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Position estimation and control of SMA actuators based on electrical resistance measurement

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Abstract. As a functional material, shape memory alloy (SMA) has attracted much attention and research effort to explore its unique properties and its applications in the past few decades. Some of its properties, in particular the electrical resistance (ER) based self-sensing property of SMA, have not been fully studied. Electrical resistance of an SMA wire varies during its phase transformation. This variation is an inherent property of the SMA wire, although it is highly nonlinear with hysteresis. The relationship between the displacement and the electrical resistance of an SMA wire is deterministic and repeatable to some degree, therefore enabling the self-sensing ability of the SMA. The potential of this self-sensing ability has not received sufficient exploration so far, and even the previous studies in literature lack generality. This paper concerns the utilization of the self-sensing property of a spring-biased Nickel-Titanium (Nitinol) SMA actuator for two applications: ER feedback position control of an SMA actuator without a position sensor, and estimation of the opening of a SMA actuated valve. The use of the self-sensing property eliminates the need for a position sensor, therefore reducing the cost and size of an SMA actuator assembly. Two experimental apparatuses are fabricated to facilitate the two proposed applications, respectively. Based on open-loop testing results, the curve fitting technique is used to represent the nonlinear relationships between the displacement and the electrical resistance of the two SMA wire actuators. Using the mathematical models of the two SMA actuators, respectively, a proportional plus derivative controller is designed for control of the SMA wire actuator using only electrical resistance feedback. Consequently, the opening of the SMA actuated valve can be estimated without using an extra sensor.

Keywords: shape memory alloy; electric resistance; feedback control; sensorless feedback control.

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1. Introduction

In the past decades, there have been continuously increasing efforts toward researching and applying shape memory alloys (SMAs) in a wide variety of areas, such as, but not limited to, aeronautical engineering, bio-medical engineering, and civil engineering, due to SMAs' unique properties. However, some properties of SMAs have not been fully explored and utilized yet, in particular the self-sensing property. The self-sensing property of SMAs refers to the phenomenon that the electrical resistance (ER) of SMA changes with the phase transformation in a deterministic manner and that this ER change enables SMAs to be used as strain/force sensors.

Application of SMA's self-sensing property dates back as early as 1990 (Ikegami, *et al.* 1990). Since then, few applications of the self-sensing property of SMAs have been reported (Ikuta, *et al.* 1988, Raparelli, *et al*. 2003, Li, *et al.*). These applications either involve only the self-sensing based on the ER change during isothermal mechanical loadings or the simultaneous actuation and sensing of SMA actuators. The latter kind of application uses the ER change of an SMA actuator due to thermomechanical loading to estimate its position/actuation force for a closed loop control, such as the ER feedback force control of an antagonistic SMA actuator (Ikuta, *et al.* 1988) and the ER feedback position control of an SMA wire actuator lifting a dead weight (Raparelli, *et al*. 2003).

The ER based feedback control of hysteretic SMA actuators is intended to eliminate the need of a position/force sensor for position/force feedback, therefore reducing the cost and size of the whole actuator assembly while time stabilizing the nonlinear actuator and improving the control precision. The benefits of using SMA's self-sensing property can help extend the applications of SMA actuators into areas where the cost and size of actuator assembly are seriously restricted.

However, the reported application research of the SMA self-sensing property lacks generality because they did not take into account the hysteresis of the relationship between ER and strain/stress. It has been revealed that the ER/strain relationship of an SMA is hysteretic and affected by several factors (Carballo 1995, Pozzi and Airoldi 1999 and Wu, *et al.* 1999), and that this hysteresis can only be neglected under certain, limited circumstances, such as the negligible hysteresis of the SMA actuator featuring an R-phase transformation (Ikuta, *et al.* 1988) and of the SMA wire actuator loaded with a large dead weight (Raparelli, *et al*. 2003). Therefore, there is a necessity to explore further the potential applications of the self-sensing property of SMAs having a typical hysteretic ER/strain relationship.

To the authors' best knowledge, no research has been reported using the ER/strain relationship of an SMA actuator with a spring-biased configuration for feedback control or self-sensing. The spring-biased SMA actuator is commonly used, and is different from the aforementioned SMA actuator configuration (Ikuta, *et al.* 1988, Raparelli, *et al*. 2003), since its return force, provided by the bias spring, is not a constant, therefore having a typical hysteretic ER/strain relationship. This notice motivates the authors to develop two application cases of the self-sensing property of the spring-biased SMA actuators: one for position feedback control, and the other for estimation of opening of an SMA actuated valve. It is worthwhile to point out that the primary concern in many applications of SMA actuators is low cost, instead of high control accuracy. Such applications include the SMA actuators to adjust the air blowing direction of a ventilation system and the SMA actuators used in self-actuated valves. Additionally, the ER-based position estimation and position control strategy, which does not use an extra sensor and is low cost, can be used as a backup for a system with external position sensors, in case of the sensor failure.

First, one of this paper's goals is to present design, testing and implementation of a position controller for a spring-biased nickel-titanium alloy (Nitinol) SMA wire actuator using ER feedback. An experimental setup is designed and fabricated for testing of the phase-transformation-induced ER change and implementation of the proposed feedback control system. This experimental setup uses an SMA wire actuator in a spring-biased configuration. Using this setup, open-loop tests of the SMA actuator are conducted to reveal the relationship between the ER and the strain of the actuator. The curve-fitting technique is then used to mathematically model the ER-displacement relationship, based on which a proportional plus derivative (PD) position controller is designed without using direct position measurement. Finally, an experiment is conducted to verify the effectiveness of the proposed controller using ER feedback.

Second, this paper also aims to present how the self-sensing property of an SMA is used to estimate the opening of a self-activated SMA valve, which is able to automatically adjust its opening in response to the inflow air temperature without using an extra sensor. By using the testing and modeling techniques similar to the first development, a mathematical model of the ER-displacement relationship of the SMA actuated valve is obtained and then used to estimate the valve opening in a functionality testing.

2. Feedback control of SMA actuators using ER property

2.1. Experimental setup

Fig. 1 shows a schematic of the experimental setup. As shown in this figure, the experimental setup mainly consists of an SMA testing platform, a real-time control system, and a programmable power supply. The platform (depicted in Fig. 2) employs a 228.6-mm long and 0.381-mm diameter Nitinol SMA wire with a bias spring. The fixed end of the wire is connected to the platform, via a nonconductive connector and the moving end is linked to a slider, through a steel cable. The slider,

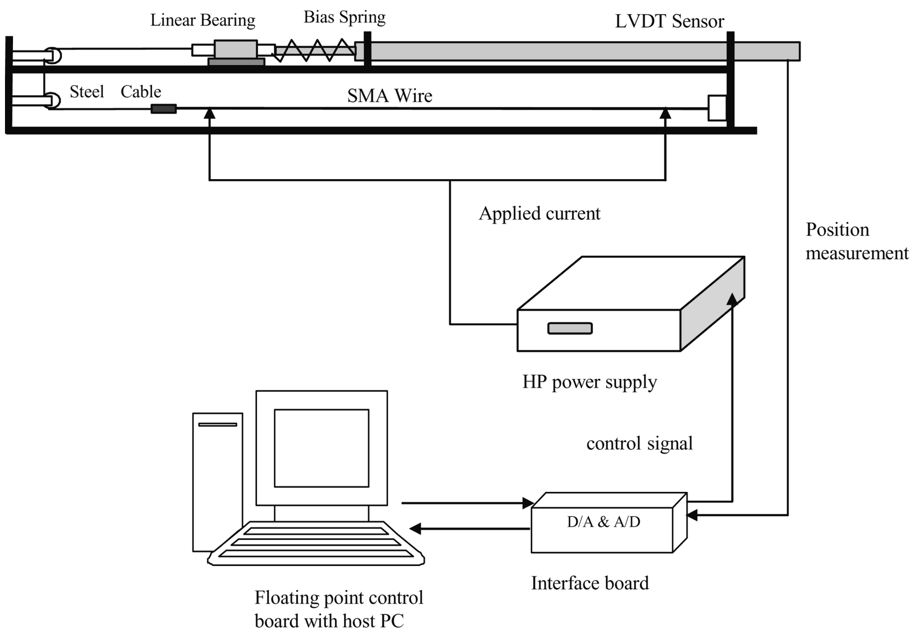


Fig. 1 A schematic of the experimental setup

supported by a linear bearing, can move only horizontally. A bias spring provides the tension applied on the SMA wire. The tension can be adjusted by changing the equilibrium position of the slider. A Linear Variable Differential Transformer (LVDT) is used to measure the position of the slider. When the SMA wire is electrically heated and undergoes the phase transformation from martensite to austenite, the wire shrinks and pulls the slider to the left. As the electrical current is shut off, the wire cools and the bias spring pulls the wire back to its "cold" length. As a result, the slider also returns to its original position.

2.2. Testing of the electrical resistance

Early findings (Carballo 1995, Pozzi and Airoldi 1999 and Wu, *et al.* 1999) have shown that the strain-ER relationship of an SMA wire is affected by several factors, such as alloy composition, types of loading, and levels of pre-strain and stress.

To explore the strain-ER relationship of the SMA wire actuator (Fig. 2), two sets of open-loop tests with different conditions are conducted. In the first set, the SMA actuator is electrically heated using a 1/60 Hz sine-wave voltage signal so that it undergoes full phase transformations. Fig. 3(a) shows the

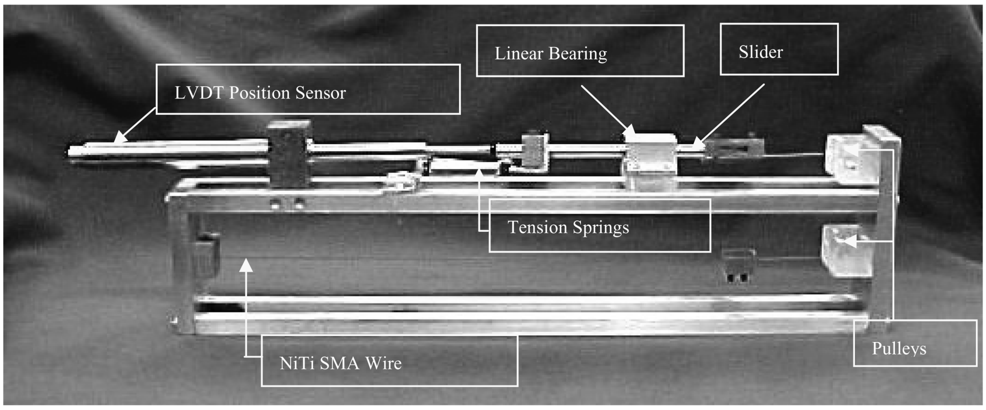
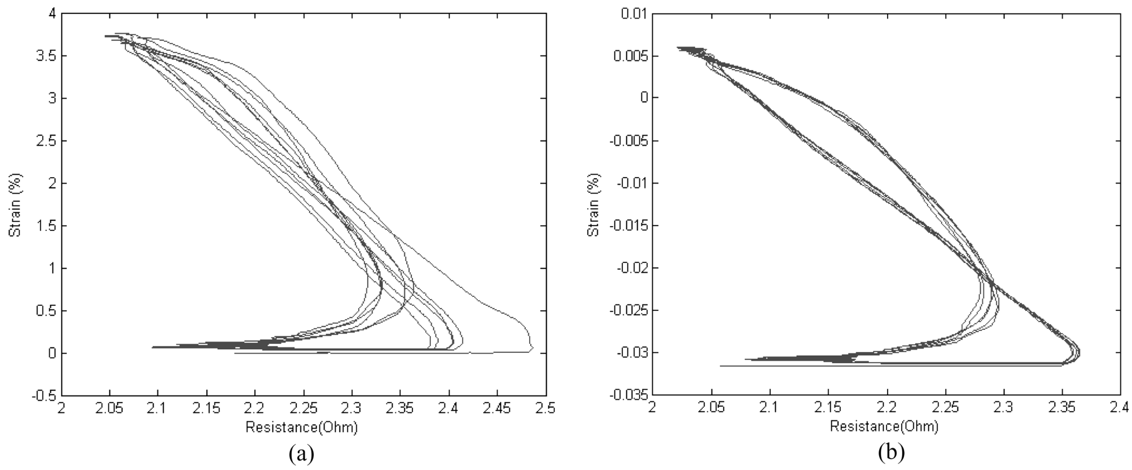
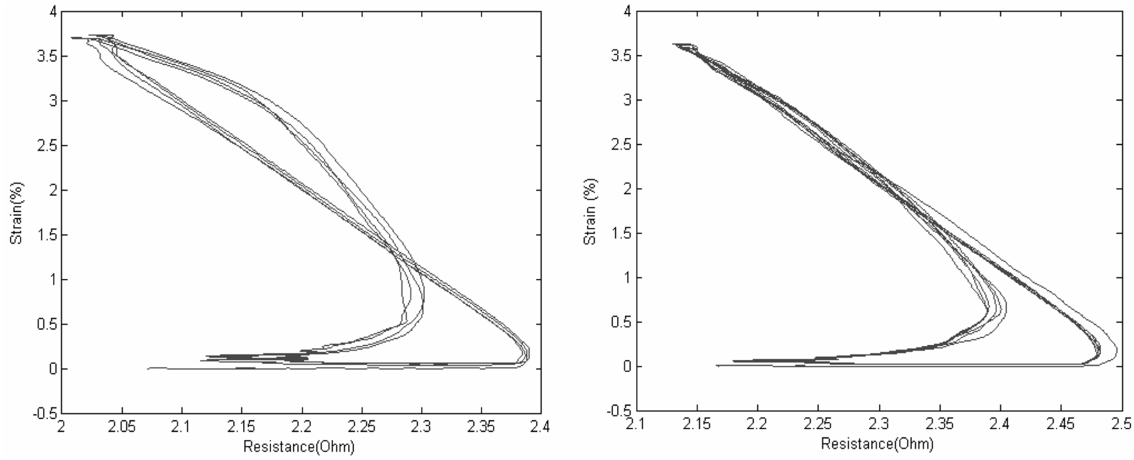


Fig. 2 The SMA wire testing platform



(a) (b)

Fig. 3 Strain vs. ER in the first test: (a) the first set of data and (b) the second set of data



(a) (b)

Fig. 4 Strain vs. ER in the second test: (a) under small pretension and (b) under large pretension

strain-ER curves for the time period from the start to the 360th second. Fig. 3(b) corresponds to the time period between the 360th second and the 900th second. The second set of tests is conducted to study the effect of pre-tension on the strain-ER relationship. In this set, two tests with different pre-tensions are conducted. Fig. 4(a) shows the strain-ER relationship of the SMA actuator with one bias spring as the pre-tension source. Fig. 4(b) shows the results with two bias springs to double the pre-tension force.

The following observations can be made regarding the strain-ER behavior of the SMA actuator based on the experimental results:

1) The strain-ER relationship is hysteretic. From martensite to austenite, the ER decreases, and, in the reverse transformation, the ER increases along a different path.
2) The strain-ER curve can be divided into the following four segments, as shown in Fig. 5:
   a. DA, where the wire is heated but no transformation occurs. This curve is horizontal (i.e. the slope is zero).
   b. AB, where ER decreases at a nearly constant rate (i.e. the slope is negative) as the phase transformation takes place and the wire shrinks.
   c. BC, where the ER changes in a different manner: increases at a large rate as the wire is cooled and elongated by the bias force. Point C corresponds to the point where the slope of the curve changes from a negative value to a positive value.
   d. CD, where the ER starts to decrease and eventually the rate of decreasing becomes zero.
3) The strain-ER relationship is not stable at the beginning of the experiment. However it is stabilized after several operating cycles. This observation is based on the comparison of Fig. 3(a) and Fig. 3(b).
4) The width of the hysteretic loop reduces with the level of pre-tension. This observation is based on the comparison of Fig. 4(a), when a smaller pre-tension force is used, with Fig. 4(b), when a larger pre-tension force is used. It is clear that the relationship in Fig. 4(a) is highly nonlinear, meanwhile, the one in Fig. 4(b) is approximately linear. In this paper, the case shown in Fig. 4(a) is considered. In the particular cases that have been studies by Ikuta, *et al*. (1988) and Raparelli, *et al*. (2003), the strain-ER relationships are approximately linear. This is no longer true when a small varying load is applied, as shown in Fig. 4(a), which clearly indicates a highly nonlinear relationship.

Therefore, the approaches by Ikuta, *et al.* (1988) and Raparelli, *et al.* (2003) cannot be applied to the nonlinear case anymore. In this paper, the strain-ER relationship will be modeled in a nonlinear fashion.

2.3. Modeling and position control design

As shown in Fig. 4(a), the strain-ER relationship is hysteretic and repeatable to some degree. The shape of the hysteretic loop is not affected by the temperature, however, it is affected by the pre-tension force. For the modeling purpose, one of the hysteretic loops is used. It should be noted that all the loops do not exactly overlap and that the use of one loop for modeling will result in some errors. However, for some applications when control precision is not a major concern, it is still worthy to estimate the position of the SMA actuator by using the ER value for feedback control design. For convenience, displacement, instead of strain, is used as the desired command in the feedback control experiment. In the following section, displacement-ER relationship, instead of strain-ER relationship, is modeled. For simplicity, the curve-fitting technique is employed.

As mentioned in the previous section, a typical displacement-ER curve, shown in Fig. 5, can be divided into three segments: AB (heating), BC (cooling with resistance increase) and CD (cooling with resistance decrease). The ER variation in the segment DA is caused by the temperature effect. No phase transformation takes place during this time and there is very little displacement change involved. Therefore, it is reasonable to ignore the displacement change in this segment.

The mathematical models for other segments are obtained using the curve-fitting technique. Segments AB, BC and CD are modeled by Eqs. (1), (2) and (3), respectively.

$$y = -64x^3 + 448.2x^2 - 1071.1x + 876.4 \tag{1}$$

$$y = 10.96x^3 - 123.0849x^2 + 363.9786x - 313.4765 \tag{2}$$

$$y = 6120x^4 - 56820x^3 + 197720x^2 - 305750x + 177290 \tag{3}$$

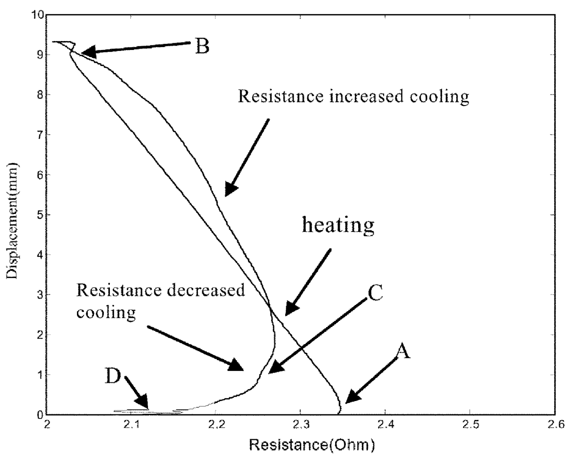


Fig. 5 A typical displacement-ER curve

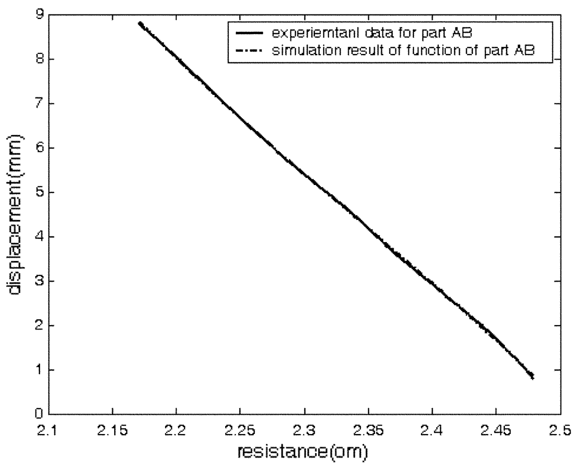


Fig. 6 Comparison between the experimental data and the simulation result (AB segment)

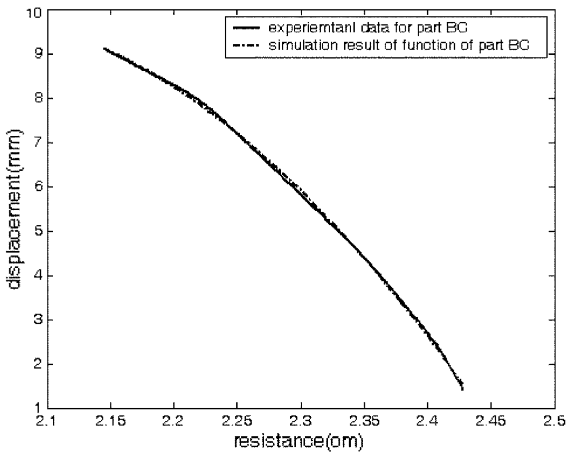


Fig. 7 Comparison between the experimental data and the simulation result (BC segment)

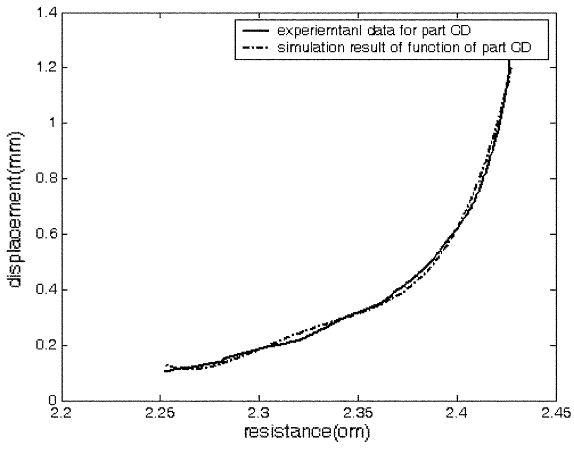


Fig. 8 Comparison between the experimental data and the simulation result (CD segment)

where y is the displacement and x is the electrical resistance value. Figs. 6, 7, and 8 show the comparison between the experimental data and the simulation results using the models.

The proposed ER feedback position control is composed of a popularly used proportional-derivative (PD) controller and an ER feedback block representing the displacement-ER model. Given the calculated ER value by using the applied voltage and the measured current, the ER feedback block estimates the displacement of the actuator, and, therefore the current position. The displacement-ER model is based on the shape of the hysteresis loop at a particular pre-tension force. The method can be applied to the cases with different pre-tension force; however, the steady-state error will increase. The PD controller is used to produce the appropriate feedback control action applied on the wire. The LVDT sensor is used to measure the position of the wire for verification purposes.

2.4. Experimental results

A multi-step command signal (as shown in Fig. 9) is used to test the position control of the SMA actuator via the electrical resistance feedback. The SMA wire was warmed up for 900 seconds before the experiment. This process is not necessary if enough thermal-mechanical treatment has been applied to the SMA actuator. The experimental result is also shown in Fig. 9. It is clear that the SMA wire actuator is able to follow the desired position, though with some steady state errors. The control system is stable throughout. The steady state errors are mainly caused by two factors. First, the relationship between the electrical resistance and the displacement is not exactly repeatable. Second, only the major hysteresis loop is modeled in the displacement-ER relationship. However, there exists minor hysteresis loops that the SMA actuator experienced in the feedback control experiment. With the elimination of the position sensor, the proposed position control system has a minimum hardware requirement and will be low cost. The position control based on an SMA's ER feedback is suitable for the low cost applications when a high control accuracy is not of primary concerns.

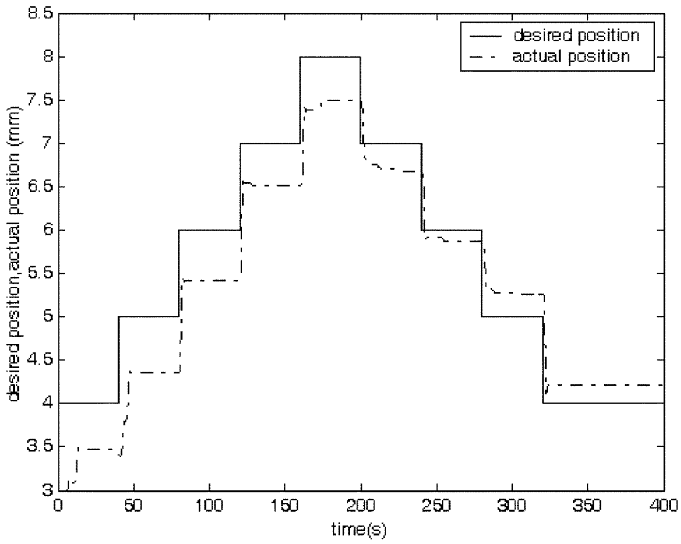


Fig. 9 Position response of the SMA wire actuator under the ER feedback control

3. Estimation of the opening of a self-activated SMA valve

3.1. Experimental setup

A self-activated 1-inport-and-2-outport air valve actuated by a SMA wire is shown in Fig. 10. In this device, the SMA wire is used as both an actuator and a sensor. With the SMA wire as an actuator, the valve will automatically direct cool air or hot air to a different outport. With the SMA wire as a sensor, the opening of the outport can be estimated without using an additional sensor. Port A in Fig. 10 is the intake. Port B is the outlet of the low temperature air flow, and port C is the exit of the high temperature air flow. A piston is placed horizontally between ports B and C. The opening level of two outlet ports is controlled by the piston's position. A Nitinol wire winds through a set of pulleys and connects the piston and two bias springs. When the low temperature air flow blows into the valve chamber, the springs' force holds the piston at its right, extreme position, so that port B is fully opened and port C is completely closed. As the temperature of the inflow air exceeds the transformation temperature, the contracting Nitinol wire overcomes the spring force to move the piston leftward to reduce the opening of port B, and to open port C. The position of the piston can be anywhere between the two extremes, depending on the balance between the Nitinol actuation force (which is determined by the temperature) and the spring force. For a particular application, users can specify the spring constant and the transformation temperature of the wire to adjust the valve properties. Without an external power source, the valve is capable of adjusting its opening according to the inflow air temperature.

On the other hand, the piston's position that indicates the opening of the ports can be estimated by the ER change of the Nitinol wire during actuation for a monitoring purpose. The objective of this section is to demonstrate the feasibility of this approach.

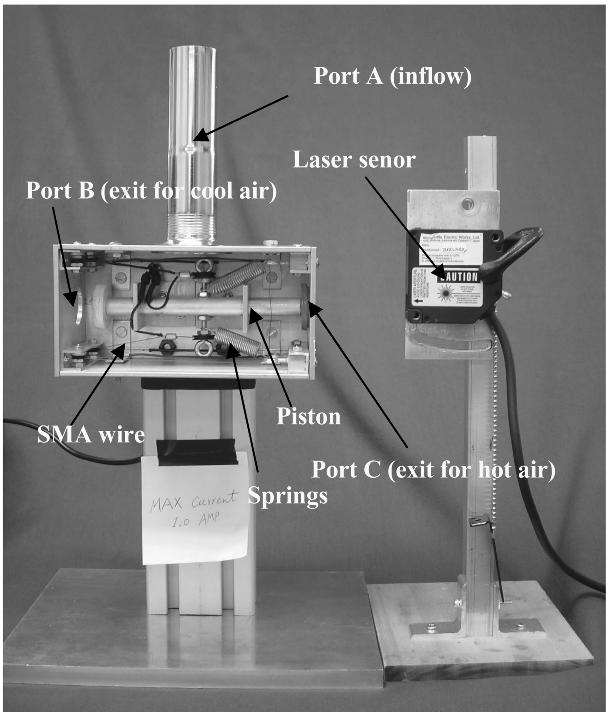


Fig. 10 Experimental setup for testing the self-activated the SMA valve

3.2. Testing of the SMA valve and modeling of ER

To obtain the relationship between the ER change of the Nitinol wire and the position of the piston, some tests are conducted. As shown in Fig. 10, the experimental setup includes the valve prototype, a laser position sensor, and a real-time data acquisition system.

In the experiment, the high temperature inflow is produced from a heat gun. As the Nitinol wire starts to contrast, the piston's position is measured by the laser sensor. A small, constant voltage is applied between the two ends of wire and the ER value is calculated based on the measurement of the varying current. The experimental result, a displacement vs. ER change curve, is shown in Fig. 11. During the martensite to austenite process, the displacement of the piston is almost proportional to the ER change; while this relationship becomes complicated during the austenite to martensite process.

Using a similar technique as used in the last section, a mathematical model of the displacement/ER relationship is developed. The curve is then divided into two segments, one of the martensite to austenite process, and one of the austenite to martensite process. The mathematical expression of the displacement/ER relationship in the martensite to austenite process is given by

$$y = -9.06x - 0.556 \tag{4}$$

where x is the ER change and y is the piston's displacement. For the austenite to martensite process, the mathematical model is given by

$$y = -5.3x^3 - 11x^2 - 10x + 3 \tag{5}$$

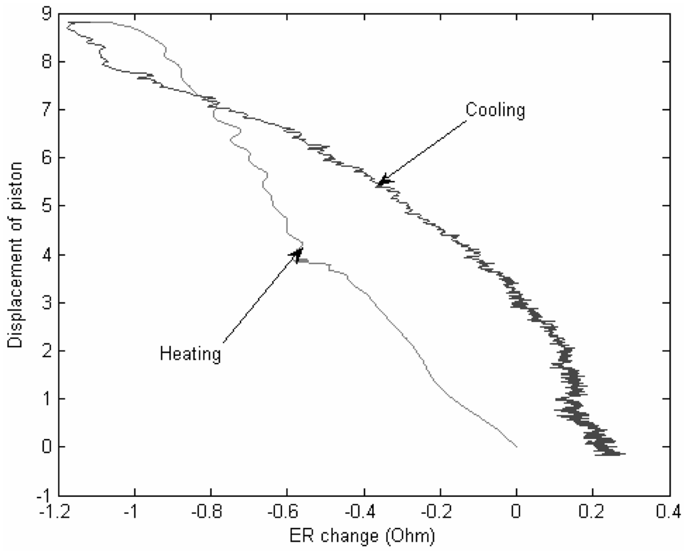


Fig. 11 Displacement of the piston vs. ER change in the testing

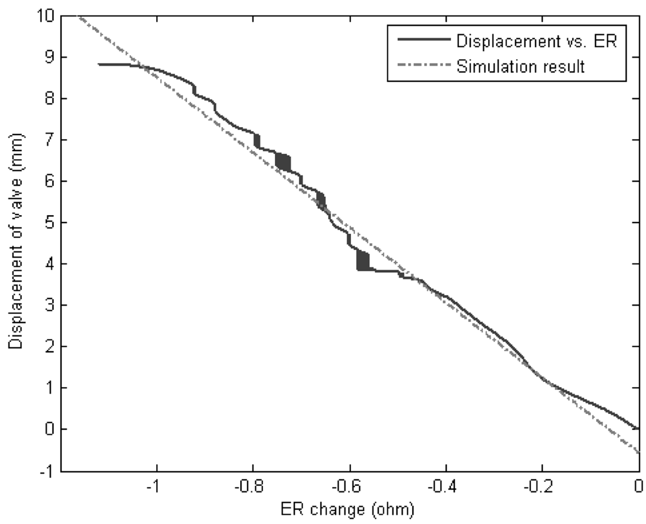


Fig. 12 Comparison between the testing and simulation results (heating part)

Then, the simulation results of the two models are compared with the real experimental results in Figs. 12 and 13.

3.3. Estimation of the valve opening by using the ER model

To verify the derived piston's displacement/ER model, tests are conducted using the same experimental setup and procedure. However, in this test, the ER models are incorporated in the real-time data acquisition system to estimate the piston's position simultaneously. The laser sensor's reading is used as

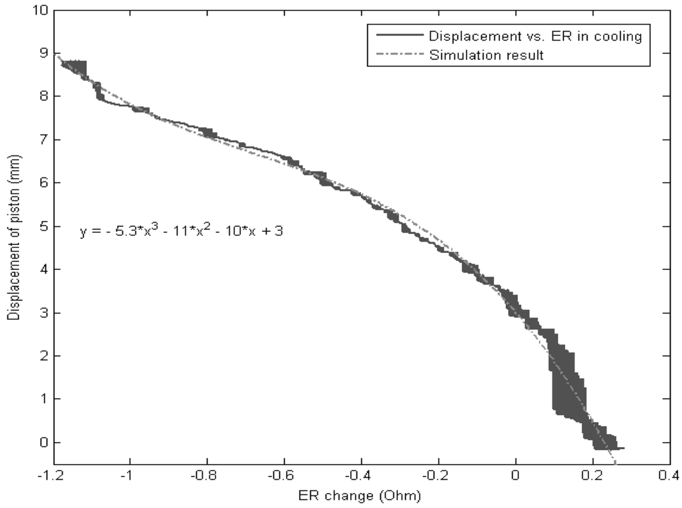


Fig. 13 Comparison between the testing and simulation results (cooling part)

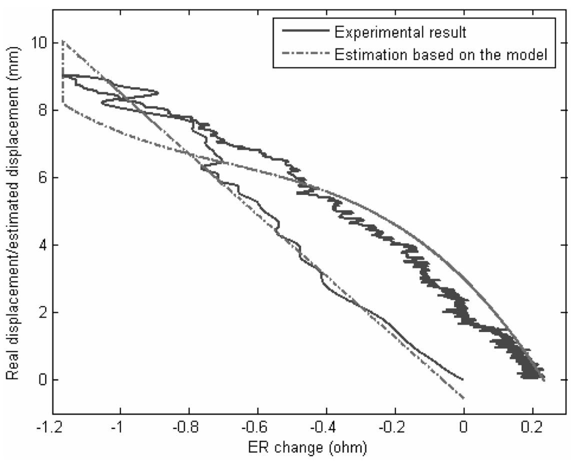


Fig. 14 Comparison between the estimated value and the experimental data

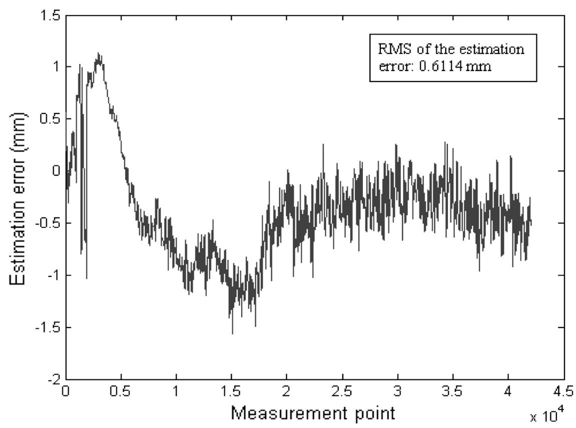


Fig. 15 Estimation error

only a reference to evaluate errors of the estimated position. The estimated displacement of the piston is shown in Fig. 14, in comparison with the laser sensor's reading. The comparison shows that the estimation of the piston's position based on the ER models is acceptable and useful. The root mean square of the estimation error (Fig. 15) is 0.6114 mm. If considering that there is no position sensor used, the accuracy is satisfactory for this application.

4. Conclusions

This paper presents the development of two spring-biased SMA actuator systems featuring a self-sensing ability, which, in fact, is based on the electrical resistance (ER) change of the SMA actuators during phase transformation.

For the first SMA actuator, a position control strategy for the actuator using its ER feedback is developed. A series of preliminary experiments were conducted on this SMA actuator to study the variation of its strain vs. ER during the phase transformation. Experimental results demonstrate that the strain-ER relationship is hysteretic and affected by several factors. The curve-fitting method was used to develop a mathematical model of this hysteretic relationship. The model was then incorporated into a proportional plus derivative (PD) controller for position control of the SMA actuator. The model was used to predict the displacements of the SMA actuator based on its ER measurement during the feedback control process. Experimental results show that proposed feedback control strategy based on the ER measurement successfully regulates the position of the SMA actuator without using a position sensor.

In the second system, the SMA's self-sensing ability is used to estimate the opening of the valve actuated by a SMA wire actuator. Testing was conduced to determine the relationship between the valve opening and the ER of the SMA wire. A mathematical model was obtained to represent the displacement/ER relationship by using the curve-fitting technique, and then it was used to estimate the valve opening based on the ER measurement in the functionality testing. The experimental results demonstrated that the valve opening can be estimated by using the SMA's ER values.

In summary, the research conducted in this paper demonstrates shape memory alloys' self-sensing ability for both measurements and feedback control without using an additional sensor.

The future work will involve the development of advanced control methods to use SMA actuators for tracking of time-varying signals based on SMA's self-sensing ability.

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