Variation of Electrical Resistance in Superelastic NiTi for Sensor Applications

By

Analisa Russo

Submitted to the Department of Materials Science and Engineering
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Signature of Author..
Analisa Russo
Department of Materials Science and Engineering
May16, 2008

Certified by..
Patricia Maes
Ambient Intelligence Group, MIT Media Laboratory
Thesis Advisor

Accepted by..
Caroline A. Ross
Professor of Materials Science and Engineering
Chairman, Undergraduate Thesis Committee

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ABSTRACT

Nickel-Titanium (NiTi) is a most commonly known as a heat-activated shape memory alloy. However, the material sometimes displays a constant-temperature property called "superelasticity." A superelastic material is one which can undergo very high reversible strains due to stress-induced change in crystal structure. In the case of Superelastic NiTi, Martensitic transformation occurs. The two crystal structures differ to the extent that the gradual phase transformation is coupled to a gradual change in resistivity. In fact, resistive sensing is a common characterization technique for shape memory alloys. The unique material properties of superelastic NiTi could also be the basis for creating a resistive sensor that is sensitive enough to measure small displacements, and robust enough to measures large displacements.

This study focuses on NiTi which displays superelastic behavior above room temperature. To assess the material's potential as a strain sensing medium, the NiTi wire is shape-set into coil springs which amplify the sensor's net deformation. The relationship between strain and resistance is measured. The study shows that various aspects of the strain-resistance response, including non-linear hysteretic behavior and temperature dependence of electrical resistivity, pose challenges to sensor design. Though the accuracy of the spring sensors is still under development, several recommendations are made with regard to effective device design. In addition, the design of a one-axis strain rate sensor, which differentiates between only two modes of behavior, is explored.

Thesis Supervisor: Professor Patricia Maes
Title: Associate Professor, Program of Media Arts and Sciences

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1 Introduction

Nickel Titanium shape memory alloy (SMA) is most commonly known for its use as a thermal actuator. At low temperatures the material is quite ductile, and applying heat drives the structure back to a preset shape. This behavior is moderated by a change in crystal structure from Martensite to Austenite at high temperature. Phase transformation in Nickel-Titanium is very slow compared to most modes of electronic actuation, but the organic feel of the material appeals to tangible media designers.

Another property of Nickel-Titanium which designers are beginning to exploit is superelasticity in the Austenite phase. Superelastic materials can undergo very high reversible strains without significant fatigue. A stress-induced Martensitic transformation, similar to the phase change which controls shape memory, defines this special behavior.

Although Martensitic transformations are not fully understood, they are well documented. Recent studies have shown that continuous changes in crystal structure upon deformation (either heat or stress-induced) are coupled to large changes in electrical resistance [1]. This relationship is of great importance because resistive strain sensing could be incorporated into Nickel-Titanium devices for performing position feedback, monitoring the evolution of the material, or collecting tangible user input data as a direct strain sensor[2].

This study specifically assesses the potential of *superelastic* Nickel-Titanium coil springs as resistive strain sensors. Four aspects of the springs' behavior are examined: 1) the usable strain range of the sensor; 2) the temperature dependence of the strain-resistance response; 3) the affect of thermo-mechanical history on the strain-resistance response; 4) the naturally hysteretic behavior of the material. The effects of these characteristics on the design of a sensor system are discussed. Finally, areas for future study are recommended.

2 Motivation for Research

There are several ways that resistive sensing or feedback could be used in an SMA device. One device in particular that could be used as a platform for experimentation is Surflex, a Polyurethane foam-based interface designed by Marcelo Coelho in the Ambient Intelligence group of the MIT Media Lab. In this device, the morphology of the foam surface can be controlled by individually addressing each SMA spring, and heating it via electric current (Figure 1). The greatest design challenge associated with Surflex is to apply the Ohmic heating at the proper voltage and for the proper amount of time in order to achieve a specific displacement in the spring. Achieving such precision in a thermal actuator is almost impossible without some type of sensory feedback. Surflex could also be a platform for tactile input via superelastic springs. In addition, resistive sensing could be used simply to monitor changes in behavior, or "functional fatigue," of the SMA as the device is used over time [3].

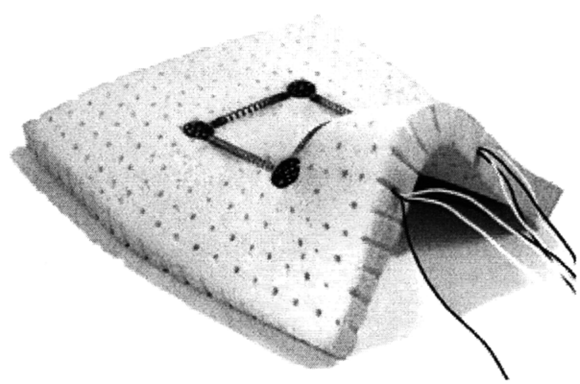


Figure 1: *Surflex* is a tangible SMA device as well as a platform for sensory feedback experimentation. Developed by Marcelo Coelho at the MIT Media Lab

2.1 Direct Displacement Sensing

Superelastic Nickel-Titanium is a good candidate material for high-strain sensing due to its strong strain-induced change in crystal structure. In addition, the strain behavior is highly repeatable, the material resists permanent deformation and traditional fatigue (propagation of cracks), and NiTi wire can be shape-set into a spring of essentially any shape. All of these properties are appropriate for a sensor which is sensitive enough to detect small strains, but robust enough to withstand large strains, thus filling a gap in the strain sensor library. Furthermore, resistance is a non-invasive cue to many material properties, and resistive sensing can be easily incorporated into a prototype device.

There are, however, several potential disadvantages to using Nickel-Titanium as a strain sensing medium. First, it has been demonstrated that both the mechanical and electrical properties of materials depend on their temperature [4]. NiTi also displays documented hysteretic behavior in many of its properties. This means that there may not be a one-to-one mapping between resistance and strain. Finally, many of the material's documented properties are non-linear [4]. These challenges must be met during the materials selection, materials processing, circuitry, and programming stages of device design.

2.2 Monitoring Thermal Actuation

Nickel-Titanium SMAs offer great dynamic range in actuation. However, accuracy of the actuated motion in thermally activated materials is difficult to achieve, particularly because its non-linear behavior is difficult to predict [2]. A resistive sensing feedback system may provide an extra level of control.

According to Ma, et. al. [2] typical "state variables" used for sensory feedback control of SMAs include position, temperature, and electrical resistance of the SMA actuator. Among these variables, position is most commonly used. However, using electrical resistance as the feedback mechanism has the distinct advantage that a separate position or temperature sensor would not be required. This makes the device slightly more self-contained because the wire infers its own position, which correlates to a change in microstructure, from instantaneous electronic properties.

Researchers (Ma, et. al.) have successfully developed a feedback system for SMAs which employs a complex control scheme. A complex neural network was set up *"to model the relationship and to predict the position of the actuator using only the electrical resistance."* [2] Essentially the model is based on a comprehensive mechanical analysis of Nickel-Titanium, the details of which are beyond the scope of this study.

2.3 Monitoring Functional Fatigue

As stated in section 1.1, Nickel-Titanium is resistant to mechanical fatigue. However, it is subject to what Predki, et. al. has called "functional fatigue" [3]. Over time, the SMA tends to develop a secondary memorized shape in the Martensitic phase. This is physically manifested as a slow relaxation of the pre-set shape upon cooling. This is a disadvantage in SMA devices because actuated structures do not maintain their shape, over time, unless heat is continuously supplied. This change in behavior is due to the evolution of microstructure, namely the development of defects in the Martensitic phase which favor some crystal orientations over others. Further study must be done to determine whether certain types of thermo-mechanical cycling exacerbate functional fatigue. Resistive sensing could be a useful technique in such studies, or as a means of monitoring functional fatigue in an existing SMA device.

3 Background

3.1 Martensitic Transformation

The material used in this study is superelastic Nickel-Titanium. Martensitic transformation is the mechanism responsible for exceptional reversible strains. It has several features which could be relevant to the strain-resistance response of Nickel-Titanium strain sensors.

With no applied stress, the entire microstructure is composed of Austenite phase grains, with an FCC crystal structure. Mechanical deformation induces the gradual creation of Martensite grains – greater strains result in a higher overall Martensite to Austenite ratio. Martensite has a BCC crystal structure, which is less dense than the Austenite phase. [4]

Martensite is formed by displacive transformation [4], rather than by diffusion. The Martensite must be nucleated before it can form. As in all nucleation and growth processes, a Martensite region must reach a critical size before it can grow. Growth involves the conversion of surrounding Austenite crystals to the Martensitic phase. There is an activation energy associated with propagation of a Martensite crystal grain into the austenite matrix. [4]

The propagation of the Martensite crystal is led by a front of dislocations [5]. The concentration and orientation of these defects could change after multiple thermo-mechanical cycles have been performed.

Martensitic transformation in Nickel-Titanium is "thermoelastic" [4]. Martensite crystals grow and shrink as the material is mechanically loaded and unloaded whereas Austenite crystals are never nucleated. Kinetic differences between the growth and shrinkage processes could account for hysteretic behavior of many of Nickel-Titanium's properties.

3.2 Spring Design

The superelastic springs considered in this study mimic the structure of coil actuators which have a dynamic range on the order of centimeters. Similar actuators are used in the Surflex device.

A study done by Wu, et. al. [1] establishes a repeatable linear relationship between resistance and axial strains in NiTi wire. The displacement achieved in this study amounts to approximately 3% of the original wire length. Many tangible Nickel-Titanium SMA devices, like Surflex, undergo significantly higher displacements upon thermal actuation or in response user input. The coil spring architecture is unique in that it achieves very high displacements by acting as a mechanical transducer: when the full structure undergoes a large axial strain, the material itself is subjected to a small amount of torsion.

The analysis of this structure was inspired by an example problem in Crandall's *An Introduction to the Mechanics of Solids.* [6]

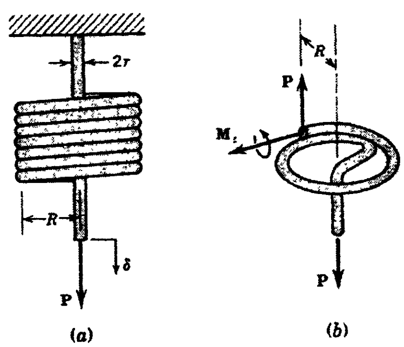


Figure 2: The coil spring converts small torsional motion of the wire into large axial displacements. Diagram from *An Introduction to the Mechanics of Solids* by Crandall.

The only non-vanishing stress components, assuming isotropy in the wire, are the shear stress and shear strain $\tau_{\theta z}$ and $\gamma_{\theta z}$ acting in around the circumference of the wire (equation 1). The twisting moment is equal to the force applied to the spring times the radius of the spring (equation 2). The radius of the spring acts as the lever arm.

$$\tau_{\theta z} = \frac{M_t r}{I_z} = \frac{4PR}{2\pi \cdot r^3} = G\varphi_{\theta z} \tag{1}$$

$$M_t = P \cdot R \tag{2}$$

The instantaneous spring constant of the coil is equal to the stress applied divided by the total displacement. Considering the amount of energy which the material stores when strained in torsion, (equation 3) shows that the spring constant is also a function of the shear modulus (G), the radius of the wire (r), the radius of the coil (R), and the number of turns in the coil (n).

$$k = \frac{Gr^4}{4nR^3} = \frac{P}{\delta} \tag{3}$$

By solving equations 2 and 3 for the applied force P, and then equating them, we find that the shear stress in the wire is proportional to the displacement of the spring (equation 4). The constant of proportionality is a function of the geometric parameters of the system.

$$\varphi_{\theta z} = \delta\left[\frac{r}{2\pi \cdot nR^2}\right] \tag{4}$$

Equation 4 also confirms that there is zero shear stress at the center of the wire (r=0) and maximum shear stress at the outer surface. Equation 3 suggests that wider springs should have a lower spring constant than narrow springs. Wide springs have a large lever arm for twisting the wire.

4 Experimental Procedures

4.1 *Material Used*

The shape memory alloy used in this study was a NiTi (55% Ti) wire obtained from McMaster-Carr. The diameter of the wire is 0.2 mm. The crystal structure of the Nickel-Titanium at room temperature and above is fully Austenite. The manufacturer did not provide the thermal shape memory transition temperature. The wire exhibits superelasticity.

4.2 *Spring Construction*

To create the coil springs, the wire was wrapped around a 1/16 inch diameter screw and clamped at either end. Because the as-drawn wire is already superelastic, this was the narrowest screw that could be used without encountering spontaneous unraveling. Each coil was annealed for 15 minutes at 515°C, and then quenched rapidly in cold water.

4.3 *Resistive Sensing*

The resistance across the spring was inferred from a voltage reading. This was achieved by placing the springs in series with a resistor. A voltage drop was applied over the resistor and spring, with one end connected to a power supply, and the other to ground. This is a voltage divider circuit [7].

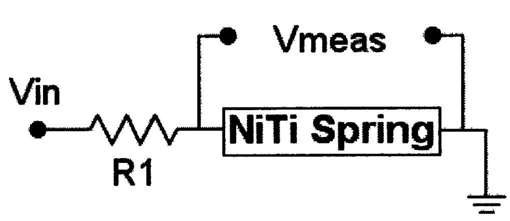


Figure 3: A voltage divider circuit is used to determine the resistance of the Nickel-Titanium spring

$$I = \frac{V_{meas}}{R_x} = \frac{V_{in}}{R_1 + R_x} \tag{5}$$

Solving for V_{meas},

$$V_{meas} = \frac{R_x}{R_1 + R_x} \cdot V_{in} \tag{6}$$

In order to obtain the greatest range in voltage readings, and therefore the greatest sensitivity in the experiment, Rx and R1 should be close in resistance. Suppose $R_1 << R_x$; the voltage across the spring will always be very close to V_{in}. On the other hand, if $R_1 >> R_x$, the voltage across the spring will always be very small. In this experiment the resistance of the wires, when relaxed, was close to 40 Ohms. However, a 330 Ohm resistor was chosen for the test circuit because it was the smallest resistor available with a low margin of error (1%).

The current through the Nickel-Titanium spring was calculated directly from Ohm's Law: V=IR. From equation 6, the resistance of the wire will tend to rise more rapidly than the voltage across it. Therefore, as the resistance of the coil rises, the current through the wire should drop. The wire will tend to undergo Ohmic heating with prolonged current flow. The heat, in joules per unit time, is proportional to the power input to the wire. The power input can be expressed in terms of combinations of voltage, current and resistance (equation 7).

$$P = I \cdot V_{meas} = I^2 R_x = \frac{V^2}{R_x} \tag{7}$$

From the last expression in equation 7, we see that since voltage across the spring rises with increasing resistance, an increase in resistance will result in increased power input to the spring.

4.4 Measuring Drift in Resistance Over Time

As described in section 4.3, the SMA will heat with prolonged current input. To examine the effect of Ohmic heating on the resistance of the spring itself, the test setup was subjected to various input voltages. The resistance of a relaxed spring was measured, as described in section 4.3, at regular time intervals. The three input voltages tested were 2, 5, and 6 Volts. Measurements were taken at 1 minute time intervals for the 2 and 5 Volt cases, and at 30 second intervals for the 6 Volt case.

4.5 Measuring Strain-Resistance Response

The relationship between strain of the SMA spring and change in resistance was measured. An acrylic jig was constructed for controlling and measuring the displacement of the spring. The static end of the jig interfaced with one end of the Nickel-Titanium spring, and the free end of the spring was attached to a screw which slid down a long notch in the side of the jig (Figure 4).

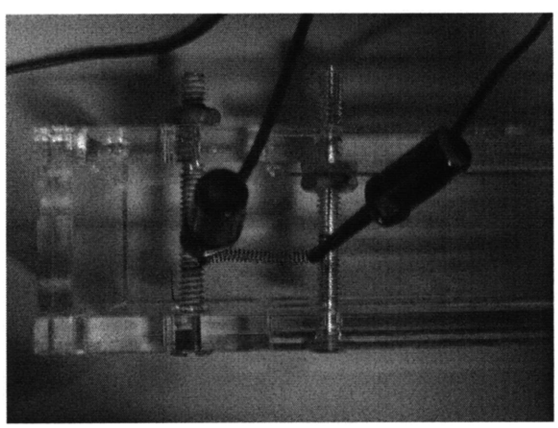


Figure 4: An acryilc test jig was designed to control and measure the displacement of the superelastic springs

The resistance of the wire was measured in the manner described in section 4.3. A constant voltage drop of 2 Volts was maintained across the 330 Ohm resistor and Nickel-Titanium spring (Figure 5). To compensate for variation in original spring lengths, the "relative resistance" [1] was measured: change in resistance divided by the original resistance of the relaxed spring. The spring was stretched at discrete intervals, and held in place by rubber bands. The displacement was measured using calipers.

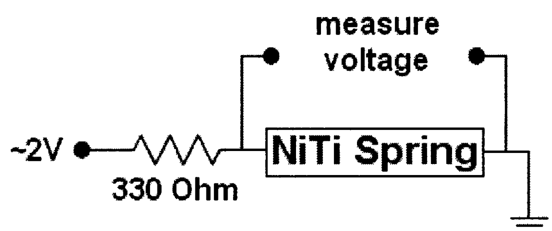


Figure 5: A voltage divider circuit is used to determine the resistance of the Nickel-Titanium spring. The voltage drop across the test setup remains constant at 2 Volts

Temperature was not a factor in the strain-resistance response tests. All experiments were done at room temperature. In order to prevent Ohmic heating, a voltage drop of 2 Volts was maintained over the test setup and the spring was allowed to settle, with no input current, for a minute before each voltage reading was taken. Heating and cooling due to the phase change in the material was not taken into account.

5 Results and Discussion

The experiments returned four key results which will inform future design of superelastic resistive strain sensors.

5.1 *Resistance is Dependent on Power Input*

Each power input test was conducted on a fully relaxed spring, as described in section 4.3. Although the temperature of the spring was not measured directly, it is assumed that prolonged current flow heats the wire. Note that variation in the absolute resistance between trials is due to shifting of the wire contacts during the test setup.

5.1.1 *2 Volt Input*

A 2 Volt drop across the test setup results in consistent resistance reading of 30.2 to 31.6 Ohms. The analysis in section 4.3 predicts that a temperature rise will occur with prolonged electric power input. However, the static resistance reading suggests that such temperature change is not taking place. It is likely that in this low power case heat loss due to convection negates any temperature rise due to Ohmic heating.

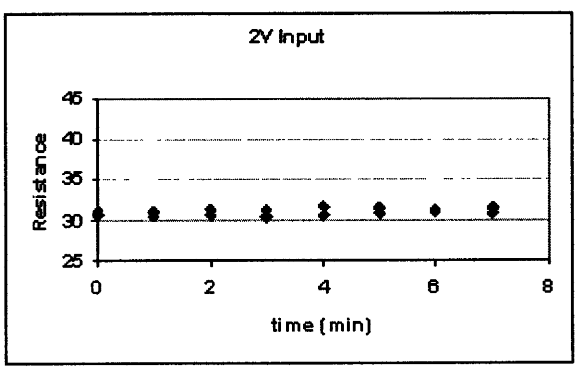


Figure 6: A 2 Volt drop was maintained over the test setup. Resistance of the spring oscillates slightly over time.

5.1.2 5 Volt Input

A 5 Volt drop across the test setup causes the resistance of the sensor to drift upwards with time. In the course of seven minutes, the resistance increases from 80.7 to 89.0 Ohms. As stated in section 4.3, the heat produced by an electric current is proportional to the power supplied to the wire. Here, electrical resistance tends to increase with temperature because molecular motion hinders the flow of electrons. It should be noted, as in section 4.3, that an increase in resistance also increases the amount of power supplied to the wire because resistance and voltage rise simultaneously. Figure 7B shows that the power, in microwatts, rises roughly linearly with time. Thus, the act of heating increases the power input to the wire and the heating process is accelerated over time. The effects of convective cooling are not taken into account here, but clearly cooling does not balance heating, as it does in the 2 Volt input case.

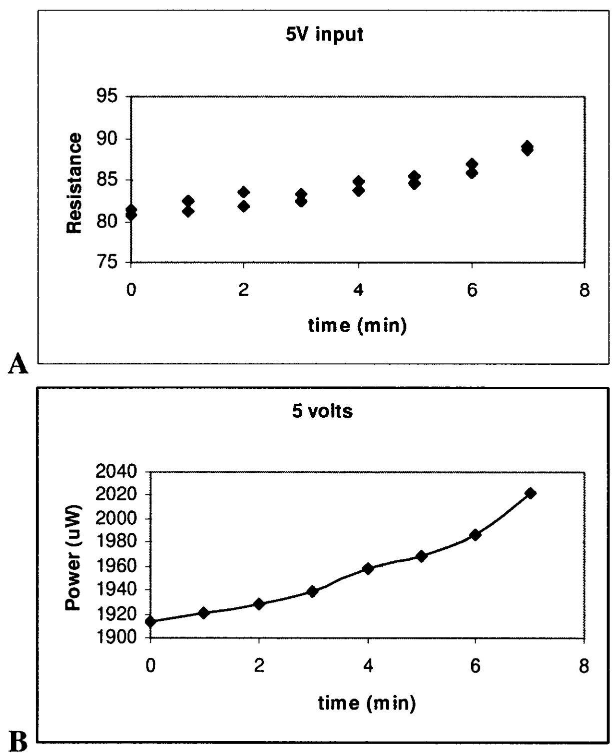
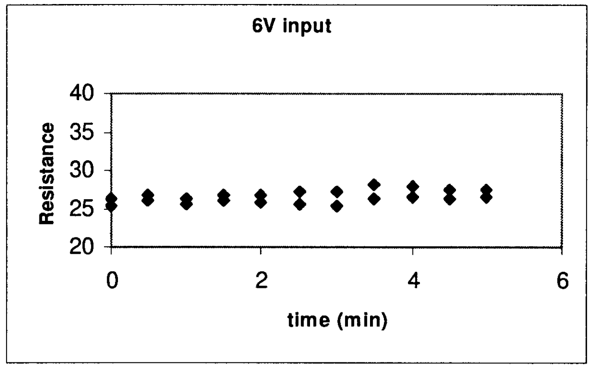


Figure 7: A 5 Volt drop was maintained over the test setup. A)The resistance drifts upwards over time. B)The power input to the spring increases with time due to the increase in resistance

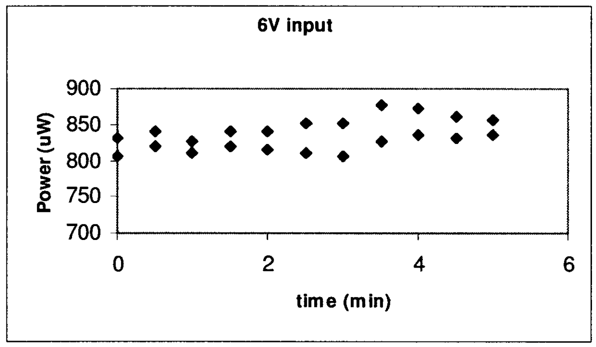
5.1.3 6 Volt Input

A 6 Volt drop across the test setup results, again, in a relatively stable resistance reading. Unlike the 2 Volt input case, the swing in resistance at any given time is rather large: 1 to 2 Ohms. It is surprising that the upward drift in resistance over time is not greater in than in the 5 Volt input case – mathematically speaking the increase of power input with rising resistance should be more pronounced.

It is possible that the system has entered a self-regulating hysteretic cycle, with the spread in resistance reading at each given time interval representing the extrema of the loops. When the temperature of the wire rises, the resistance rises, as stated in section 5.1.2. However, this causes the current to drop, possibly causing the rate of Ohmic heating to drop as well. The resulting drop in temperature restarts the cycle. Figure 8B shows the fluctuation in power input to the spring.



A



B

Figure 8: A 6 Volt drop was maintained over the test setup. A)The resistance enters a hysteretic loop which stabilizes the effect of Ohmic heating. B)The power input to the spring fluctuates over time.

5.2 Strain-Resistance Response Depends on Thermo-Mechanical History

At the start of the strain-resistance tests, it was noted that the resistance of the superelastic spring fluctuated erratically, as in Figure 9A. The data did not form a coherent trend until the spring had been mechanically strained approximately 15 times through its entire dynamic range.

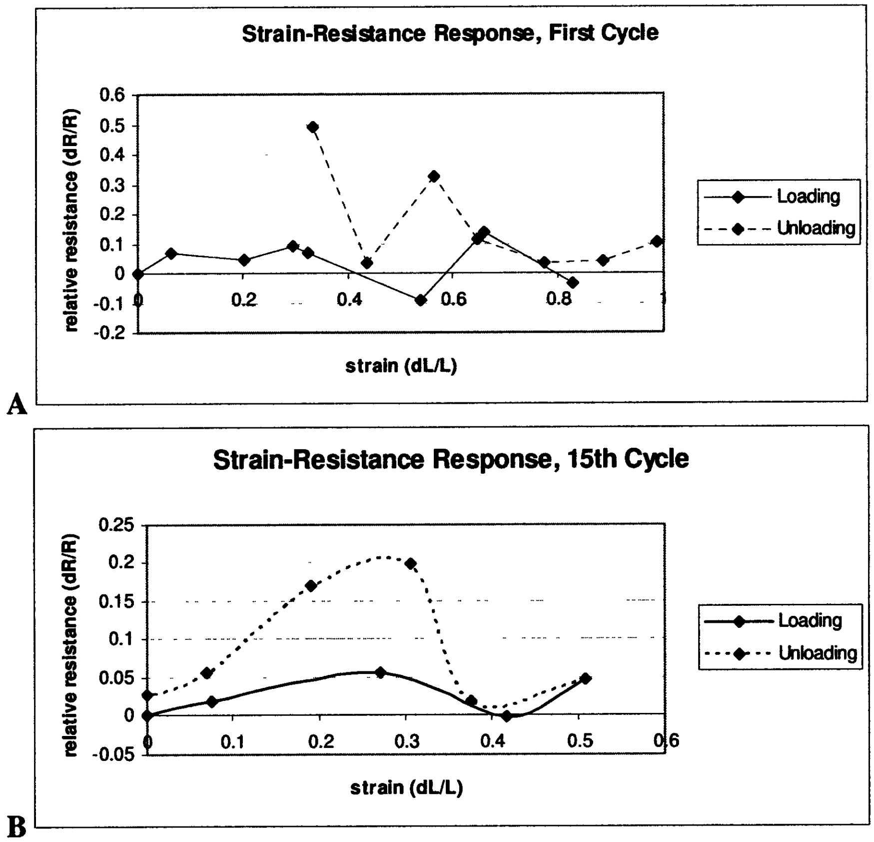


Figure 9: A 2 Volt drop was maintained over the test setup. A)The resistive response of a freshly mades spring was very irregular. B)After being deformed 15 times, the strain-resistance response stabilizes

The behavioral dependence on thermo-mechanical conditioning may be associated with dislocation motion. Predki, et. al. [3] suggests that as cyclic strain accumulates within the material, more and more dislocations are introduced into the microstructure. As stated in section 3.1, a cluster of dislocations leads the growth of Martensite regions. By remaining present in the Austenite phase, these defects "stabilize" the Martensitic phase by making the transformation to some versions of the Martensitic crystal structure more energetically favorable than others [3]. This result is more consistent mechanical and electronic behavior from cycle to cycle.

For the first cycle test, the loading case varies in resistance between 27 and 32 Ohms. In the 15th cycle, upon loading, the resistance varies between 43 and 45 Ohms. Not only does the gap between high and low resistances narrow, the absolute resistance rises significantly. (The electrical leads were not altered between these tests.) This is significant evidence for the development of a higher concentration or higher dispersion of dislocations upon repeated loading. The upward translation of resistance from cycle to cycle has been previously documented in other studies [1].

5.3 General Strain-Resistance Response

The general features of the resistance versus strain plot are observed for an actuator which has been mechanically deformed at least 15 times, as described in Section 5.2.

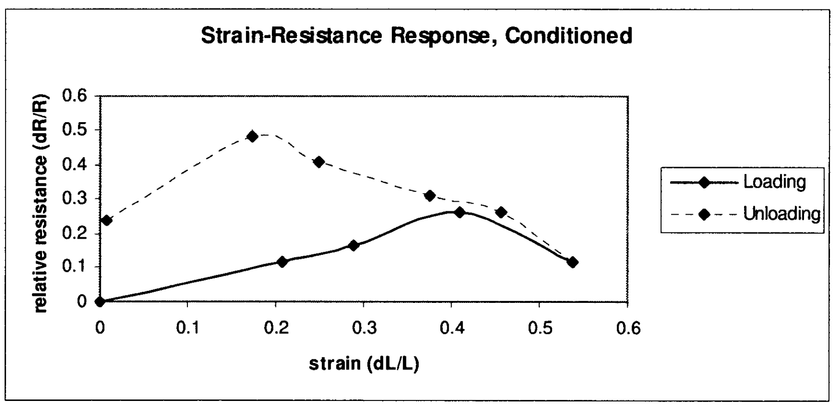


Figure 10: A 2 Volt drop was maintained over the test setup. The strain-resistance response is nearly linear up to 40% strain. The behavior is highly hysteretic.

The loading case has a notable nearly linear response relating relative resistance to applied strain, as well as a significant change in resistance from 7.5 to 9.5 Ohms. The trend breaks down at the 40% strain mark. This may mark a sudden change in microstructure due to the extent of shear strain in the wire. Previous studies have noted that sharp changes in response to a stimulus can be attributed to sudden microstructural events [3].

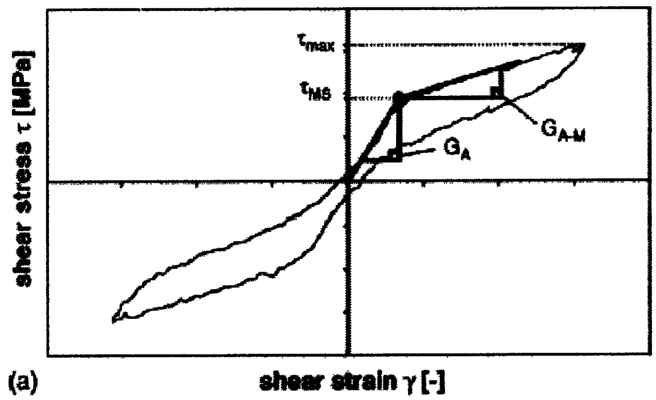


Figure 11: Stress-Strain behavior of Nickel-Titanium from Predki, et al.

Predki shows that the start of the shear strain shear stress response involves the deformation of the Austenite phase alone. The first sharp feature in the graph corresponds to the onset of Martensitic transformation. Evidence suggests that in the superelastic spring, the beginning of the torsion process involves a gradual conversion of Austenite to Martensite crystal structure. At 40% strain, perhaps the transformation accelerates.

The unloading case also displays a roughly linear trend, although it does not follow the same path as the loading curve. This behavior is discussed in section 4.4.

5.4 Strain-Resistance Response is Hysteretic

Resistive hysteresis is very clearly noted in the data from this study. The resistance-strain loop is closed, but follows entirely different paths upon loading and unloading. The process of Martensitic transformation is inherently hysteretic. As stated in section 3.1, the Martensite and Austenite crystal structures have different densities. This means that when the material is in a transitional state, some regions are in tension and others are in compression. This complex stress state does not resolve itself along the same path as it was created.

Limiting the dynamic range in the spring to 40% axial strain, it is interesting to note that the resistance actually continues to rise as the material is transferred from a loading to an unloading condition. This effect could be attributed to dislocation motion. Concentration as well as the location of dislocations during the propagation of the grain boundaries affects the resistivity of the material. [5] For example, a low concentration, highly dispersed could be a greater block to electron flow than a high concentration of dislocations grouped together. It is possible that the reverse transformation upon unloading (i.e. shrinkage of the Martensitic regions) tends to disperse defects in the lattice before they settle back into their original orientation, causing an increase of resistance upon unloading instead of a decrease.

6. Recommendations for Sensor Design

The results presented in section 4 pose challenges to strain sensor design. Each key aspect of strain-resistance response in superelastic Nickel-Titanium must be addressed at some level of device construction: processing, electronics, or programming.

6.1 Temperature Control

Section 5.1 describes the time-dependent response to various input voltages. It is recommended that the power input to the sensor remain as low as possible in order to prevent Ohmic heating. A moderate amount of heating causes the resistance of the sensor to drift upwards over time. A large amount of initial heating changes the electronic properties of the material enough that it begins to enter unstable hysteretic states. A good heat sink and air flow will allow any Ohmic heating to be balanced by conduction and convection with the surroundings.

Alternatively, a temperature compensation scheme could be employed. By comparing the outputs of two sensors which are affected equally by temperature, the effect of resistance drift could be negated to some extent.

6.2 Monitoring Mechanical History

Section 5.2 describes the change in strain-resistance response with repeated mechanical deformation. Namely, the spring must be actuated completely at least 15 times in order to develop consistent behavior. This implies that a sensor must be mechanically conditioned before it is calibrated in an electronic device. One must also keep in mind that the properties of the material may change at long time scales, as well. The device may need to be re-calibrated periodically in order to compensate for this "functional fatigue." [3]

6.3 Identifying Usable Ranges

Sections 5.3 and 5.4 describe the general behavior of the sensor, including observed hysteresis. First, the strain-resistance response shows a distinct peak at 40% strain, as demonstrated in Figure 10. This sudden change in properties implies that the usable range of the superelastic springs may be limited to 40% strain in order to maintain one-to-one relationships between resistance and strain upon loading.

The hysteresis in the strain-resistance response, as seen in Figure 10, is a clear challenge to sensor design, as most strain sensors follow the same deformation path upon loading and unloading. Between the loading and unloading cases, even if constrained to a maximum of 40% strain, there does not exist a one-to-one mapping between resistance and strain. In order to function as a sensor of absolute position, the sensor system must be constantly aware of whether it is in a state of loading or unloading when the resistance measurement is taken. This could be achieved on the programming level of design, by logging the previous resistance reading and using this to infer the direction of deformation.

7 Designing a Digital Accelerometer

The superelastic spring has potential as a strain-rate sensor or one-axis accelerometer. Since the precision of the sensor is still under investigation, it may be possible to construct a device which differentiates between slow and fast actuation, regardless of loading direction. Rather than sensing a spectrum of strain rates, there would be a single threshold rate for comparison. Essentially, the sensor would be a switch: slow deformation rates would induce one output, and fast deformation rates would induce another. The proposed device consists of four circuit stages, a microprocessor, and a physical output, all described in the following sections. Note that this scheme does not differentiate between loading and unloading cases.

7.1 Wheatstone Bridge

The Wheatstone Bridge is a commonly used circuit component for precision resistive sensing [7]. An example bridge is shown in Figure 12. The right leg of the bridge consists of a voltage divider similar to that described in section 4.3. If the two resistors are of the same value, the output voltage from that leg will be half of the reference voltage. The left leg contains the resistive sensor between the reference voltage and the second output, and a static resistor between the second output and ground. Assuming that the static resistor in this leg is equal in value to the resistance of the fully relaxed sensor, this leg will produce a second output voltage which is either equal in value to or lower than the first output voltage.

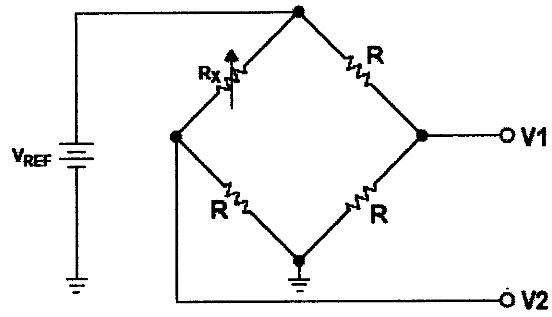


Figure 12: The Wheatstone Bridge is commonly used for precision resistive sensing. Rx represents the sensor.

7.2 Non-inverting Differential Amplifier

The non-inverting amplifier consists of an Op-Amp with negative feedback [7]. This circuit component is shown Figure 13A. The output voltage is equal to the difference between the two input voltages, multiplied by a constant determined by the resistor values: $V_{out} = (V1-V2)*(R2/R1)$. The maximum and minimum output voltages are capped by the power supply rails to the Op-Amp, for example zero to 5 Volts. Considering the condition stated in section 6.1 that V1 is always greater than V2, the output voltage will always be positive. R1 and R2 are chosen so that the output varies between zero and 5 Volts for maximum sensitivity.

7.3 Differentiator

The strain rate is the change in strain per unit time, or the instantaneous derivative of the strain. Here, a differentiator circuit can be applied to the output of the amplifier. The differentiator is an RC circuit containing an inverting Op-Amp [7]. The circuit is shown in Figure 13B. The output voltage is proportional to the time derivative of the input voltage, with a proportionality constant equal to the RC time constant: $V_{out} = -RC*(dV_{in}/dt)$. The result is a signal which rises and falls with strain rate in the sensor.

7.4 Comparator

The comparator sets a single threshold value with which to compare an input signal. It consists of a single Op-Amp with no dynamic feedback [7]. The circuit component is shown in Figure 13C. The reference voltage will determine the threshold between "slow" and "fast" strain rates. This value is easily found by experimentation. The result is a square wave that is high when the sensor is strained quickly and low when the sensor is strained slowly. The output values, again, are limited by the power rails of the Op-Amp.

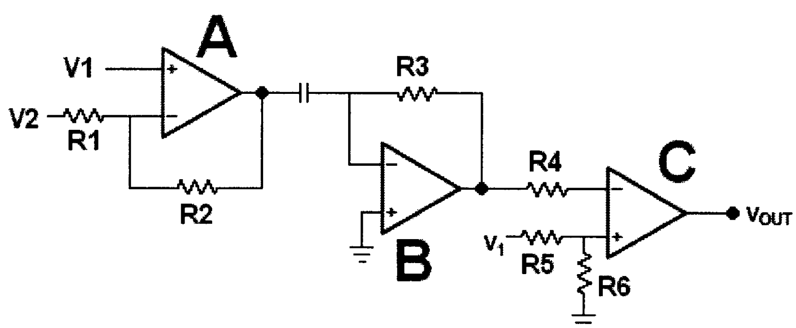


Figure 13: The output of this circuit is a digital signal which represents the strain rate of the spring sensor. A) Differential amplifier receives inputs from Wheatstone Bridge. B) Differentiator. C) Comparator.

7.5 Output Response

The square wave produced by the comparator will be fed to a microprocessor through one of the digital input pins. The data will signal various behaviors in a small LED display. At the point of processing, the data can be manipulated in a number of ways. The LED display could directly mimic the motion of the sensor (i.e. a static sensor will induce one behavior and a sensor in motion will produce another) or the LED display could change its behavior to a new static state after the sensor is quickly strained once.

8. *Conclusions and Future Work*

The superelastic Nickel-Titanium spring shows promise as a strain sensor up to 40% strain. There are several factors which could hinder its use an accurate strain sensor. The first is the drifting resistive response due to Ohmic and ambient heating. The second issue is the effect of mechanical loading history on future behavior. Another is the hysteretic strain-resistance response. Some of these factors can be compensated for at the device design level. Further investigation is recommended for the others. In order to design more effective sensors, we must attempt to better understand the mechanical and electronic behavior of Nickel-Titanium.

First, the stress-strain behavior of superelastic NiTi should be tested. This relationship between strain and applied stress in Nickel-Titanium is known to be very non-linear and hysteretic. Stress and strain can be found simultaneously by putting the superelastic spring in series with a stiff linear spring having a known spring constant. Since the force on the two springs will be equal at any given time, the force on the superelastic spring can be gained by applying Hooke's law to the linear spring. It will be interesting to see whether the characteristic features of the stress-strain behavior match occur at the same strains as the characteristic points of the strain-resistance response. Perhaps these tests will reveal that the stress-resistance behavior gives more meaningful sensory data than the strain-resistance response.

Next, the behavior of the spring can be changed by experimenting with the annealing profile during the shape-setting process. There are many variables that can be changed, including the annealing time, annealing temperature, and the heating and cooling rates. This portion of the thermal history may have an affect on the way that the sensor evolves while in use.

Finally, the spring geometry can be refined to suit the requirements of a specific application.

References

[1] Wu X D, Wu J S andWang Z 1999 The variation of electrical resistance of near stoichiometric NiTi during thermo-mechanic procedures *Smart Mater. Struct.* **8** 574–8 **[ref 11]**

[2] Ma N, Song G and Lee H-J 2004 Position control of shape memory alloy actuators with internal electrical resistance feedback using neural networks *Smart Mater. Struct.* **13** 777-783

[3] Predki W, Klonne M and Knopik A 2006 Cyclic torsional loading of pseudoelastic NiTi shape memory alloys: Damping and fatigue failure *Materials Science and Engineering A* **417** 182-189

[4] Schimizu, Kenichi. "Shape Memory Effect: Mechanism." Shape Memory Alloys. Ed. Funakubo, Hiroyasu. New York: Gordon and Breach, 1984.

[5] Hosford,William F. Physical Metallurgy. Boca Raton: Taylor and Francis, 2005.

[6] Crandall, Stephen H; NC Dahl; TJ Lardner. An Introduction to the Mechanics of Solids. Ed 2. New York: McGraw-Hill, 1976.

[7] "Op-Amps For Everyone." Ed. Mancini, Ron. Dallas: Texas Instruments Incorporated, 2002.