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DRAFT: SENSORLESS CONTROL OF SMA USING SEEBECK VOLTAGE

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ABSTRACT

Active research of SMA has presented the measurement of thermoelectric properties as a useful and a potential tool in the study of phase transformations. The Seebeck coefficient is sensitive to the martensitic transformation behavior of SMA and can potentially be used to determine the state of Martensitic transformation of a SMA. The combination of Shape Memory Alloy having a positive Seebeck coefficient and Constantan with a negative Seebeck coefficient (-35 μV/K) is a suitable thermocouple pair to measure temperature. This relation along with the displacement characteristic provides a feasible method to determine the state of SMA at any point during Martensitic phase transformation. Future work aims at utilizing the thermoelectric relation of the SMA-Constantan thermocouple as a feedback variable in replacing external sensor.

INTRODUCTION

Among different active materials available, Shape Memory Alloys (SMAs) are popular as an actuator due to its unmatched energy density. Active research is being carried out in the areas of actuation and control of SMA where large force and displacement are required from a relatively small dimension of SMA wire. Many applications of SMAs, as actuators, have been developed in recent years. The high power-to-weight ratio and fast strain recovery rate of SMA has been useful in vibration absorbing applications [1].The low driving voltages and high strain of SMA is attracting the use of SMA in robotics and biomimetic applications such as artificial hand [2] and robotic jellyfish [3].

The crystallographic transformation from symmetric monoclinic Martensitic state to body centered symmetric Austenite state by resistive heating of SMA and recrystallizing to Martensitinc state upon cooling has made the Shape Memory Alloy a highly potential candidate for control applications.The force and the displacement characteristics of SMAs largely depend on the path and the volumetric ratio of Martensitic to Austenite phase during transformation. The change in electrical resistivity is frequently used as a measure to determine the degree of phase transformation of SMA [4–8]. Many researchers have used electrical resistance as a feedback variable to control the position of SMA [9, 10]. The hysteric behavior of SMA's strain characteristics has been modeled with soft computing methods such as Neural Networks [11–13] for control problems with resistance as feedback.

A common sensorless control of SMA uses resistance of SMA as a feedback variable. The disadvantage of this method is that the resistance change has a hysteric behavior and resistance measurement is specific to a particular length and diameter of SMA wire. Although, previous research has shown that the Seebeck coefficient of SMA is affected by the temperature induced phase transformation and has a nonlinear hysteric behavior [14],thermoelectric properties of SMA have not been used in control applications. Evaluating the Seebeck coefficient of an

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activated SMA to use it as a feedback variable is practically difficult. Recently, SMA is controlled by alternating the driving voltage of Thermoelectric devices (TEDs) such that the temperature of SMA is sensed by using Seebeck voltage of TED as feedback [15]. The use of thermoelectric properties of SMA in determining the state of phase transformation and controlling SMA is the goal of our research.

In a step towards the sensorless control, of SMA having Seebeck voltage as feedback,the present work deals with the characterization of Seebeck voltage of SMA-Constantan thermocouple and propose a stategy in using SMA as a collocated actuator and sensor. Seebeck voltage is independent of the diameter or length of SMA wire and this is one of the advantages of using Seebeck voltage for feedback. In section 2 of our present work, an SMA-Constantan thermocouple is characterized and a polynomial fit is determined for the thermocouple pair. Although the Seebeck coefficient of SMA has a hysteric behavior, we have shown that a linear fit is sufficient to describe the relationship between Seebeck voltage-temperature of SMA-Constantan thermocouple. In section 4 we propose an innovative idea using the linear Seebeck voltage -temperature relationship for sensing the temperature of SMA for controlling a cantilevered bimorph.

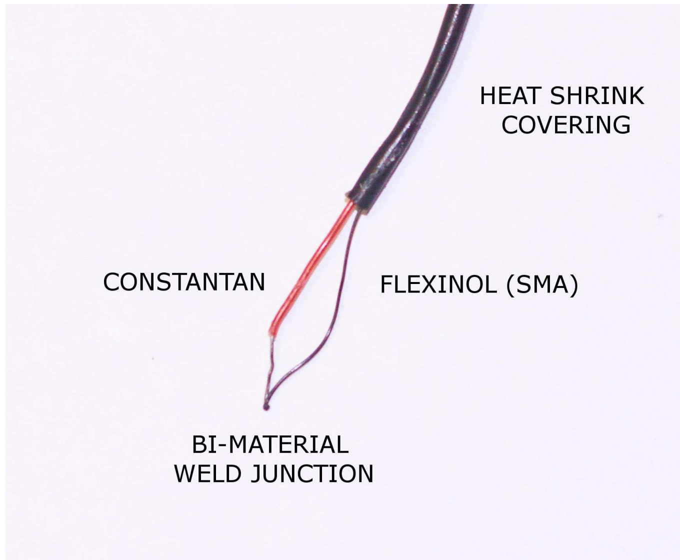

FIGURE 1. FLEXINOL(SMA)-CONSTANTAN THERMOCOUPLE

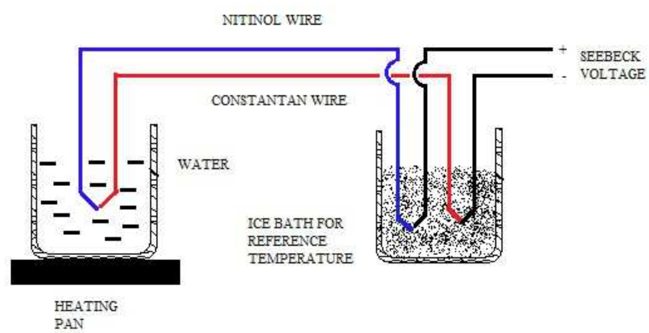

FIGURE 2. EXPERIMENTAL SETUP FOR SEEBACK VOLTAGE CHARACTERIZATION

SEEBECK VOLTAGE-TEMPERATURE CHARACTERIZATION

In a thermocouple the relative Seebeck coefficient (S_{AB}) of a pair of dissimilar materials with individual Seebeck coefficient S_A and S_B is given by:

$$S_{AB} = S_B - S_A = \frac{\Delta V_B}{\Delta T} - \frac{\Delta V_A}{\Delta T}, \qquad (1)$$

where ΔV_A and ΔV_B are the thermoelectric voltages developed across the terminals of materials A and B due to a temperature difference of ΔT.The Seebeck coefficient largely depends on the free charge carriers of the material and thereby the crystallographic structure of the material. Equation 1 shows that a combination of positive Seebeck coefficient material (such as SMA) and a negative Seebeck coefficient material would result in a thermocouple pair with higher sensitivity.Previous research, [14] has shown that the thermoelectric sensitivity (or Seebeck coefficient) is positive all throughout the phase transformation cycle of SMA. After careful consideration Constantan with a Seebeck coefficient of about -35μV/K is paired with Flexinol wire (from DynAlloy Inc. [16]) to form a thermocouple. Flexinol and Constantan wires of equal diameters have been welded using a capacitive discharge spot welder to form a bimetallic junction at one end as seen in Figure 1. The bare terminals of both the materials have been welded with copper wires. The temperature gradient along the length of the wires gives rise to a built-in electric field resulting in Seebeck voltage. To measure the temperature at the SMA-Constantan junction, a reference temperature is required at the other end of the thermocouple wires. The reference temperature junctions SMA-Copper and Constantan- Copper junctions are maintained at 0°C by an ice water bath as show in the Figure 2. The voltage developed due to the temperature gradient across the dissimilar materials is measured at the bare copper terminals. The thermoelectric electromotive force (emf) developed in one copper wire due to the temperature gradient is nullified with the emf generated by the other copper wire. Hence the voltage generated across the free copper terminals is the difference

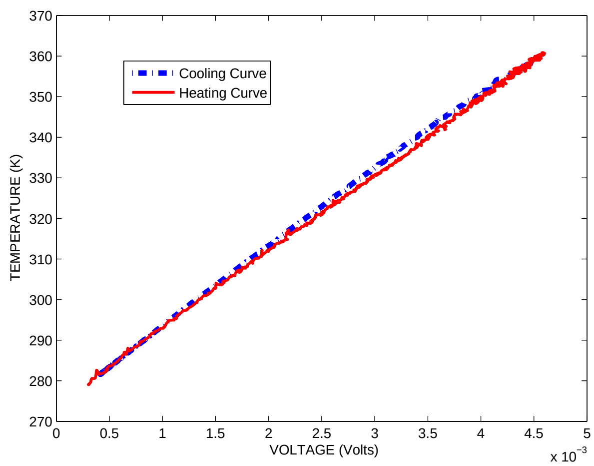

FIGURE 3. THERMOELECTRIC VOLTAGE vs TEMPERATURE

between the emfs generated across the SMA wire and the Constantan wire. This is Seebeck Voltage of the SMA-Constantan thermocouple.

Contrary to the general laws of thermocouples, the room temperature plays an important role in SMA-Constantan thermocouple pair. Due to the change in external temperature SMA wire experiences a phase transformation, thereby changing the thermoelectric sensitivity of SMA material and hence the thermocouple. But at a constant external room temperature the Seebeck coefficient of Flexinol is constant. A constant room temperature of 295K is maintained throughout the experiment. It has been observed that variation of room temperature by 1-2 degrees does not have an adverse effect in the thermoelectric voltage measurement.

The transformation temperatures of Flexinol are observed to lie within the temperature range of [293K 298K] at stress free state. The thermoelectric voltage and temperature characteristic is measured by heating the tip of the bi-material thermocouple. The SMA-Constantan junction is inserted in a cold water bath and the water is heated from 283 K to 358 K using a heat pan. Repeatability of the Seebeck voltage-temperature trend is observed with different rates of heating water and with different diameter thermocouple pairs. To confine the transformation of NITINOL to the thermocouple junction the SMA-Constantan junction placed just below the water surface. A K-type thermocouple is also placed at the same horizontal level as the tip of the SMA-Constantan thermocouple pair to avoid the effect of thermal gradient in the water. Throughout the experiment the temperature of the reference junction is maintained at the 273 K. The thermoelectric voltage of the SMA-Constantan thermocouple is recorded along with the temperature obtained from the K-type thermocouple. The SMA-Constantan thermocouple characteristic relation is plotted in the Figure 3. The heating curve (red) corresponds to the relation between thermocouple voltage and temperature during thermal loading and the cooling curve (blue) gives relation during thermal unloading. The water is cooled by placing the setup in an ice water bath. There is a negligible effect on the thermoelectric voltage characteristic due to the rate and method of cooling water. The slope of the thermoelectric voltage temperature characteristic gives the relative Seebeck coefficient of SMA-Constantan pair as seen in Figure 4.

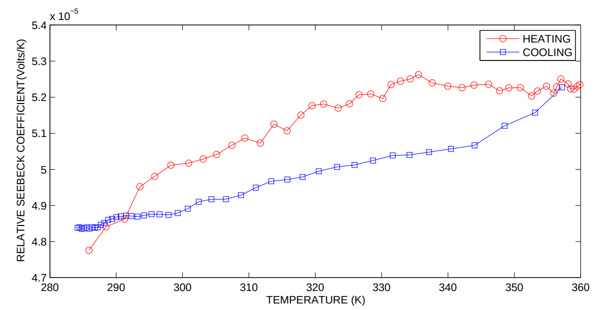

FIGURE 4. RELATIVE SEEBECK COEFFICIENT CHARACTERISTIC

A slight hysteric behavior is observed in the thermoelectric voltage characteristic of the SMA-Constantan thermocouple. In this case, to avoid the chaotic motion at the surface of water, a small portion of the thermocouple is inserted in water and thus a small hysteresis is observed.The shorter the SMA wire in the water the closer the heating and cooling curve. It was later observed that a heat shrink rubber tube, used to insulate the SMA-Constantan thermocouple from the change in room temperature, efficiently reduces the hysteric effect. With the help of the MATLAB curve fitting tool box [17] a linear fit and a quadratic fit are obtained for the data for different cycles and the best set of equations are presented here. The linear fit corresponding to Heating curve is given by,

$$T = 18810V_{sma} + 274.277. \tag{2}$$

The linear fit corresponding to Cooling curve is obtained by,

$$T = 19430V_{sma} + 273.9508. \tag{3}$$

The linear fit corresponding to Average of Heating and Cooling curves is given by,

$$T = 19120V_{sma} + 274.1139. \tag{4}$$

where T is the temperature corresponding to the Seebeck voltage Vsma. The quadratic fit corresponding to Heating curve is

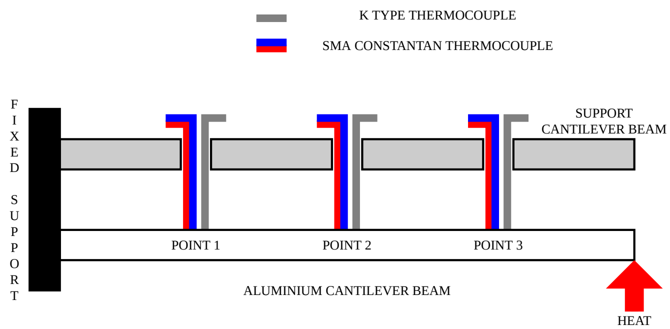

FIGURE 5. EXPERIMENTAL SETUP FOR VALIDATION OF SEEBACK VOLTAGE RELATION

obtained by,

$$T = -3.978x10^5 V_{sma}^2 + 2.106x10^4 V_{sma} + 272.8985. \quad (5)$$

The quadratic fit corresponding to Cooling curve is obtained by,

$$T = 9276 V_{sma}^2 + 1.886x10^4 V_{sma} + 274.234. \quad (6)$$

The quadratic fit corresponding to Average of Heating and Cooling curves is obtained by,

$$T = -203538 V_{sma}^2 + 19960 V_{sma} + 273.5663. \quad (7)$$

as before T is the temperature corresponding to the Seebeck voltage Vsma.

VALIDATION OF SMA-CONSTANTAN THERMOCOUPLE

To validate the thermoelectric Voltage-Temperature characteristic of SMA-Constantan thermocouple the temperature distribution at three points along the length of an aluminum cantilever beam is measured. The cantilever beam is heated at one end with the help of a heating pan. Both the SMA-Constantan thermocouple and the K-type thermocouple are put in place with the help of another supporting cantilever beam.Temperature measured using K-type thermocouple is used as reference for comparison with SMA-Constantan thermocouple. The thermocouples are positioned such that only the tips of the thermocouple lie on the beam to be heated. An ice water bath is taken to be one of the reference temperatures for the SMA-Constantan thermocouple. The beam is heated from room temperature to 363K and allowed to cool back to room temperature naturally. Three different points are selected along the length of the beam and temperature is measured as shown in Figure 5. The temperature of the pan is raised at several intervals.

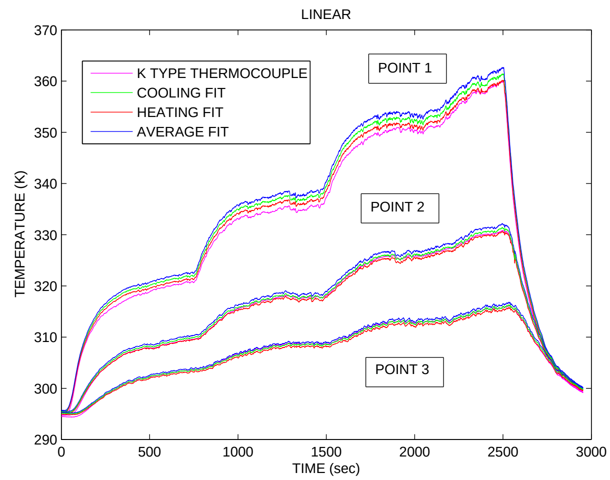

FIGURE 6. K-TYPE THERMOCOUPLE AND LINEAR FIT FOR VALIDATING THE SEEBECK VOLTAGE - TEMPERATURE RELATION

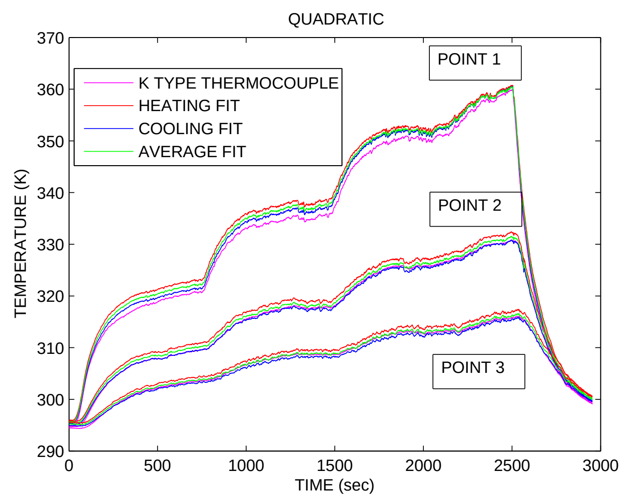

FIGURE 7. K-TYPE THERMOCOUPLE AND QUADRATIC FIT FOR VALIDATING THE SEEBECK VOLTAGE - TEMPERATURE RELATION

The temperature of the cantilever beam is computed from the Seebeck voltage of the SMA-Constantan thermocouple pair using the linear fit and quadratic fit. The heating , cooling and average of the heating and the cooling relations for the linear fits are compared with the temperature obtained by the K-type thermocouple and the results are plotted in Figure 6. It can seen from this plot that the heating relation predicts a temperature much closer to the actual temperature measured using K-type thermo-

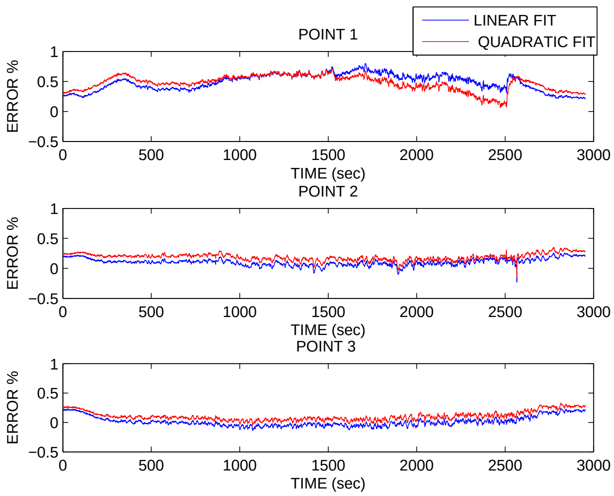

FIGURE 8. COMPARISION OF ERROR % BETWEEN LINEAR FIT AND QUADRATIC FIT

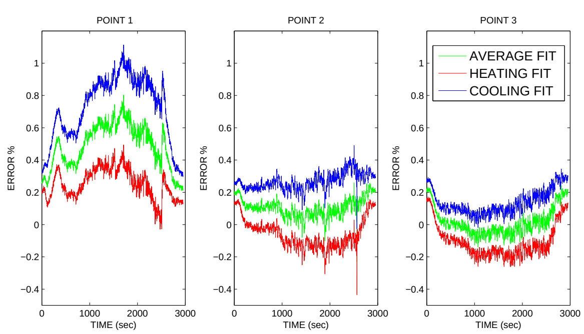

FIGURE 9. COMPARISION OF ERROR % BETWEEN HEATING FIT, COOLING FIT AND AVERAGE FIT FOR LINEAR RELATION

couple. Similar plot for quadratic fit can be seen in Figure 7. Contrary to the linear fit, the cooling relation predicts a much better temperature than the heating and average relations.

Upon comparing the error percentage of linear and quadratic fits for average relation in Figure 8,it can be deduced that the linear fit has a lesser error than the quadratic fit for all points. The maximum error for both the linear and quadratic fits is less than 0.8% for POINT 1 and less than 0.4% for the other two points. This shows that the the Seebeck Voltage of SMA-Constantan thermocouple can be approximated with a linear relationship with temperature.

Among linear fits it is observed that the heating relation fits much better than the cooling relation or the average relation for POINT 1 and POINT 2. But for POINT 3 the average fit gives a much better temperature prediction. The error percentage range

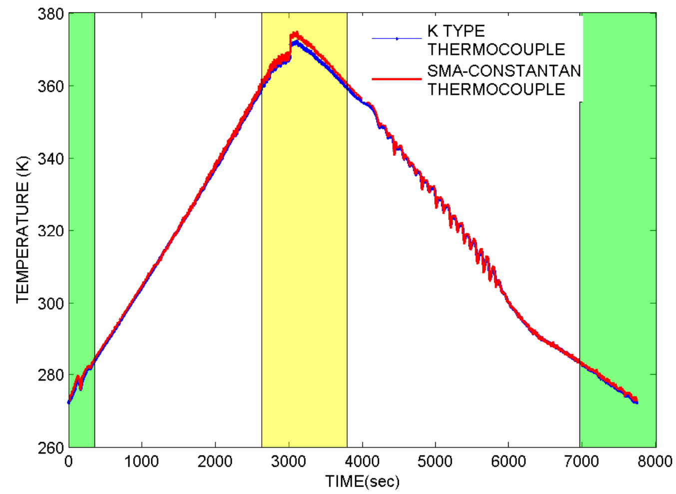

FIGURE 10. CHECKING EXTRAPOLATION OF LINEAR FIT

of heating relation is [-0.2% 0.4%] and that of cooling relation is [0.1% 1.1%] as can be seen in Figure 9. This experiment shows that the linear fit of the heating relation gives the best result among all the relations.

In another experiment the temperature of a chamber is varied from 268 K to 375 K to test and validate the equation for an extrapolated range of temperatures.The data obtained from the K-type thermocouple and temperature predicted using the linear SMA-Constantan relation is plotted in Figure 10. Green shade and yellow shade emphasize the portion of data which is outside the range of Seebeck voltage -temperature characterization. From the plot it can be inferred that the linear fit is predicting in the lower temperature with an error less than 0.4 % and in the higher temperature ranges with an error less than 0.7 %. This shows that the linear relation obtained can be extended for lower and higher temperatures with acceptable error.

SMA ACTUATOR - SENSOR DUALITY

In the previous section a linear relation between the Seebeck voltage of SMA-Constantan and temperature has been established. Using this relation SMA can be used to sense temperature when coupled with Constantan. The principle idea in eliminating an external sensor can be explained with an example of a bimorph cantilevered (clamped free) beam configuration as illustrated in Figure 11. The thin layers of Shape Memory Alloy (SMA I and SMA II) cover the cantilever beam on either sides such that the cantilever and the SMAs are electrically insulated from each other. The three layers are mechanically fastened with each other i.e. activation of any SMA layer results in the actuation of the cantilever beam along with the other SMA layer. At

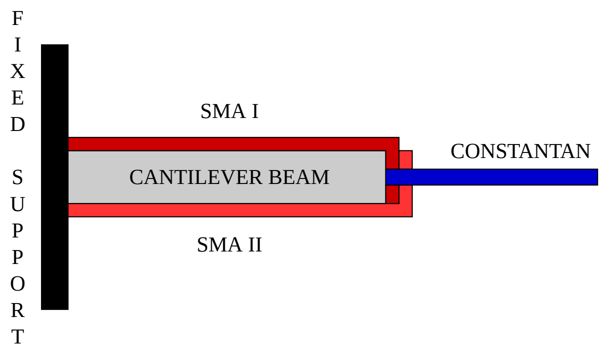

FIGURE 11. CANTILEVERED BEAM BIMORPH CONFIGURATION

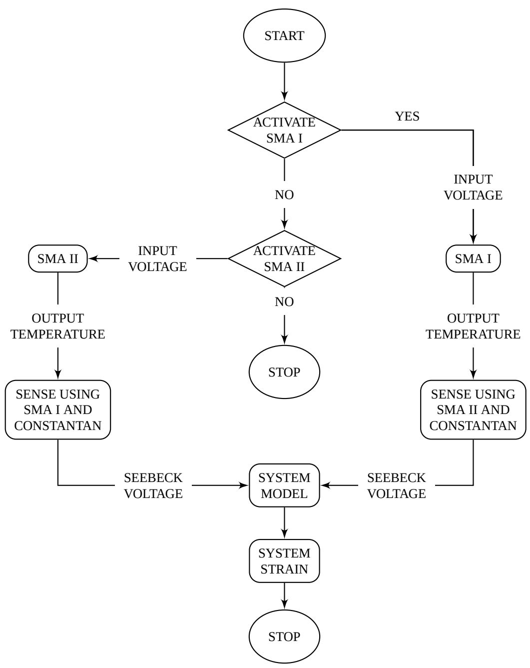

FIGURE 12. FLOWCHART

the free end of the cantilever, SMA I and SMA II are in thermal contact with each other. A Constantan wire is implanted at this end of the cantilever to have an electrical contact with each SMA. This configuration allows each SMA to form two bimaterial junctions with Constantan.

This bimorph configuration along with the linear relationship of Seebeck voltage and Temperature is presented as a sensorless control configuration statagy. Application of the Seebeck Voltage Temperature relation to the cantilever bimorph is described with a flowchart as seen in Figure 12. To activate SMA I, voltage is applied across both its ends as shown in the Figure 13 B. The resistive heating of SMA I leads to the rise of temperature of this layer and the actuation of the cantilever beam.

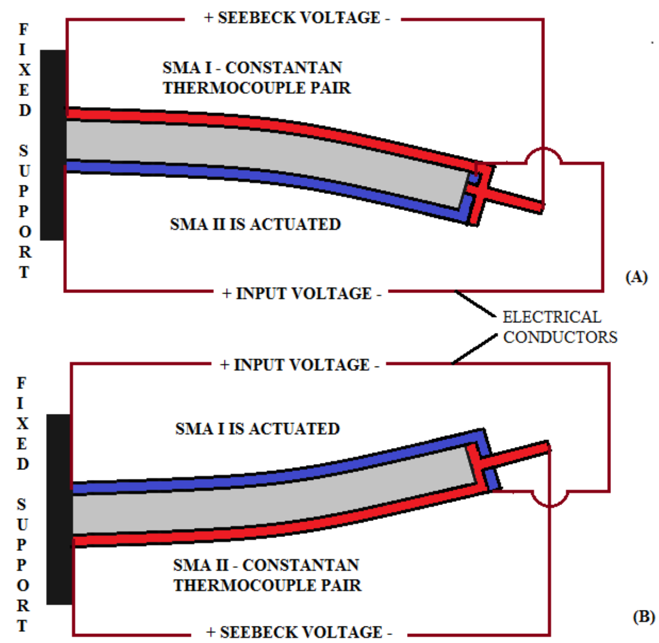

FIGURE 13. ACTUATOR-SENSOR CONFIGURATIONS USING SMA LAYERS AND CONSTANTAN

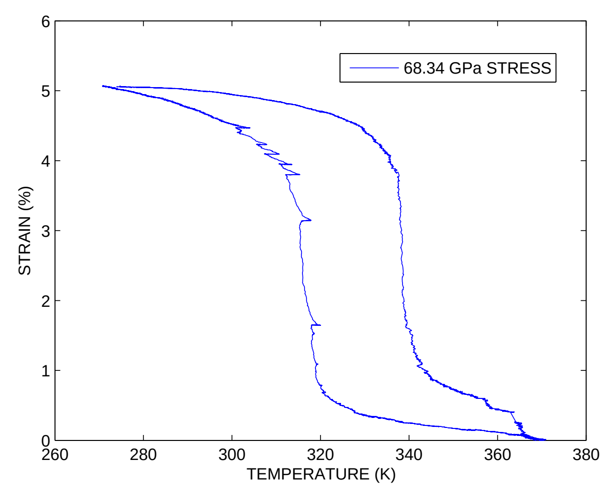

FIGURE 14. STRAIN TEMPERATURE CHARACTERISTICS

The change in temperature of SMA I is sensed at the SMA I-Constantan bi-material junction. The displacement of the cantilever beam is in direct relation with the phase transformation in SMA I. The phase transformation of SMA I can be detected by measuring the temperature of SMA I. SMA II-Constantan thermocouple pair senses the temperature change in SMA I at the free end of the cantilever. An internal electrical field developed in SMA II layer and Constantan wire due to temperature gradient developed across the junctions. This field results in a thermoelectric emf across the free end of the Constantan and the SMA II. The developed voltage is measured and the temperature of SMA I is obtained from the linear relation of SMA-Constantan thermocouple pair.

Using the temperature of SMA I and SMA displacement and temperature relationship, the displacement of the cantilever beam can be determined using the system model.A sample temperature-strain relation of Flexinol at constant stress of 68.34 GPa is shown in Figure 14. The system model consists of the temperature-strain relation for any constant stress. Similarly when SMA II is activated the temperature of SMA II is detected with SMA I and Constantan thermocouple pair and the system properties are deduced from temperature using the system model. The above discussion illustrates the advantage of the bimorph cantilever configuration and the methodology of using SMA as an actuator and sensor.

CONCLUSION

Although Seebeck coefficient of Shape Memory Alloy show hysterisis with temperature, a linear relationship describes the Seebeck Voltage and temperature relationship of a SMA-Constantan thermocouple. This relation is only valid when the temperature at the bi-material junction is changed and rest of the SMA is at room temperature. Using this relation a control strategy is presented to actuate and sense a cantilevered bimorph. Future work would experimentally verify the control stratagy discussed in this paper.

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