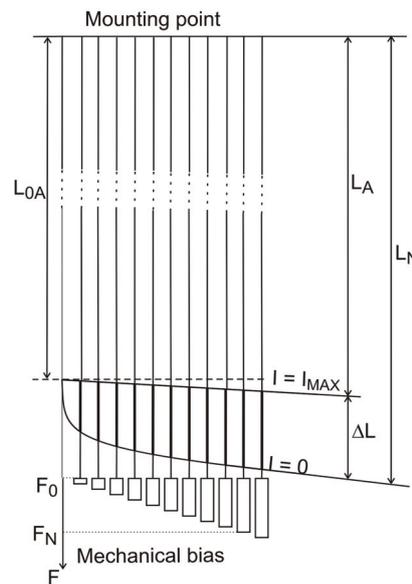

Fig. 10. Actuator length as a function of mechanical bias [2]

Fatigue tests performed in [8] showed that even with relatively small loads the actuators did not reached rated number of cycles guaranteed by producer. When designing actuators, using SMA wires, it is necessary to take into consideration the length change due to mechanical load. Final regulation of actuator length should be done after some testing cycles.

5. Summary

Shape Memory Alloys are becoming more and more popular in several applications. Knowing its properties makes their usage easier and more reasonable. Designed and built measuring stand allows for semi-automatic measurements of wide range of SMA wires. Such examinations are necessary for understanding SMA behavior and for preparing empirical mathematical model. Such a models are needed for advanced control systems, giving opportunity for SMA servo drives construction.

Presented measuring stand allows not only for drawing thermo-mechanical characteristic but also many other characteristics (e.g. resistivity vs. supply current or resistivity vs. length of actuator, power supply and efficiency). More experiments should lead to improvement of existing mathematical models of SMA actuators and elaboration of new ones, useful in real time control systems. Additionally, measuring stand allows for examining of other light-weight actuators. It is only necessary to change supply source and controlling software.

Presented stand is planned to be upgraded in two ways:

1) The thermal insulation chamber will be built for stabilization of ambient temperature during measurements. It will allow for performing all the measurements in the same conditions.

2) Electromechanical system will be built for loading the actuator instead of hanging mass. It should allow for full automatic measurement process.

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