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Design, Development and Validation of a Rig to Test SMA Actuators

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Abstract: In this paper, design, development and validation of a test rig to characterise shape memory alloy (SMA) actuators is presented. Sensors for measurement of strain, force and temperature were selected and calibrated. The test rig used a CCD (charge coupled device) based laser displacement sensor to accurately measure strain. An enclosure was also developed for isolating actuators from the ambient air currents. Laboratory Virtual Instrument Workbench (LabVIEW) software was used to actuate the wire actuators and record the test data. To validate the rig, two Nickel-Titanium based SMA actuators 0.2 mm in diameter were tested. The results of those tests were found compatible with the data sheet provided by the manufacturer.

Keywords: Shape memory alloy, Test rig, Laser displacement sensor, Force sensor, Thermocouple

1. INTRODUCTION

The need for miniaturised and embedded systems has resulted in a shift from the use of conventional to smart actuators (Sreekumar *et al.*, 2007). Conventional actuators produce power in proportion to their volume hence their ability to produce power is severely reduced for miniature and micro applications (Mavroidis *et al.*, 2000). On the other hand, the power produced by some smart materials like SMAs depend on diameter of actuators. Therefore miniaturisation does not affect their force capabilities as diameter of actuators is only a fraction of a millimetre (Mavroidis, *et al.*, 2000).

Shape memory alloys possess special property of remembering their shape. SMAs can occur in two distinct temperature dependent microstructures. The high temperature phase is called Austenite and low temperature phase is known as Martensite **(Fig.1).**

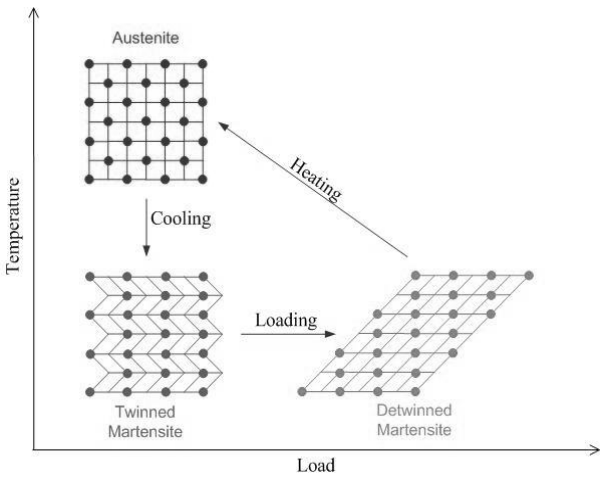


Fig. 1. Phase transformation in SMAs (Mavroidis *et al.*, 2000)

The temperatures at which phases change are called transformation temperatures. The transformation temperature of alloys used as engineering actuators lies between 70-90 ^{0}C (Dynalloy, 2011). When alloy is heated above its transformation temperature, it contracts. This contraction can be used to actuate the component to which actuator is attached. SMAs can develop very large forces. The amount of force developed is a function of its diameter. The maximum tensile stress which SMAs can be subjected to is limited to 600 MPa but for cyclic applications this stress is to be limited to 190 MPa (Gilbertson, 2000). Similarly, maximum strain that SMA actuators can undergo is 8 % but for cyclic purposes it should be confined to 3-5 % (Braunovic, 2007). Due to biocompatibility, ease of manufacture and better anticorrosion properties, Nickel Titanium based SMAs are widely used for medical and engineering applications (Ibuki, *et al.*, 2008; Andrianesis, 2008; Kyung *et al.*, 2008; Bundhoo, *et al.*, 2009; Hong and Priya, 2011; Daudpoto *et al.*, 2012).

The characterisation of conventional actuators like DC, pneumatic and hydraulic actuators is quite straightforward as their behaviour has already been fully understood. However, behaviour of SMA actuators depends on many factors like heating power, ambient temperature and level and type of bias force. This necessitates the provision of some experimental setup to find the properties of actuators under various loading conditions.

The system identification of the SMA actuated systems has been reported in the literature (Bundhoo *et al.*, 2009; Spinella *et al.*, 2009; Hong and Priya 2011). However, only one test rig to characterise SMA actuators have been reported in literature (Mosley and Mavroidis, 2000; Mavroidis, 2002). This test set up has

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two drawbacks. First, it uses contact type (LVDT) method for measurement of length of stroke/strain. Second, it uses load cell at the bottom end of the actuator. Measurement of strain using LVDT and use of load cell at the bottom end of actuators interfere with the test results. Additionally, the test rig mentioned above can only be used for dead weight bias force and not for spring bias testing. The rig designed, developed and validated in this research has following advantages:

1. It uses laser displacement sensor for accurate measurement of strain.
2. The load cell has been attached at the top end of the actuator hence it does not add to the bias force on actuator.
3. Test rig can equally be used for both dead weight and spring bias characterisation of SMA wire actuators. It can be used to characterise both single wire and bundled SMA actuators.

In section 2, design and development of test rig is described. In section 3, the validation of test rig is presented. The validation was carried out by first calibrating displacement, force and temperature sensors and then carrying out tests on 0.2 mm diameter SMA actuator.

2. DESIGN AND DEVELOPMENT OF THE TEST RIG

(a) Structure

A 75 cm high structure made from 4 cm x 4 cm cross section Aluminium profile was designed and developed **(Fig. 2).** Structure was raised on 20 cm x 60 cm x 1 cm Aluminium base. The standard Aluminium profile was used as it comes with standard fasteners for attachment of sensors.

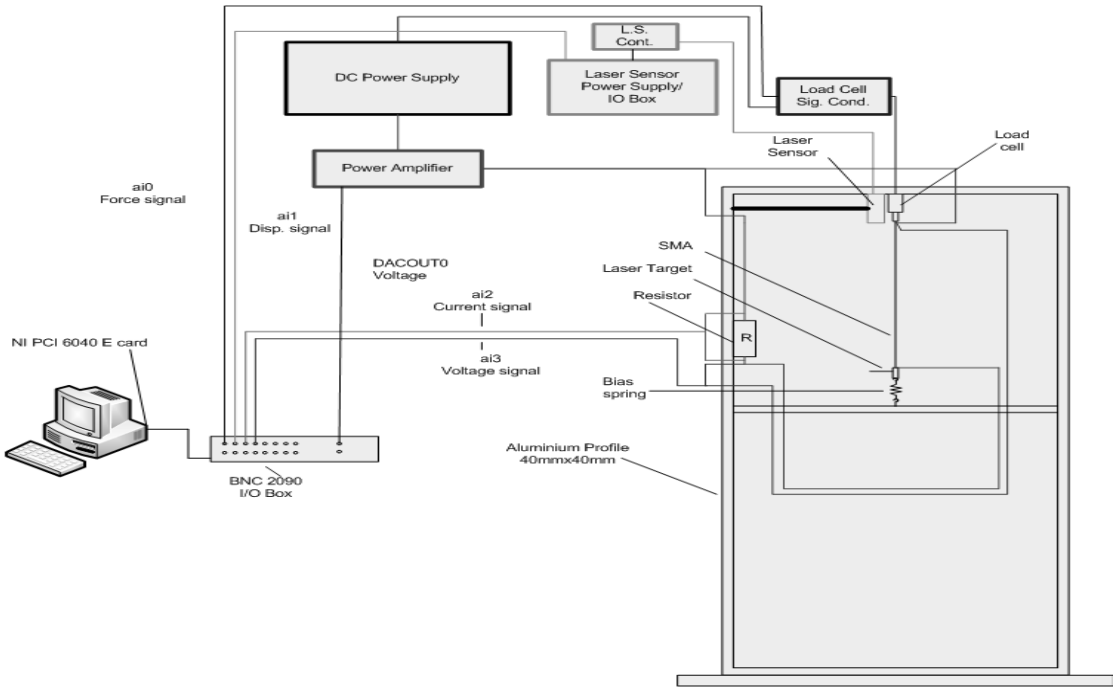


Fig. 2. Experimental setup for testing SMA wire actuators

(b) Enclosure

As SMA actuators are very sensitive to type of cooling (Reynaerts and Brussel, 1998), it is necessary to isolate them from movement of air. A box made of plastic was made to isolate the test rig from the changes of temperature around the test wires.

(c) Force measurement

SMA actuators require a bias force to bring them back into detwinned Martensitic state. This was done by using an extension spring at the bottom end of the actuator. The correct setting of the bias force was necessary for investigating the strain characteristics. Hence a load cell obtained from Transducer Techniques was used for this purpose. This force sensor can measure forces of up to 11 N. As the maximum pull force of the actuators used in this research was about 5.8 N (Dynalloy, 2011) this sensor was capable of measuring it. Signal from load cell was conditioned by signal conditioner which was then fed into the data acquisition system.

(d) Strain measurement

The strain of the actuator was measured by using laser displacement sensor having a resolution of

0.1 mm. Signal conditioner conditioned the signal before sending it to data acquisition system.

(e) Measurement of Temperature

Initially, infrared temperature measurement was tried, as it is not only fast but is also noncontact type. A K-type thermocouple having diameter of 0.125 mm was used for measurement of temperature. A heat resistant tape was used to attach thermocouple to the actuator.

(f) Data Acquisition

A National Instruments data acquisition card with a sampling rate of 500 kilo samples per second was used to capture the signals from load cell, laser displacement sensor and thermocouple. A connector block was used to connect sensor leads to data acquisition card. National Instruments LabVIEW was used for recording test data and generating the voltage signals for the actuator.

3. VALIDATION OF TEST RIG

Validation of test rig was carried out in two parts. Subsection 3.1 describes the calibration sensors. In subsection 3.2 results of sample tests are presented. The results of the tests are compared with the data sheet supplied by the manufacturer.

3.1 Calibration of Sensors

(a) Force Sensor

The calibration was carried out by applying a known mass to the force sensor **(Fig. 3).** The plot shows a nearly linear relationship between force (N) and output signal (V).

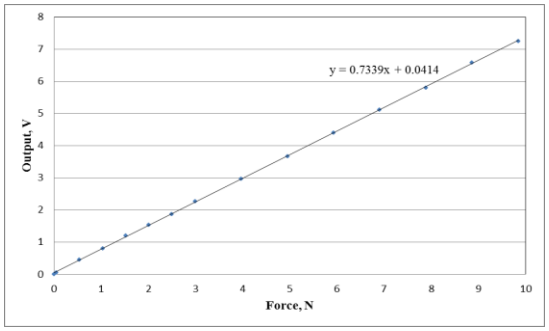


Fig. 3. Force Sensor Calibration

(b) Laser sensor calibration

Calibration of laser displacement sensor was carried out by using gauge blocks with an increment of 1 mm. The laser displacement sensor gives the output in DC Volts (V). The calibration plot is shown in **(Fig. 4)** below. The plot shows a linear relationship between displacement (mm) and output signal (V).

(c) Temperature sensor calibration

The temperature measured by temperature sensor (K-type thermocouple) was compared with an accurate temperature meter. The results are recorded in **(Table 1)** below.

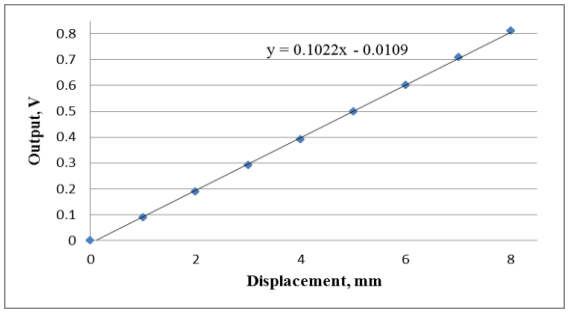


Fig. 4. Laser sensor calibration plot

Table 1. Thermocouple Calibration

Thermocouple Reading (^{0}C)	Calibration Thermometer Reading (^{0}C)	Error (^{0}C)
23	23.5	0.5
34	34.5	0.5
46	46.5	0.5
59	59.5	0.5
67	67.5	0.5
73	74	1
78	79	1
82	83	1

3.2 Test Results

To check the overall validity of the test rig, actuation tests were carried out on a commercially available equi-atomic Nickel-Titanium based SMA actuator known as Flexinol (FLEX). The properties of this actuator provided by the manufacturer are as follows. Transformation temperature: 90 ^{0}C, Diameter: 0.2 mm, Resistance: 31 Ω/m, Maximum pull force: 590 gram force, Actuation current: 610 mA.

A 200 mm long wire was tested under the bias force of 3 N exerted by an extension spring having spring rate of 0.12 N/m. Two actuators were used; one was actuated with 4 V and the other with 4.5 V. Each test piece was cycled for 100 times. Each cycle consisted of 2 of actuation (heating) and 8 s of cooling. The plot of length of stroke and strain against number of cycle is shown in **(Fig. 5).** The average strain for actuation voltage of 4 V was found to be about 4.15 %. Similarly, the same for 4.5 V actuation was found to be about 4.35 %. These results are comparable to those suggested by the manufacturer (3-5 %). The results confirm that higher actuation voltage results in greater strain due to greater heating power.

4. CONCLUSIONS AND FUTURE WORK

In this paper, design, development and validation of a test rig to find the actuation properties of SMAs is presented. Sensors are selected for measurement of force, displacement and temperature. The test rig equipped with a laser displacement sensor

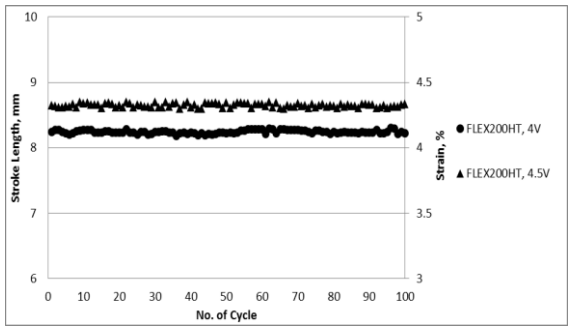


Fig. 5. Strain vs. Number of cycle for test specimen (Daudpoto, 2012)

and capable of characterising both single wires and bundle of wires is the original contribution of the research presented in this paper. Calibration of sensors is carried out and results are presented in the form of graphs and table. To check the overall performance of the test rig, two actuators were tested for their actuation strain. Actuators were cycled for 100 times. The average strains for actuation voltages of 4 V and 4.5 V were found to be 4.15 % and 4.35 % respectively. The magnitude of strain fell within the range (3-5 %) specified by the manufacturer in the data sheet. In this work actuators were actuated with DC voltage. Due to series circuitry, voltage output from the power amplifier was adjusted against the voltage losses in the circuit. It is suggested that tests be conducted by supplying current output from the power amplifier as there will be no loss of current in a series circuit. Moreover, as the force developed by the single wire actuator is only about 5.8 N, bundles of the wire actuators are proposed for the development of larger magnitudes of forces.

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