*Sindh Univ. Res. Jour. (Sci. Ser.) Vol. 48 **(4D)** 39-44 (2016)*

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Design, Development and Validation of an Experimental Test Bed for SMA Actuators

M. A. SOOMRO, J. DAUDPOTO, A. M. NIZAMANI

Mechatronics Laboratory, Mehran University of Engineering and Technology, Jamshoro

Received 28rd August 2016 and Revised 17th October 2016

Abstract: The actuation behavior of Shape Memory Alloy (SMA) is not yet fully understood due to their nonlinear and hysteretic behavior. Moreover, the data provided by the manufacturers are not exhaustive and can therefore, only be used as a guideline. The SMA actuation behavior depends on environmental temperature, bias load, cycle time and actuation current. Hence measurement of actuation characteristics is required in order to effectively utilize these actuators for a particular application. An experimental test bed was designed and developed to characterize SMA actuators. The test bed was validated by conducting the tests on a commercially available SMA actuator of diameter 0.15 mm. The strain during actuation was measured with Laser displacement sensor. Load cell was used to measure bias load on SMA wire. National Instruments FPGA based controller myRio with LabVIEW software was used for cyclic actuation. The tests were conducted using constant current circuit specially developed for the test bed. The SMA actuator was actuated with 200-400mA currents for 1 second. A bias load resulting in the recommended stress of 100 MPa was used. Actuation strains recorded were within the guidelines provided by the manufacturer.

Keywords: Shape Memory Alloy actuators, characterization, test bed

1. INTRODUCTION

Shape memory alloys (SMAs) belong to group of metallic alloys, which have ability to 'remember' their shape. This effect is caused by a change in temperature dependent crystallographic structure, known as shape memory effect (SME) (Otsuka. *et.al.,* 1998). SMAs exhibits two distinct phases, one is Martensite phase that occurs at low temperatures and other is Austenite phase, which occurs at high temperatures. The working principle of SMA actuators, that is shown in the (**Fig-1)**.

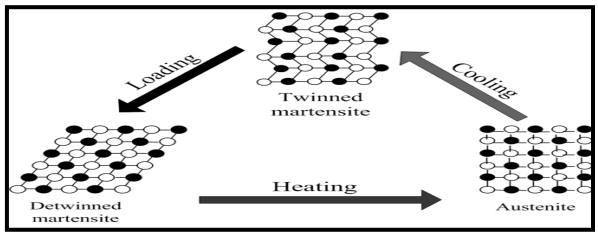


Fig-1 SMA actuator phase transformation during actuation

SMAs, as an actuator, are commercially available in the form of wire. A SMA actuator having nearly equivalent atomic composition of Nickel and Titanium known as NITINOL is the most commonly used SMA actuator. Nitinol based actuator offers good mechanical properties, greater fatigue life and high corrosion resistance (Brailovski *et. al.,* 2003). SMA's being small in size, owing high force to weight ratio, Bio compatibility, makes it superior in comparison to that of other conventional actuation systems such as motors, pneumatic and hydraulic systems (Pfeiffer. *et.al.,* 1999). Therefore, SMAs have been exploited as an actuation device in numerous domains such as robotics (Kennedy. *et.al.,* 2004). automotive (Williams. *et.al.,* 2008). and aeronautics (Strelec. *et.al.,* 2003).The maximum strains up to 8% is achievable but for cyclic purpose it should be restricted to 3%–5 % 9 (Dynalloy. 2014, 2015).

Despite the advantages as mentioned above, the application of SMA actuator possesses certain limitations. The performance of SMA actuators is dependent on number of factors, which includes: stress, strain, temperature and the number of loading cycles. The amount of current running through the wire should be controlled for preventing any damage to the wire. Moreover, the non-linear and hysteretic characteristics of SMA wire during phase transformation, causes difficulties to control it accurately. To effectively use SMAs as an actuating device, their characteristics must be known. They are highly sensitive to their environment but the testing of SMAs as an actuation device is not yet standardized. Moreover, data provided by the manufacturer could only be referred as guideline. Hence in this proposed work, an experimental setup, as shown in Fig. 2, is developed to investigate the characteristics of SMA wire actuators where the wire will contract upon Joule heating and expands when cooled at room temperature with the aid of bias load.

Different experimental setups had been developed to evaluate behavior of SMAs i.e. (Georges. *et.al.,* 2013) developed experimental test bench to characterize SMA actuators. They had captured actuation behaviour of SMAs using encoders. Cheng (Low. *et al.*, 2013). constructed an experimental setup to access contraction displacement produced by the wire using linear potentiometer. O'Toole, K. et al. (Toole. *et al.*, 2007). built a vertical experimental test rig for characterization of bundle of SMA wire actuators, strain developed in the bundle was measured using linear variable differential transformer (LVDT). Michael J. Mosley et al. (Mosley. *et al.*, 2000) designed and constructed an instrumented test rig where linear displacement produced by the SMA bundle was sensed by ultra-small contact type position transducer. The flaw in the above mentioned techniques of characterization of SMAs is that they have an adopted contact type method to measure strain in the SMA actuators, contact type sensors requires large displacement for readable output. (Daudpoto. *et al.*, 2013). developed vertical test rig to evaluate actuation behavior of SMA actuators, although the author had used non-contact sensor but the vertical arrangement of displacement sensor may affect measurements. Moreover, author tested actuator by supplying DC voltage which results voltage losses in series circuitry. In this work, a horizontal instrumented test bed was designed and developed to determine performance characteristics of SMA wire actuators. Author has used non-contact laser displacement sensor to accurately access strain behaviour of wire during actuation. SMA actuator commercially available under the brand name of Stabinol and Flexinol having diameter of 0.15 mm were characterized and test setup was validated by comparing the results with the ones provided by the manufacturers.

2. MATERIAL AND MATHODS

2.1 Material

2.1.1 Actuator

Nickel-Titanium based SMA actuators namely Stabinol and Flexinol having diameter of 0.15 mm (150µm) were tested. The strain recovery and force produced by the actuator is proportional to the diameter of SMA wire. The cooling time for the wire of smaller diameter is relatively lower than that of the wire having larger diameter. Hence, actuator of 0.15 mm diameter was tested.

2.1.2 Experimental Test Bed

Due to sensitivity of the SMAs, it was a challenging task to develop a rigid experimental test bed. The test bed illustrated in Fig. 2, was developed using aluminum plate having thickness of 9mm. The structure of aluminum was selected because it possesses fair mechanical characteristics in terms of solidity and lightweight. Test bed consist of specimen holder i.e. crimps for mechanically fixating of SMA actuators. A SMA wire having diameter of 0.15mm and length of 80mm had been connected in the series to a bias load inducing stress of 100MPa. The SMA actuator was fixed to a load cell at one end and to the bias load at other end. A non-contact position transducer was placed parallel to the SMA wire to measure contraction displacement induced in the wire. LK-G500 controller was connected to laser displacement sensor to set working range and to amplify signals. Strain produced in SMA is the function of applied bias load therefore, load cell had been used to measure applied bias load to the actuator. The signal conditioner was connected to load cell for amplification and conditioning of the signals.

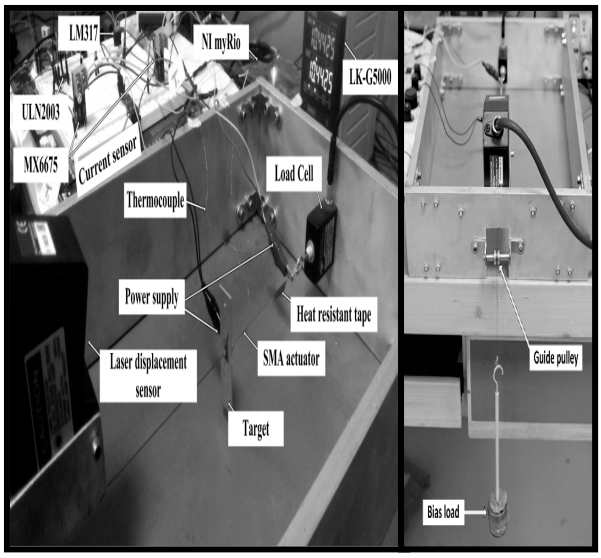


Fig-2 Experimental bed for testing of SMA actuators

A fine gauge K-Type thermocouple attached to the actuator using heat resistant tape to measure temperature of SMA wire during actuation. MX6675 connected in series with thermocouple for cold junction compensation (CJC) and to digitize the signals from thermocouple. During experiments, SMA wire was actuated by applying constant current. One of the challenging tasks of testing SMA actuator is controlling the amount of current running through the wire. Enough current must be supplied to get the adequate results, but supplied current must not be in exceeding amount to avoid wire from burning out. An optimum current and resistance per length for SMA wire is specified in the technical data sheet provided by the manufacturer [9]. A circuit was made using LM317 for maintaining specific constant current to test the SMA actuator. Current running through the wire was measured by Hall IC based current sensor AC712. The custom circuitry

had been designed for cyclic actuation, which was programmatically controlled using high voltage and current driver IC ULN2003. The input signals from all the connected instruments were acquired through National Instruments Field Programmable Gate Array (NI FPGA) based controller myRio and outputs were recorded using Lab VIEW software. Furthermore, the acquired data was exported to Microsoft Excel for analysis.

2.2 Methods

2.2.1 Calibration

The experimental test bed was developed to investigate the different properties of shape memory alloys therefore calibration of each measuring instrument was necessary to ensure its accuracy and minimize any measurement uncertainty.

2.2.1.1 Load cell

Load cell used to measure bias load was calibrated by applying known mass Fig.3. The plot between mass (g) and output (V) shows linear relationship.

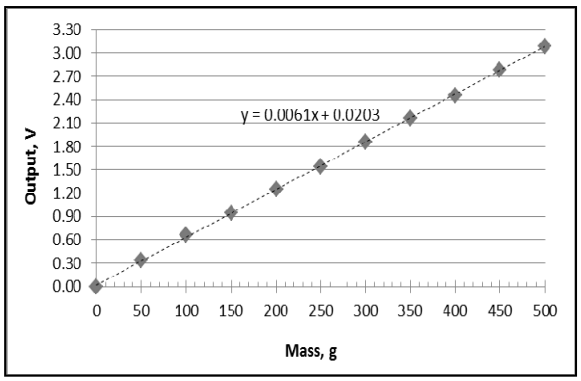
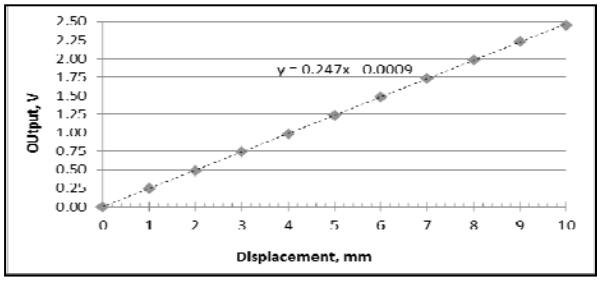


Fig. 3. Load Cell Calibration

2.2.1.2 Laser Displacement Sensor

Laser displacement sensor was calibrated by using aluminum block as target and output was captured by moving block aluminum at an increment of 1 mm on standard ruler. **(Fig.4).** the plot between displacement.



(mm) and output (V) shows linear relationship

Fig. 4. Laser Displacement Sensor Calibration

2.2.1.3 Thermocouple calibration

The calibration of fine gage K-thermocouple was carried out at room temperature, where the thermocouple was immersed in hot water along with other calibrated K type digital thermometer. MX6675 was connected in series with fine gage thermocouple to provide cold junction compensation (CJC) and digitize Signals. During calibration, digital output from Fine gage K-type thermocouple was compared with calibrated K-type digital thermometer KT300. The results are tabulated in Table 1.

Table-1: Thermocouple Calibration

Thermocouple readings (°C)	Calibrated Thermometer readings (°C)	Error (°C)
100.2	100.0	0.2
88.9	88.0	0.9
84.6	84.4	0.2
74.1	74.7	0.6
65.0	65.5	0.5
56.4	56.8	0.4
50.1	50.7	0.6

2.2.1.4 Current Sensor (AC712)

Current sensor was calibrated by applying known current from DC power supply, the plot between input current (mA) and output (V) shown in **(Fig.5).**

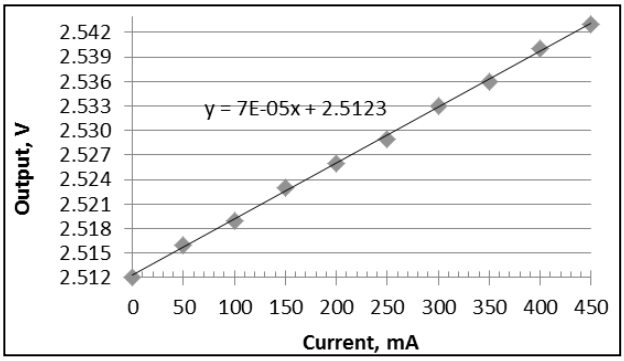


Fig. 5. Current sensor Calibration

2.2.2 Experiment procedure

1. The focus of this experiment was to study contraction displacement produced by SMA actuators i.e. Stabinol and Flexinol having diameter of 0.15 mm and length of 80mm.
2. One end of the actuator was crimped and screwed to load cell while other end was attached to bias load.
3. Application/implementation of Bias load was necessary to get SMA back to pre-deformed shape; mass of 180 g resulting in the recommended stress of 100 MPa was attached.
4. A fine gage K type thermocouple was attached directly in contact with SMA wire using heat resistant tape.

5. Throughout all the tests constant current was applied on a SMA wire actuator.
6. During experiments, SMA wire was subjected to manufacturer specified range of possible input current values, i.e. 200-400mA for SMA wire having diameter of 0.15mm.
7. Input current was kept constant and tests were conducted at room temperature.
8. In this work, the SMA actuator was characterized for the application of cyclic actuation therefore actuator was loaded for 100 cycles. Each cycle consist of 1 sec of contraction (heating) and 2 sec of relaxation (cooling).
9. Sampling rate for data acquisition device (DAQ) was set to 10 ms i.e. 100 data points in 1 sec
10. All the measurements were collected using data logger for the further evaluations.
11. Recorded data was then exported from Lab VIEW to Microsoft excel for analysis.

3. RESULTS AND CONCLUSIONS

3.1 Results

3.1.1 Characterization of SMA wire actuator

Strain is defined as how much an object has been stretched due to applied stress.

$$\varepsilon = \Delta L/Lo$$

i.e. change in length per unit original length recovery of a strain in SMA wire actuator resulting from applied stress of 100Mpa is presented in section. The strain shown in the graphs are in negative because of contraction of the wire during actuation. The actuation behaviour of SMA actuator Stabinol having diameter of 0.15mm was recorded and result for one complete cycle at different input currents i.e. 200-400mA is displayed in **(Fig.6).**

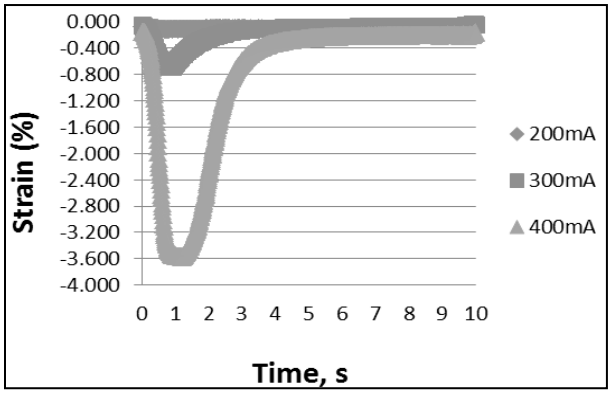


Fig. 6. Strain behavior of Stabinol 0.15mm SMA wire at different input currents

It had been observed that heating SMA wire at 200mA for 1 sec was not sufficient; the average strain was around 0.122% throughout 100 cycles. When the wire heated at 300mA for 1 sec, the small strain of about 0.690% had been measured but when the current of 400mA for 1 sec was applied, the average strain of 3.577% was achieved.

The graph of strain versus different cycles at maximum recommended current is shown in **(Fig.7)**. The maximum strain of 3.577% was achieved during 50^{th} and 90^{th} actuation cycle. It had been seen that an average strain achieved during total actuation cycles was nearly around 3.5%.

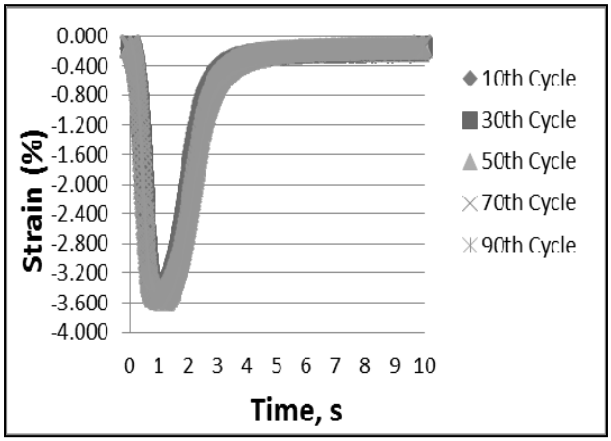


Fig. 7. Strain behavior of Stabinol 0.15mm SMA wire at different cycles

3.1.2 Validation of Test Bed

SMA actuator commercially available with trade name of Flexinol of diameter 0.15mm and having length of 80mm, has been tested for 100 cycles. The recovery of strain in the wire investigated by applying maximum recommended input current i.e. 400mA. The achieved average strain of 3.693% is illustrated in **(Fig. 8)**. Hence, it validates the test bed by comparing results to those suggested by the manufacturer i.e. strain recovery of 3-5 % of original length of the wire.

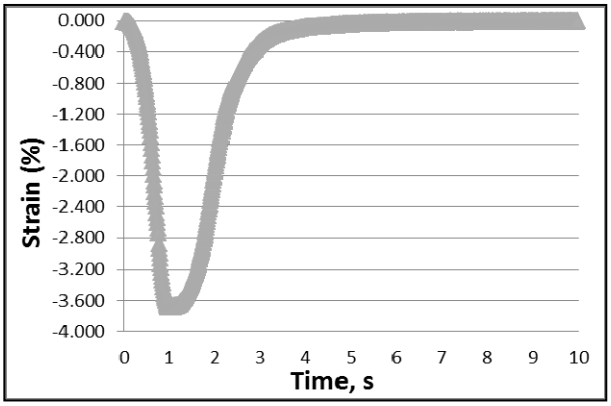


Fig. 8 Strain recovery in Flexinol 150LT at 400mA

3.2 CONCLUSION

In this research, an experimental test bed was designed, developed and validated for characterization

of shape memory alloy wires using precision transducers. Calibration of the precision transducers was carried out to avoid any measurement uncertainty and the results are presented in the form of graphs and table. Numerous experiments were designed and performed to investigate the properties of shape memory alloy wires. In this proposed research, a constant current series circuit was specially made for testing. Hence, for avoiding any current loss in the circuit. An actuator named as Stabinol of the diameter 0.15mm, was tested to record its cyclic actuation behavior at different input currents. The average strain of around 3.57% was observed throughout experiments. Test bed has been validated by testing Flexinol 150LT SMA wire by comparing acquired results with the provided datasheet of the manufacturer. The temperature measurement of the phase transformation of SMA actuator was found to be one of the toughest part of its characterization. During actuation cycle, SMA wire contracts, due to which thermocouple that is wrapped around SMA actuator loses its contact due to which temperature of the wire was not captured during tests. It is suggested that proper method of the temperature measurement of the wire must be adopted in future to determine the transformation temperatures.

REFERENCES:

Brailovski V., S. Prokoshkin, P. Terriault, and F. Trochu, (2003). Shape memory alloys: fundamentals, modeling and applications: École de technologie supérieure. Vol.1 , 403–548.

Dynalloy. (2014, 26/04/2015). Flexinol Technical sheet. Available: http://www.dynalloy.com/pdfs/TCF1140.pdf Accessed on 02/06/2016.

Daudpoto. J., A. Abbasi, and D. Pathan,(2013). "Design, Development and Validation of a Rig to Test SMA Actuators," Sindh University Research Journal-SURJ (Science Series), vol. 45 (1), 197-200.

Georges. T., V. Brailovski, and P. Terriault, (2013). "Experimental bench for shape memory alloys actuators design and testing," Experimental Techniques, vol. 37, 24-33.

Kennedy. D. K.., F. K. Straub, L. M. Schetky, Z. Chaudhry, and R. Roznoy, (2004). "Development of an SMA actuator for in-flight rotor blade tracking," Journal of Intelligent Material Systems and Structures, vol. 15, 235-248.

Low. C. Y., M. A. A. Kasim, T. Koch, R. Dumitrescu, H. Yussof, R. Jaafar, et al., (2013). "Hybrid-actuated finger prosthesis with tactile sensing," International Journal of Advanced Robotic Systems, vol. 10, 351.

Mosley. M., and C. Mavroidis, Sep. (2000). "Design and control of a shape memory alloy wire bundle actuator," in Proceedings of the 2000 ASME Mechanisms and Robotics Conference, 10-13, Baltimore, Maryland.

Mabe. J. H., F. T. Calkins, and R. T. Ruggeri, April (2007). "Full-scale flight tests of aircraft morphing structures using SMA actuators," in The 14th International Symposium on: Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, VOL. 6525,48.

Otsuka. K., and C. Wayman, (1998). "Mechanism of shape memory effect and superelasticity," Shape memory materials, 1st Edition. 27-49.

Pfeiffer. C., K. DeLaurentis, and C. Mavroidis, (1999). "Shape memory alloy actuated robot prostheses: initial experiments," in Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on, 2385-2391, Detroit, Michigan .

Singh. K., J. Sirohi, and I. Chopra, (2003). "An improved shape memory alloy actuator for rotor blade tracking, " Journal of Intelligent Material Systems and Structures, vol. 14, 767-786,

Strelec. J. K., D. C. Lagoudas, M. A. Khan, and J. Yen, (2003). "Design and implementation of a shape memory alloy actuated reconfigurable airfoil," Journal of Intelligent Material Systems and Structures, vol. 14, pp. 257-273,

Toole. K. O'., M. McGrath, and D. Hatchett, (2007). "Transient characterisation and analysis of shape memory alloy wire bundles for the actuation of finger joints in prosthesis design," Meta, vol. 21, 65-69.

Williams. E., and M. H. Elahinia, (2008). "An automotive SMA mirror actuator: modeling, design, and experimental evaluation," Journal of Intelligent Material Systems and Structures, vol. 19, 1425-1434.