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Effect of Pulse Width Modulation Current Control on Shape Memory Alloy Actuators

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Abstract

This paper proposes the design, construction and performance of a single element based tactile display. The technology employed utilizes a 100µm diameter heat actuated wire of Nickel-Titanium (NiTi) shape-memory alloy (SMA) which contracts when pulsed with an electrical current (in effect heating the metal) under pre-stress. The display can produce a maximum pin deflection of 5mm which can be raised and lowered to approximate the desired output signal. In other words, SMA materials can directly convert thermal energy to mechanical work. This phenomenon, which provides a unique mechanism for actuation, is associated with the unique interaction between the martensite and austenite crystal structures of the SMA material. The paper discusses the design and evaluation leading to the dynamic performance of the system via step responses as well as the control of tactile sensor length and displacement using pulse width modulated current control technique.

Keywords: Shape Memory Alloy SMA; Pulse Width Modulation PWM; Displacement; Force; Tactile Display.

1. Introduction

Shape memory alloys (SMA's) are novel materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure [4,6]. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their shape prior to the deformation. These alloys exhibit the so-called mechanical-memory effect caused by a structural transition between a martensitic phase and an austenitic phase, characterized by higher crystalline symmetry. This transition starts when the alloy is heated past its austenitic start temperature and ends upon reaching the austenitic finish temperature [8,9,10].

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It is actually the power balance relating electrical power supplied by pulse modulated current signals to rate of heat lost and rate of heat to raise temperature of the SMA actuator. The heating is generated by electrical current i.e. the electric field is used as a potential heat source [1,2,3]. The primary goal of this work is focused on sensors that transduce the mechanical input into an electrical output signal, and to demonstrate that the Shape Memory Alloy wire length and displacement can be controlled accurately and rapidly by the use of Pulse Width Modulation current control technique using a PIC Microcontroller to perform all the necessary control and signal conversion [2,4]. The work explores the control of tactor length and displacement by determining an average pulse modulated current sufficient to maintain the tactor in its controlled configuration with the amount of energy delivered being dependent on the current. This paper will cover the experimental setups of the mechanical design manufacture of the shape memory alloy spring-biased tactile sensor and display. The paper will also describe the EPROM based 8-bit PIC16C74 microcontroller used in this work and will cover its initialization requirements in terms of its communication protocol, data ports, signal conversion frequency and resolution, pulse width modulation and timers [5].

2. Experimental Setup

The tactile display consists of aluminium and Perspex frame box consists of tactile sensor, an axial cooling fan, a pin chuck and a measurement controller board. The technology employed utilizes the Flexinol 100 µm heat actuated NiTi SMA wire which contracts when heated under pre-stress and produces up to 5% strain recovery. The overall design of the tactile display is shown in Figure 1.

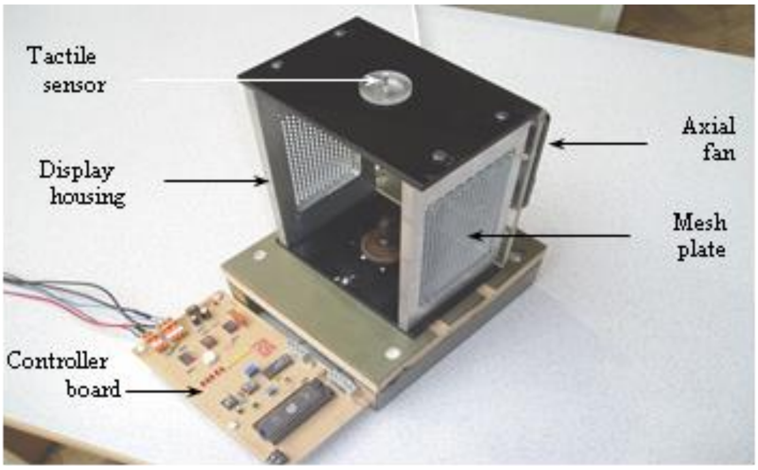

Figure 1: SMA element actuators unit.

One of the major challenges of designing the display is to make it mechanically stable and to allow a good cooling environment for the SMA wire. Therefore, two mesh type plates were attached on both sides of the display; these plates will help circulating the air when the cooling fan is on. A pin chuck is used to hold the bottom end of the wire and to provide any length adjustment required for the wire. The axial fan is used to allow faster tactile sensor response and to provide a stable thermal environment. The electrical connections of the NiTi wire are made by means of electric wires connected to both ends of the wire through the crimps.

The mechanical design and assembly of the tactile sensor is shown in Figure 2. The sensor is made of a combination of a 1mm diameter x 40mm long steel pin, a bias spring type-Steel SS 1774-04, and a 100 mm long of 100 micrometer NiTi wire crimped to the steel pin.

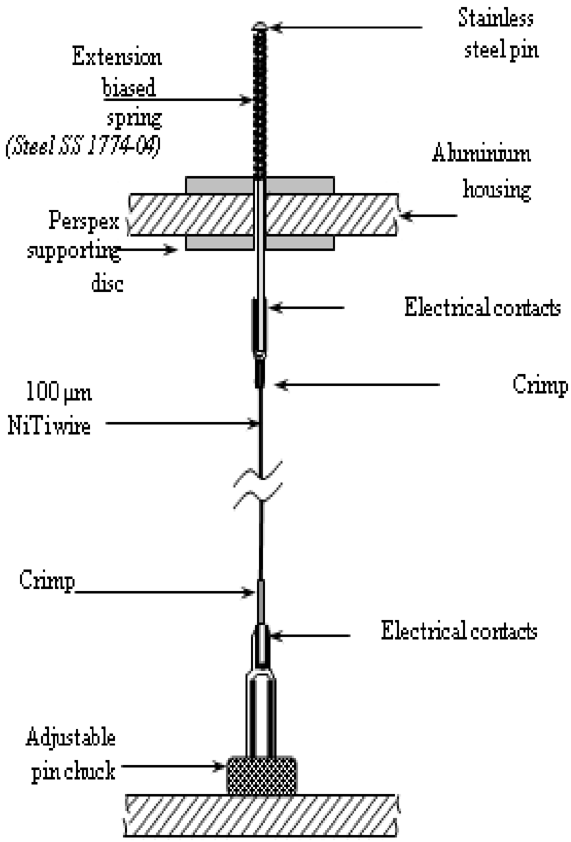

Figure 2: SMA tactile sensor. Assembly**.**

The steel pin is crimped to the wire from the top end into a hole in a Perspex disc through a bias spring. The extension spring with a spring rate C of 0.46 N/mm and a free length of 10 mm is used to provide the required reversible motion for the tactile sensor and to keep it under tension when relaxed. The spring was selected to represent an initial stress on the wire of roughly 70 MPa. This amount of stress is hoped to rise the transition temperature and effectively makes the alloy into a higher transition temperature wire. The spring has a slightly bigger diameter than the steel pin, so it can move freely. The picture of Figure 3 shows the attachment of the SMA tactile sensor. Table 1 shows specifications of the extension spring [2].

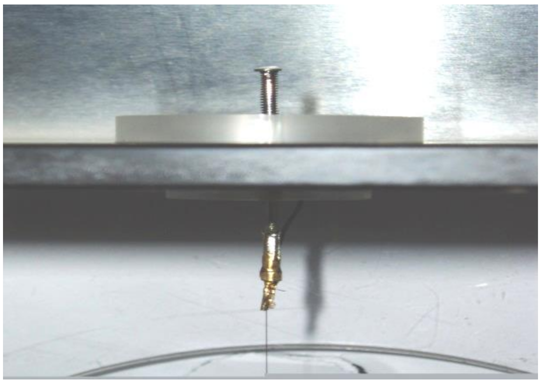

Figure 3: Upper side attachment of the sensor.

Table 1: Specifications of the extension spring.

Description	Value
Wire diameter	0.2 mm
Inner diameter	1 mm
Total number of coils	34.3
Pitch	0.45 mm
Loaded length (min working length)	9.2 mm
Outer diameter	1.4 mm
Maximum working temperature	150 ^{o}C
Spring rate	0.274 N/mm
Spring free length	10 mm
Spring full compressed length	5mm
Spring force at max displacement	1.37N
Spring initial displacement	2mm
SMA stress at initial displacement	70 MPa
Force applied at initial displacement	0.548 N

3. Experimental method

The PIC 16C74A microcontroller initiates a train of current pulses in the form of pulse-width modulated signals to actuate the SMA wire and to control its displacement. The PWM signals are delivered to the wire with a frequency of 1 KHz and duty cycle values ranged 10% to 100 % via a MOSFET. This method and the applied cooling establish an average current sufficient to maintain the SMA wire in its contracted configuration without overheating it. Duration of the duty cycle and frequency of the pulse-width modulated signal are under software control.

A schematic representation of the system setup is shown in Figure 4. During heating process, the shape memory alloy element undergoes a phase change, which increases its tension and shortens its length and hence decreases its electrical resistance. This yields a combination of both force and displacement. The amount of force and displacement is dependent on the exact geometry of the SMA element and the amount of heating. They produce a unique mechanism for actuation.

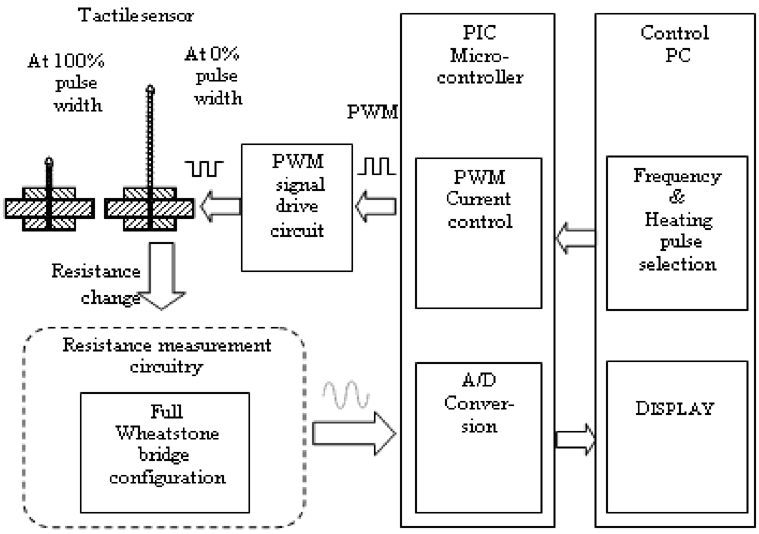

Figure 4: Schematic representation of the wire position control system setup.

The resistance of the SMA wire is measured through a Wheatstone bridge circuit which provides a convenient method for resistance measurement. The PIC then receives this analogue measured signal and converts it into a digital number then transmits it via RS232 serial communication interface to be read by the host computer.

3.1. PIC Micro-controller Initialization

This Section covers a brief description on the PIC microcontroller, some of the features that we have made use of, and its initialization settings for this work. The PIC 16C74A microcontroller is the heart of the control electronics. It is a member of the PIC16CXX family of low cost, high performance and fully static EPROM based 8-bit CMOS microcontrollers. The PIC has 192 bytes of RAM and 33 I/O pins. It was selected for our application because of its several useful peripheral features [5] including; three timer/counters, two capture/ compare/ PWM modules and two serial ports. An 8-bit Parallel slave port is provided and eight channels of high-speed 8-bit A/D. These special features reduce external components, thus reducing cost, enhancing system reliability and reducing power consumption.

In this work, the PIC is used to provide the required heating current to activate and control the SMA wire. It initiates a train of current pulses in the form of pulse-width modulated signals with various duty cycles. The PIC microcontroller provides the modulated current source for controlling the tactile element through a pulse width modulated signal. It provides an average current sufficient to maintain the SMA wire in its controlled configuration without overheating it. The length of the starting pulse duty cycle of the PWM is under software control. The PIC is responsible for altering the pulse width modulation control signals accordingly and sending these control signals to the tactile element. The supply voltage to the controller circuit is supplied through a voltage regulator which provides a stabilized output voltage of 5v dc from a fluctuating dc input voltage of 15v dc. The PIC microcontroller receives data signals (ASCII strings) from the host computer via a serial data link, interprets them and drives the tactile element through a driver circuit. The input data signals from the host PC to the PIC micro-controller are received through a MAX 233 driver/converter. This driver/converter was used because data signals are transferred from PC through RS 232 serial data link. This serial data link is a standard for the serial exchange of digital data and defines a voltage level greater than 3v as a logic 0, so this chip is used to convert the digital output signal from the Micro-controller to the RS 232 voltage levels and vice versa. The PIC has eight input/output channels and operates at a supply voltage of (+5v). It receives its clock oscillation from an external crystal oscillator. This crystal clock oscillator is used to provide the PIC with an external oscillation source of 16 MHz through Pin1.

3.1.1. PIC Micro-controller Software

Previous related work by Moser, Taylor and Creed [14], they used an Assembly code for programming PIC micro-controllers. In this work, the PIC microcontroller software program was written in C language using the PIC C Compiler [5,7], which provides a platform for developing the software code for Micro-chip microcontrollers. Using a higher level C language provided a better alternative. It can be read and edited with more ease, by other people working on the system and for future development. This software performs the selection of operating frequency, generation of PWM current signals, analog to digital conversion, alteration of tactor position and the detection of touch/force. A PICSTART 16C development programmer for Microchip PIC Microcontrollers was used for loading programs into the PIC microcontroller [5,11]. This programmer can be connected to the PC via RS 232 serial interface. The programmer supports the so-called on-board programming mode. This uses a 40-pin ZIF programming socket which allows PIC microcontrollers to be programmed out-of-circuit.

3.1.2. Timer Initialization

The PIC 16C74A microcontroller is equipped with three timer modules [5,11]. Each module can generate an interrupt to indicate that an event has occurred (i.e. timer overflow). The timer modules are TMR0, TMR1 and TMR2. One timer (Timer2) was selected to determine the time limit of the PWM signals to be used to actuate the SMA wire. The PIC C Compiler has a function which writes the 8-bit value to the PWM to set the duty. This function was written as: **SETUP_TIMER_2 (value);**

3.1.3. Pulse Width Modulation Initialization

Pulse Width Modulated signal is a periodic train of pulses, where the base frequency is fixed, but the pulse width is a variable. The pulse width is directly proportional to the amplitude of the original un-modulated signal [4,13]. In other words, in a PWM signal, the frequency of the waveform is a constant while the duty cycle varies (from 0% to 100%) according to the amplitude of the original signal. The frequency of the PWM is simply the inverse of the period (1/period).

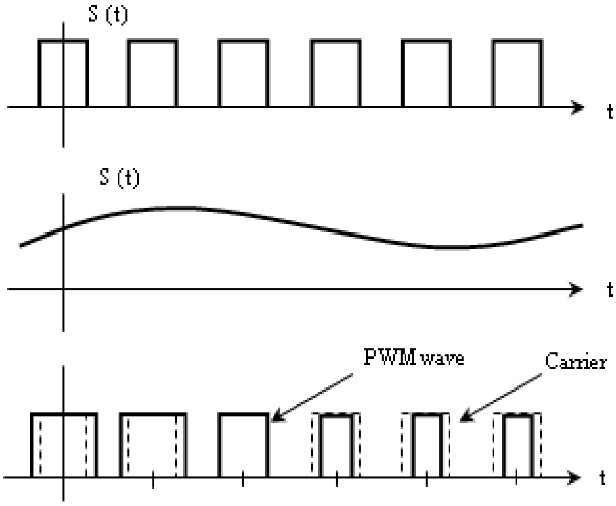

Figure 5: Pulse Width Modulations.

Figure 5 shows an un-modulated pulse train, a representative information signal *S(t)*, and the resulting pulse width-modulated (PWM) waveform. The width of each pulse varies in accordance with the instantaneous sample value of *S(t)*. The larger the sample value, the wider is the corresponding pulse. Since the pulse width is not constant. Thus, as the amplitudes of the signal increase, the power transmitted also increases. The versatility of PWMs makes it ideal for our particular control application. Here, the PWM technique is used to control the amount of energy transferred to the SMA wire to actuate it and hence control its length. When using PWM current pulses, the time-averaged energy delivered to the SMA wire with a fixed duty cycle is the same regardless of the period of the PWM signal. The period of the PWM signal was determined by selecting Timer2 period register (PR2). The cycle time is obtained using the following formula: **(1/clock)* 4 *(PR2+1)* (TMR2 pre-scaler value)**, where clock determines the operating frequency of the PIC and it was s set to 16 MHz, PR2 is the period register which determines the PWM operating period and it was set to 255 and TMR2 is pre-scalar value, it was set to 16. Now the duration of the PWM output pulse can be given by: Cycle time= (1/2000000) * 4* 16 * (255 + 1) * 1 = 1.02 ms, this corresponds to a PWM operating frequency of 0.98 KHz. The followings are the functions used in the software code for PWM: **SETUP_CCP2 (CCP_PWM);** this function configures the CCP2 counter to measure pulse width. **SETUP_TIMER_2 (T2_DIV_BY_16, 255, 1);** this function sets up timer 2 to instruction clock and calculates the PWM period. **SET_PWM2_DUTY (153);** this function sets the duty cycle for PWM, in this case the value was selected as 152 as an example. This value of 153 is in decimal representation, it is the duty cycle, and it represents 60% of the PWM period of 255. This carries an amount of heating current of up to 185mA capable of heating the SMA wire up to 65 ^{o}C. See Figure 6.

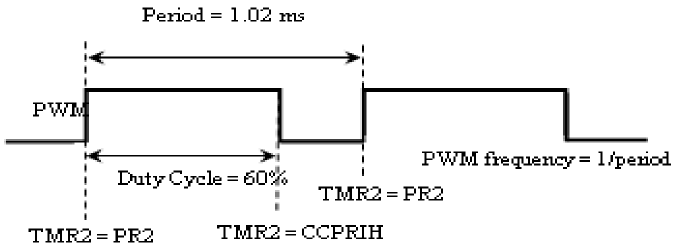

Figure 6: Pulse Width Modulation output.

3.1.4. PWM Drive Circuitry

The drive circuit for the tactile element in Figure 7 uses the PWM signal from the PIC microcontroller to supply a corresponding current to the SMA wire. The PIC Microcontroller controls the gate voltage to the MOSFET (metal oxide semiconductor field effect transistor) permitting a voltage pulse from the +5 volt supply via the MOSFET to actuate the SMA wire. This type of transistor used has low power consumption, high input resistance, and high frequency response.

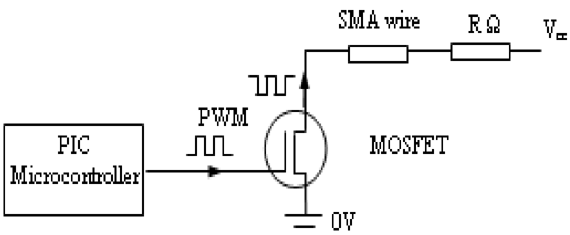

Figure 7: NiTi SMA wire drive circuit.

3.2. Determination of Effective Voltage For a PWM Signal

When using PWM current pulses, the time-averaged energy delivered to the SMA wire with a fixed duty cycle is the same regardless of the period of the PWM signal. The primary effect of increasing duty cycle is to increase the energy delivered to the SMA wire and thus the total wire displacement. To determine the effective voltage or current of a varying voltage (for heating) the most common mathematical method is the root-mean-square (r.m.s). When using a pulse width modulation, the DC voltage is converted to a square-wave signal alternating between fully on to off. In other words, the power is supplied to the wire on and off very rapidly giving the wire a series of power (kicks). The following diagram of Figure 8 shows how the voltage is switched periodically by adjusting the duty cycle of the signal (modulating the width of the pulse, hence the PWM) .i.e. the average energy can be varied, and hence the wire temperature.

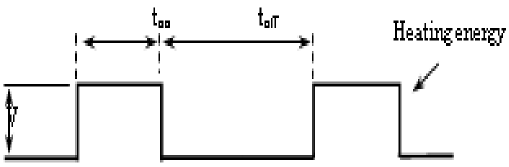

Figure 8: Energy/cycle diagram.

Since the power is given by $P=VI$, so the energy delivered in t_{on} can be determined by:

$$P_{sma} = \frac{t_{on}}{t_{on} + t_{off}} x P_{on}$$

where t_{on} is the period where power is carried on, t_{off} is the period where power is off, and P_{on} is total power across the whole circuit. The following example of Figure 9 shows the method which was used to determine the effective heating power from a PWM signal delivered to the SMA wire to actuate it. From the Figure, a PWM input signal is used to actuate the SMA wire. To work out the effective heating power P_{sma}, we start with finding out the r.m.s voltage and current across the SMA wire.

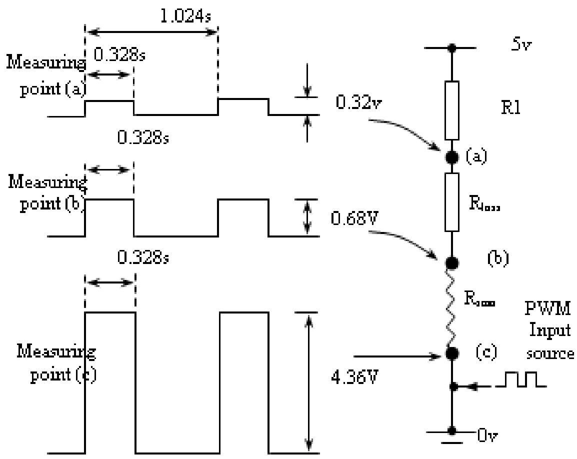

Figure 9: PWM effective voltage measurements**.**

The effective heating power P_{sma} can be determined using the Equation:

$$P_{sma} = \frac{t_{on}}{t_{on} + t_{off}} x P_{on}$$

The r.m.s voltage across the SMA wire is the difference in voltage measured between measuring points (b) and (c) in Figure 9, it can be determined as:

$P_{on}=V_{sma}\ x\ I$

$V_{sma}=4.36-0.68=3.68V$

The current *I* across *R1* is common for the whole circuit, which means it is the same current across the SMA wire.

Now, by measuring point (a) we find that, the signal has an r.m.s voltage V_{rms} = 0.32V at a time t_{on} = 0.328s.

$$I_{sma} = \frac{0.32}{1} = 0.32A$$

Using Equation: $P_{on}=V_{sma} \times I$

$P_{on}=3.68 \times 0.32=1.178W$

Now, we can get the heating power delivered to the SMA wire to actuate it as:

$$P_{sma} = \frac{0.328}{1.024} x1.178 = 0.377W$$

4. Results and Discussion

The SMA tactile sensor can be controlled accurately and rapidly for both length and position. When the element is pulsed with a train of heating current pulses it can be raised and lowered to approximate the desired output position. This is a software selectable process. The software sets a command for a particular tactile element level position. The PWM current controlled signals are transmitted via a serial data link from the host computer. Figure 10 shows PWM input signals for different duty cycles versus the sensor pin deflection.

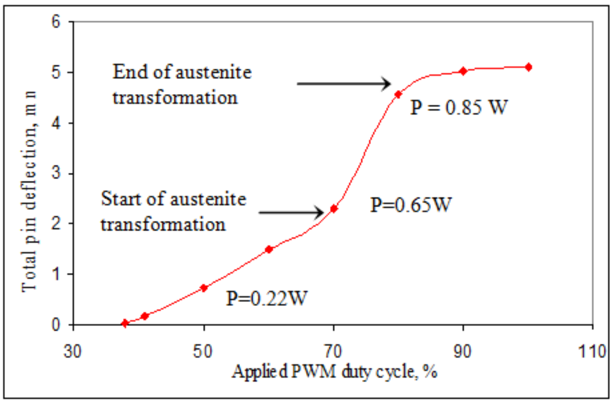

Figure 10: The effect of duty cycle on tactile element displacement.

The PWM values are set as bytes ranged from 0 to 255. They represent the actual input signal determined by duty cycles ranged 0 to 100%. Series of tests were performed on the SMA tactile sensor to observe its displacement response in the heating phase under forced cooling condition. Figures 11, 12, 13, 14 and 15 show the pin displacement under forced cooling condition and its corresponding PWM pulse input. The displacement was measured by a Micro-Epsilon laser sensor [12].

A train of PWM current pulses in the power range of 0W to 1.5W was applied. For steps of heating pulse inputs less than 50 % (0.34W), there was no measurable contraction. It is only after a 50% heating pulse input, the contraction starts. At an input pulse of 70% duty cycle approximately 0.6W a complete shift from martensite to austenite transformation appeared producing considerably more contraction than did the previous steps. This behaviour is most likely due to differences in the exact phase condition on the SMA wire where phase transition takes place. For powers in excess of 0.85W, the characteristic curve takes almost a linear course showing no further displacement. This means that, a further increase in temperature would not give rise to a further change in the crystal structure and will eventually damage the wire.

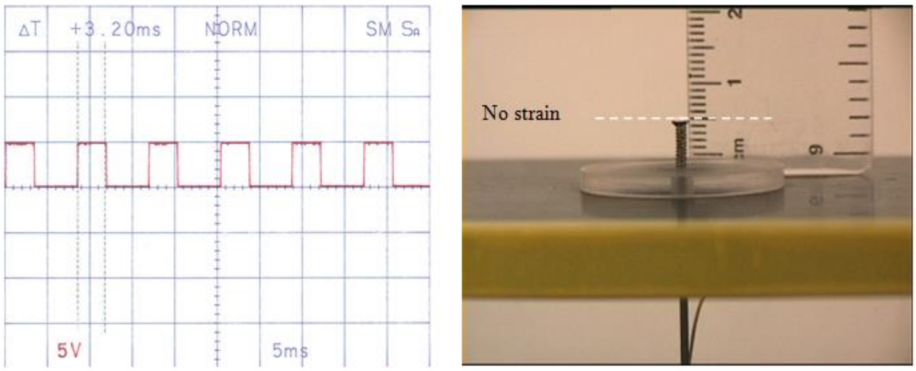

Figure 11: Pin displacement at 40% heating pulse and 0.22w heating power.

Figure 11 shows a step input of 40 % heating pulse under forced cooling condition causing no sign of contraction. The SMA is still in its martensitic phase.

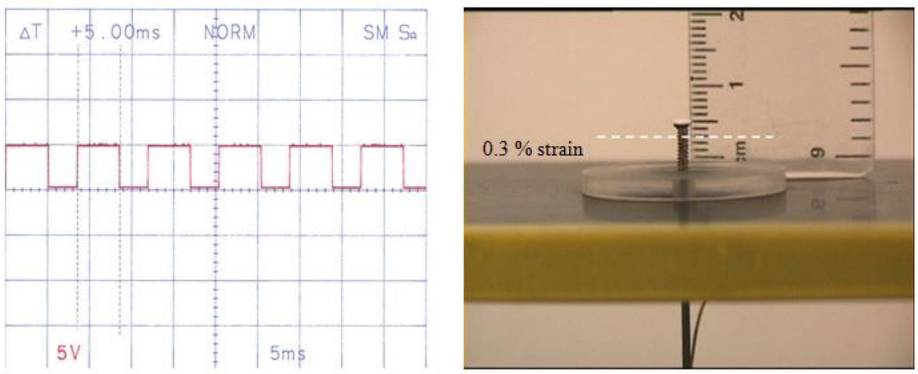

Figure 12: Pin displacement at 50% heating pulse and 0.34w heating power.

In Figure 12, the effect of PWM signal on the wire starts. However, there is a very small measurable contraction of approximately 0.3 mm, and phase transition is still not started yet.

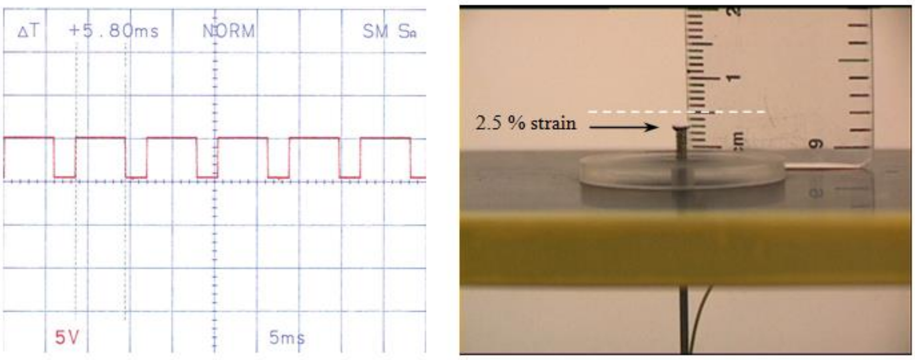

Figure 13: Pin displacement at 70% heating pulse and 0.65w heating power.

Figure 13 shows a clear sign of measurable pin deflection of approximately 2.3 mm as a result of 70 % heating pulse of approximately 0.65 W. Here the SMA has just entered the phase change transition by shifting from martensitic to austenitic phase.

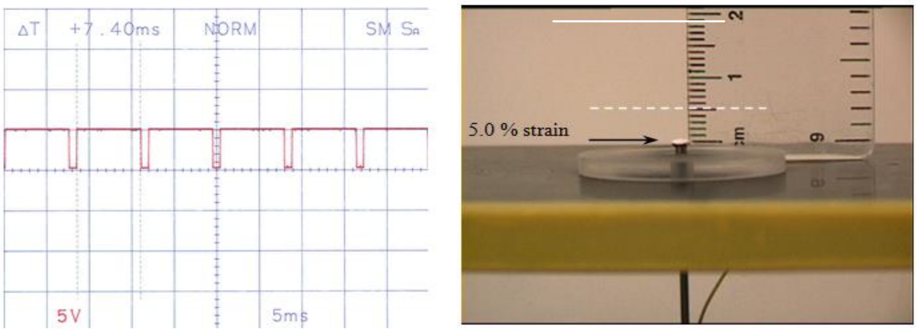

Figure 14: Pin displacement at 80% heating pulse and 0.85w heating power.

Here, the SMA wire movement stops as in Figure 4. The wire leaves the phase change region and enters the austenite finish temperature limit. Heating the wire beyond that will not cause any further displacement as shown in Figure 15.

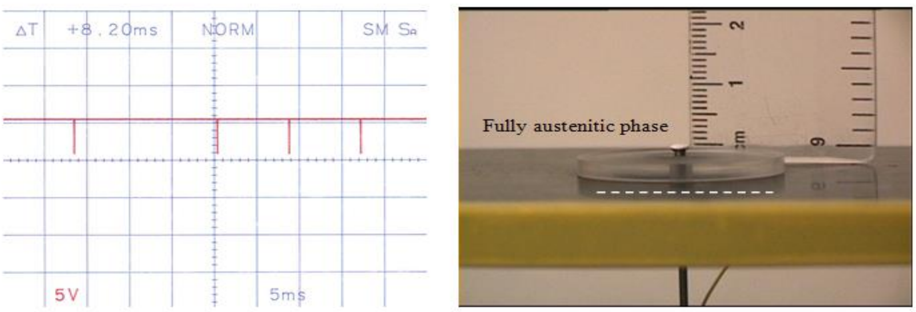

Figure 15: Pin displacement at 100% heating pulse and 1.48w heating power.

The rise and fall of the tactile sensor displacement as a function of the applied current was observed using a storage oscilloscope. The step response of the tactile sensor as a function of a heating current pulse of 280 mA is shown in Figure 16.

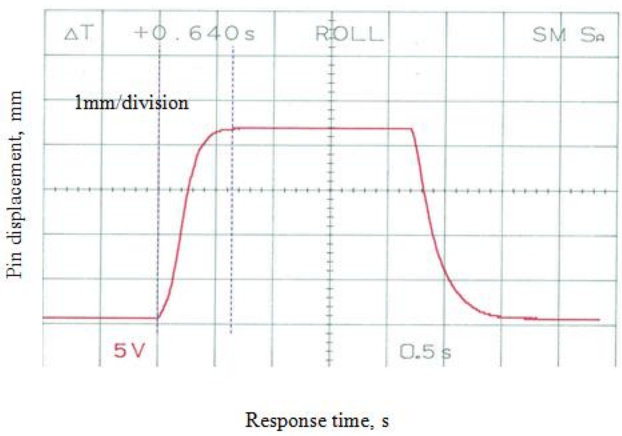

Figure 16: Oscilloscope recording of tactile step response at 280 mA heating pulse.

The step response of the tactile element which was measured by the Micro-Epsilon laser sensor rises exponentially within a minimum response time of approximately 0.64 second. The fall time which is limited by the transition temperature variations of the SMA material influenced by the rate of cooling and also stress of the extension spring takes longer response time of approximately 1.0 second (current is turned off).

5. Conclusion

After several tests, we can conclude that the use of PWM current control has proved and demonstrated that the SMA wire can be controlled accurately and rapidly in approximating its desired position and length. However, we should emphasize that it is extremely difficult to control the speed of wire displacement when pulsed with PWM signals of 75 % to 85% duty cycles (65W to 85W heating pulse). This is where the wire enters the austenitic temperature region in a response time of approximately 0.1 second. This justifies the neglecting of employing touch detection in the phase transition region of temperatures A_s to A_f. The touch detection tests were employed when the wire's temperature remained near A_s and just after A_f temperature regions. The use of SMA wire as an actuator has proved its capability of providing the necessary motion displacement, and its physical characteristics suitability for electrical actuation. However, slow recovery time of the tactile element of 1.0 second was observed. This is because the fall time is limited by the rate of cooling. Cooling takes significantly longer than heating; therefore, it takes longer to return to the martensitic phase than it took to reach the austenitic phase. This longer cooling time in turn limits the bandwidth of the SMA actuator with an adverse effect on actuator control and simulation quality when use in a haptic display. Due to the highly non-linear behaviour of the SMA wire and the slow thermal response, hysteresis of 10-20 % was clear evident in many published curves in accordance with parameters related to temperature, displacement and resistance characteristics. If we consider the heating phase condition, we find there is a significant delay between the increase of the input heating current and the appearance of the force increase due to the integrating effect of the thermal mass of the wire. On the other hand, the descending phase show more causing far more pronounced hysteresis due to the slow cooling rate, so that temperature drops more slowly than heating current. Finally, it should be emphasized that, all the work involved in this project does not consider the dynamics of the SMA material in itself. Thus, it is not meant to physically predict the behaviour of the SMA element in time when the material is submitted to a constant stress. All our relations are algebraic relations in the involved quantities. i.e. temperature, resistance and neglecting the dynamics, which may provide a useful platform for further research.

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