Development of Controlled Current Heating Module and Measurement System for Shape Memory Alloy

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Abstract. Shape Memory Alloys (SMAs) are a unique class of materials that have the ability to recover their shape when the temperature is increased. It has significant potential in many areas such as aerospace, biomedical, automobile, vibration-dampers, etc. In these applications, light weight SMA element can be used in place of bulky motor driven systems for making linear as well as angular movements. SMA can be electrically activated to produce joule heating which triggers a phase transformation in the SMA wire causing it to expand and contract. Right configuration of these wires can be utilized to form an alternative to the motors and solenoids to provide an actuation signal. It provides potentially simple, silent and smooth operation and auto sensing ability thereby providing a controlled displacement that can be utilized to generate mechanical work. To attain repetitive and desired displacement, the SMA element needs to be properly biased at the end of each heating-cooling cycle. For such phase transformation of these SMAs, the appropriate heating module is required for the precise movement of the wire. Due to phase transformation in SMA wires, the resistance of SMA wires changes significantly. For the usage of data driven control and self-sensing SMA devices, precise measurement of different data parameters, like, voltage (VSMA), current (ISMA), ambient temperature (Ta), wire temperature (TSMA), displacement (D), and resistance (RSMA) are required. These parameters can be used further to derive the relationship between difference resistance (dR) and displacement. dR is the difference between resistances of two SMA wires.

The present work details current controlled heating module (CCHM) and measurement system for SMA wire. CCHM consists of PWM generation using PC, low pass filter (LPF), operational amplifier with appropriate feedback for the controlling the current. This CCHM provides the appropriate current needed to operate the SMA movement. The measurement system incorporates the precise measurement of voltage, current and ambient temperature and displacement. Thermocouple sensors are used to measure the temperature of the SMAs. Filtering and signal processing needed for these parameters are studied and discussed in the present article. Performance analysis of heating module & measurement system is carried out and their results are reported.

I. INTRODUCTION

Shape memory Alloy (SMA) are family of smart materials. These materials remember their shape upon the changing phase transformation [1, 2]. On given temperature stimulus, SMA returns to its predefined shape. This observed phenomenon is called shape memory effect (SME). The phase transformation is re-arrangement of crystalline structure (transformation) from low temperature martensite (M) phase to high temperature austenite (A) phase [3].

The most commonly used SMA material is wire made by Nickel and Titanium alloy popularly known as Nitinol (NiTi). Nitinol has advantages of resistant to corrosion, super-elasticity high power to mass ratio, large force and displacement [2,4]. During the phase transformation, materials may change their shape, size, stiffness among other properties. The change in length of and stress results in their usage in different applications to generate mechanical work. It has significant potential in many areas of micro-robots in aerospace, biomedical, etc., wherein light weight SMA element can be used in place of bulky motor driven systems for making linear as well as angular movement.

To attain repetitive and desired displacement, the SMA element needs to be properly biased or excited at the end of each heating-cooling cycle. The excitation can also be through the imposition of electrical, electromagnetic, temperature of stress fields etc. [5]. Most of the literature reported [3,6] commercially available power supply to provide the current/voltage excitation signal to SMA wire. Very few authors reported the transistorized [7], current amplifier [2, 4] driver circuit for providing excitation. In present work, an attempt is made to develop current controlled heating module (CCHM) for providing the current excitation to SMA. Such kind of heating module [8] is used in past for heating application of micro heating for gas sensors

Characteristics and behavior of SMA wire involves many dynamics and not fully understood. This includes Thermo-electrical-mechanical behavior. It is device design specific, and involves the ambient environmental conditions. Moreover, with changing phase from martensite-to-austenite and austenite-to-martensite, resistance of SMA wire changes significantly [2]. This can be used as a self-sensing element in most of controlling applications [1-4]. So, the resistance parameter is significant and desirable. Also, SMA have self-sensing ability to sense its own status by knowing the values of other parameters like temperature of SMA. So, precise measurement of any of these parameters can be used to derive the movement generated by SMA device. This fulfils the reduction need of bulky Linear Variable Differential Transformer (LVDT) sensors to sense the movement.

The advantage of CCHM is providing constant current of the order of 0-1amp needed for the SMA wire. The measurement unit provides direct measurement of the Voltage across (V_{SMA}) and current through SMA (I_{SMA}). For the resistance measurement (R_{SMA}), ohm's law is used. CCHM would further enable to model various parameters using the complex mathematical equations of R_{SMA}. Ambient temperature, wire temperature and displacement are also measured for the usage of data driven control [6] and senseless devices. These parameters are important for study and understanding the behavior of the SMA wire as well as hysteresis between Displacement (D) and difference Resistance (dR), and Displacement (D) and current (I_{SMA}) for making of any device using these wires for real life applications.

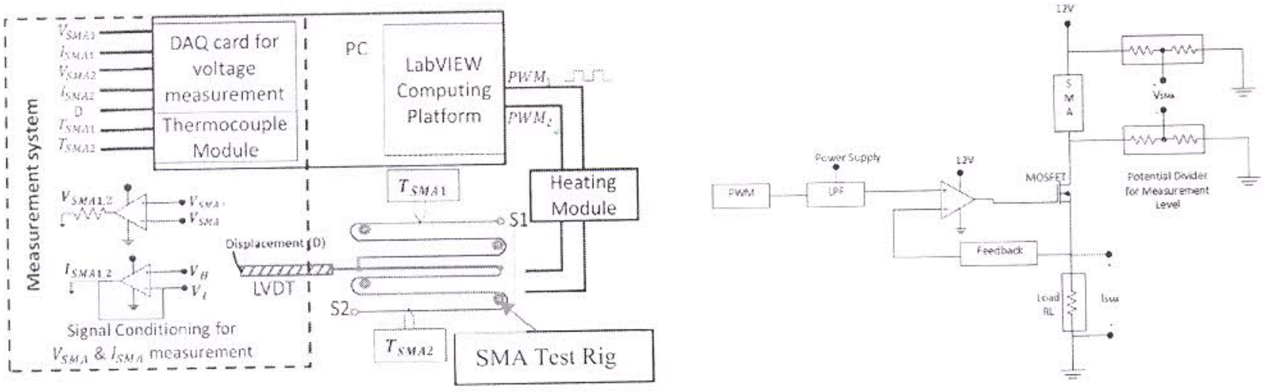
Main contribution of this paper is development of CCHM by designing a simple electronic circuit for SMA excitation and measurement system to obtain the various parameters. Developed CCHM along with experimental setup detailed in section II. Section III deals with measurement of various parameters of SMA wire. The control signal generated and applied to CCHM and the various observed responses of SMA wire are described in the results and discussion section IV. The final section concludes the summary of the proposed work.

II. HEATING MODULE

Experimental setup consists/composite of PWM generation using PC, CCHM, test rig of SMA wire, LVDT for position sensor, thermocouple temperature sensor and measurement system. The power requirement of the circuit is fulfilled using a power supply of 12V/5A and 15V. The functional block diagram for experimental setup is given in fig. 1(a). Specifications of experimental setup is given in Table 1.

Commercially available LVDT and k-type thermocouple temperature sensors are used for measurement of Displacement and Temperature respectively. They are assembled with SMA wire. CCHM is developed and used for giving the current excitation to the SMA actuator. The measurement system provides the interface of SMA wire to the NI DAQ. All channels of NI DAQ are configured in Differential mode. Test rig made up of two SMA wires denoted as SMA1 and SMA2 are connected in antagonist way to provide Bidirectional movement. Maximum displacement generated by using this arrangement is 6.5mm.

Developed electronic circuit CCHM provides the appropriate and controlled current needed to operate the SMA movement. CCHM composed of low pass filter (LPF), operational amplifier with appropriate feedback for controlling the current as shown in fig.1(b). To ensure the requirement of the range of constant current between 0-1A, it can operate/handle 1-10Ω SMA resistance variation precisely. LPF filter is designed by first order RC filter having 0.1 second time constant (τ). It provides average voltage of 0-5V to given 0-100% duty of PWM of 5V amplitude. For current limit, power resistance of 5Ω is connected to source terminal of IRF540N Metal Oxide Semiconductor Field Effect Transistor (MOSFET). An appropriate negative feedback is connected from load to input of heating module using LM358SN.



(a) (b)

FIGURE 1. (a) functional block diagram/ Schematic of experimental setup for bi-directional SMA Actuator (b)

Table 1 Specifications of experimental setup

Test Rig	Two SMA wire in antagonist way	
Software	LabVIEW17.0	
Sensor	K-Type Thermocouple	
	LVDT sensor	
Data Acquisition	SCB-68A Connector Block	
	DAQ Card	NI PXIe 8134 and PCI-6341
	Temperature Module	NI USB-9162
Heating Module	PWM generation	
	Low pass filter	
	Current source with appropriate feedback	

Measurement system includes the precise measurement of V_{SMA}, I_{SMA}, Displacement, ambient temperature and SMA wire Temperature (I_{SMA}). The system consists of signal conditioning for V_{SMA} and I_{SMA}, NI DAQ card 6341, LVDT and thermocouple module. These signals are interfaced from CCHM module to the A/D converter of NI DAQ through the suitable signal conditioning circuit. The signal conditioning is consisting of differential amplifiers, Unity gain amplifiers and attenuator. All these components are assembled together with SMA wire test rig as indicated in fig.1(a). Thermocouple sensors are used to measure the temperature of the SMAs.

The software is developed for data acquisition, processing and PWM generation on LabVIEW software platform. It helps in selection of user input parameters like duty cycle, frequency of the heating pulse PWM and assessing required input electrical heating power based on the target output parameters such as electric resistance of actuator elements, displacement and required transformation temperature. Two PWM channels are used to control the two SMA wires. The PWM signals are fed to the CCHM to produce the controlled current needed for SMA wires. The amount current is controlled using the PWM duty.

The heating module and measurement system are capable to generate the controlled current and acquire the SMA wire resistance, temperature and displacement data. It enables to study and experimental investigations of the behavior of the SMA hysteresis during displacement in both directions.

III. MEASUREMENT OF SMA WIRE PARAMETERS

SMA element undergoes electrical, mechanical and thermal variations. This variation involves lots of dynamics and variations in parameters. So, the need of measurement of SMA wire parameters such as Electrical resistance (R_{SMA}), displacement (D), Temperature (T_{SMA}), voltage across SMA (V_{SMA}) and current through SMA (I_{SMA}) are essential to study and characterize the SMA behavior. Significance of measurement of these parameters is as given below:

- Current is controlled to maintain linear relationship between applied PWM input and current through SMA (I_{SMA})

- Wire temperature (T_{SMA}) indicates the information about the phase transformation
- Ambient temperature (T_a) affects the cycle of heating and cooling during the experiment. It is important to measure the ambient temperature.
- Resistance of the SMA wire (R_{SMA}) changes dynamically according to the temperature of wire. It is due to change in length and diameter of the SMA wire. Resistance gets decreases as the temperature rise up.
- Change in resistance is indicated as a change in voltage
- On temperature stimuli, SMA wire contracts due to phase transformation this results in change in Displacement. This results in mechanical movement, which is measured by LVDT. Mechanical movement also gives the strain of wire.

Measurement of I_{SMA} and V_{SMA}

Current through SMA (I_{SMA}) and voltage across SMA (V_{SMA}) are measured by applying controlled PWM signal through CCHM and load resistance R_{Load}. The I_{SMA} is obtained by dividing voltage across R_{Load} and the value of R_{Load}. The V_{SMA} is obtained from voltage across SMA wire as given in fig.1(b). I_{SMA} and V_{SMA} are calculated by equation (1). These signals are interfaced to the NI DAQ card through DA's, Unity Gain Amplifiers and attenuator.

For the measurement of SMA wire electrical resistance (R_{SMA}), standard resistance measurement technique using Voltage across SMA and current through SMA is used. R_{SMA} is resistance of SMA wire measured in ohm (Ω) as calculated in equation (1). The advantage of measurement of R_{SMA} is that one can derive the relation between electrical resistance and displacement. Such self-sensing technique enables to replace the costly LVDT sensors in micro-robot and medical applications.

$$I_{SMA} = \frac{(V_H - V_L)}{R_{LOAD}} \; , V_{SMAx} = V_{SMA+} - V_{SMA-} \, , \quad R_{SMA} = \frac{V_{SMA}}{I_{SMA}} \qquad (1)$$

Commercially available LVDT sensor RS-646-505 having sensitivity of 164mm/mV is used to measure the displacement generated from the test rig of SMA wires. The range sensor measurement is 25mm. The output of the LVDT sensor is voltage and its corresponding value of displacement is derived in the LabVIEW software using the sensors sensitivity. As the temperature is one crucial parameter in phase transformation, accurate temperature measurement is required. This change in temperature is measured using two k-type thermocouple temperature sensors.

IV. RESULTS AND DISCUSSION

The measurement and heating module are utilized to obtain the behavior of SMA wires. PWM of frequency 1kHz, with initial duty 20% is applied to the Low pass filter for SMA1. Input PWM is given in increasing and decreasing order ranging from 10% to 90% duty cycle as shown in figure 2. The PWM duty cycle is increased in step_size of 1% up to 90% duty cycle and then decreased up to 20% minimum level of duty cycle. During the experiment 20% minimum level of duty is applied to ensure the pre-heating of the SMA wire. The scan rate to change the PWM is 1 sec. The scan rate of 1 sec is selected due to range of limited actuation frequency of SMA wires [1,3]. To understand the minimum and maximum hysteresis behavior of SMA wire, major and minor loops of measures of Displacement, I_{SMA} and R_{SMA} are to be attained. The sequence of PWM signals enabled to generate major loop of Displacement, I_{SMA} and R_{SMA}. To obtain the minor loops, maximum PWM duty is decreased by 10% in each cycle. The current produced by CCHM is in proportional to PWM input to this module as in equation (2).

$$generated\ Current\ using\ CCHM\ (mA) = 10 * Input\ PWM\ duty \qquad (2)$$

The plot given in fig. 2 depicts the measured current through, voltage across SMA and generated displacement from test rig. Two complimentary PWMs are given to two channels of SMA wire as shown in fig. 3. dR is obtained by calculating the resistances R_{SMA1} and R_{SMA2} of two SMA wire. The obtained dR along with complementary PWM signals are given in fig. 3. The measured value of V_{SMA} and I_{SMA} is verified using the standard KEYSIGHT multimeter to obtain voltage across SMA and current supplied by standard APLAB regulated power supply display respectively.

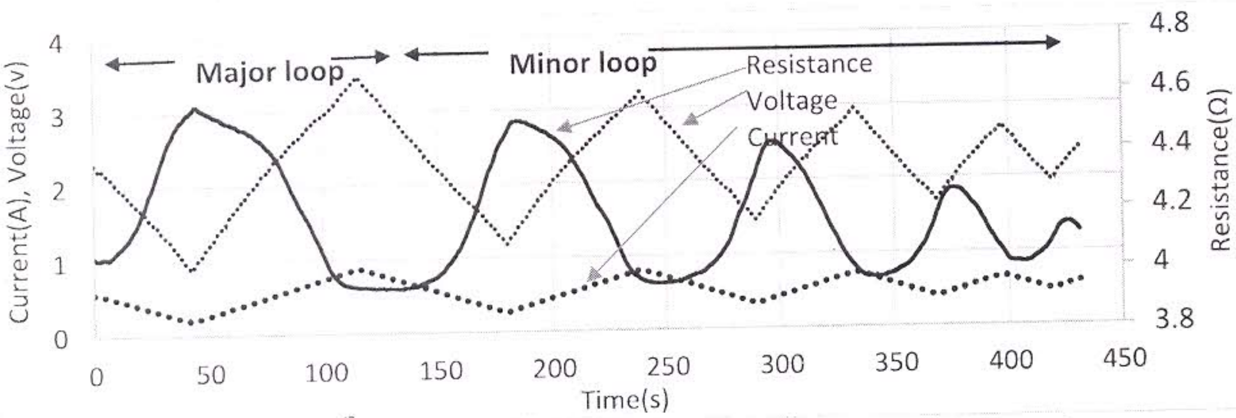


FIGURE 2. Measured current through, voltage across SMA and generated displacement from test rig.

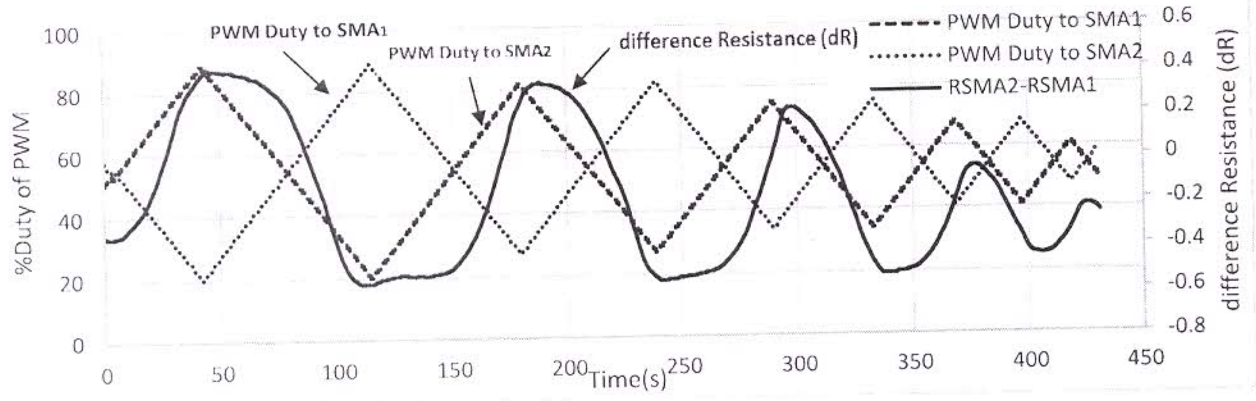


FIGURE 3. Applied PWM (in complimentary mode) in both SMA wires and derived difference Resistance

The obtained curve of Displacement with respect to time is shown in fig. 4. When the current is flowing through wire 1, displacement is generated in one direction and reaches to the maximum of its strain. Once the current is removed from wire 1 and applied in another wire immediately displacement occurs in reverse direction. This curve is not smooth and can vary according to the ambient temperature. There is slight shift in displacement which is due to ambient temperature variation and thermal equilibrium conditions. So, parameter measurement of the ambient temperature is significant. This causes hysteresis is generated in SMA wire generated displacement. To monitor the temperature of SMA wires, 2 k-type thermocouple sensors are used. Variations in temperature is recorded using NI - 6212 temperature modules. Sampling rate for this module is 96 Samples/channel. The same hysteresis is also observed in measured wire temperature and applied current. On given input PWM, measured temperature is show in in fig. 4(b). The measured temperature of SMA wire ranges from 32° to 60° C. Due to minimum applied current of amount 200mA, SMA wire do not cool up to ambient temperature.

Various experiments are performed to measure the parameters of SMA wire. The SMA behavior is studied and reported by applying the controlled current through CCHM. The observations and measured parameters agree with reported literature [1]. The electronic circuit of CCHM and measurement system is tested and its performance analysis is carried out by deriving various response of SMA wire on the test rig.

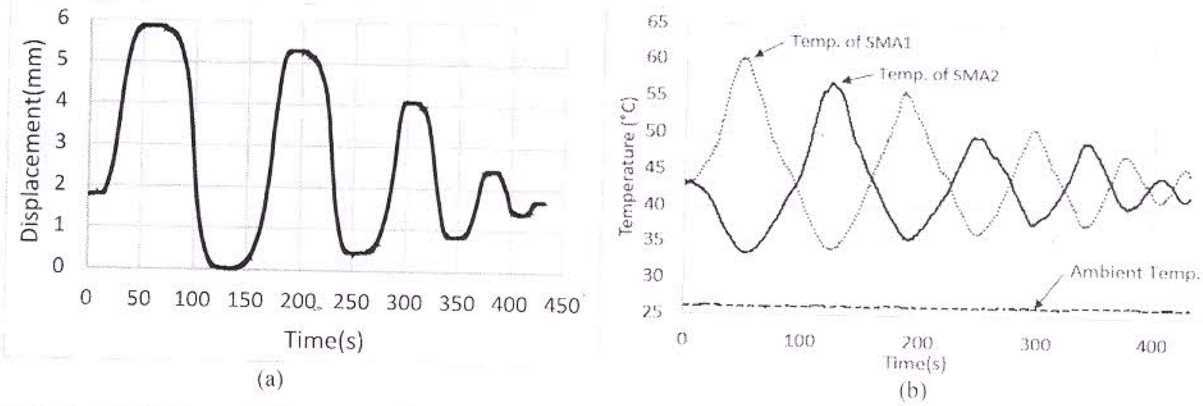


FIGURE 4. (a) Displacement (D) generated by SMA wire test rig and (b) Temperature measurement (T_{SMA}) with the applied PWM

CONCLUSION AND DISCUSSION

The CCMH and measurement unit is developed and its performance analysis is detailed in this article. Different Experiments are performed to investigate the developed hardware. Various experiments were conducted to validate the measurements. SMA parameters such as R_{SMA1}, R_{SMA2}, difference Resistance (dR), I_{SMA1}, I_{SMA2}, T_{SMA1}, T_{SMA2} and Displacement have been recorded. Their observations are recorded to study the SMA behavior. This unit serves the dual purpose of providing constant current and the resistance measurement unlike reported literatures. As the Resistance is varying during the heating and cooling cycle, heat calculation based on resistivity of material becomes difficult during the heating and cooling cycle.

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