THE EFFECT OF SHAPE ON THE PULL FORCE OF SHAPE MEMORY ALLOYS

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ABSTRACT

Shape Memory Alloys, or SMAs, are useful as actuators in engineering applications due to their ability to contract or expand to their initial orientation with an applied heat. A crucial parameter when applying SMAs in engineering applications is the shape to which they are annealed. Annealing is the process of heating the SMA and then allowing it to cool in order to remove any internal stresses it may have and reshape it to its new orientation. Based on the shape it is annealed to, therefore, the SMA will actuate with a different intensity, or pull force. Nitinol wire, a type of SMA, was annealed to five different shapes (3D elliptical spring, 3D circular spring, 3D triangular spring, 2D sine wave, 3D square wave), and a constant current was applied to each shape in order to measure the time-dependent response of the pull force. The 3D elliptical spring was found to have the highest steady state force at 0.92 newtons and the 3D triangular spring was found to have the lowest at 0.17 newtons. The 2D square wave was found to have the lowest settling time at 3.52 seconds, and the 2D sinusoidal wave was found to have the highest at 8.25 seconds.

INTRODUCTION

Shape Memory Alloys, or SMAs, are a type of Shape Memory Materials, which means they have the ability to return from a deformed state to their original shape when an external stimulus, such as a change in temperature or current running through the material, is applied [2]. The SMA is thus able to pull or extend with a certain force, allowing it to be able to push or pull objects it is attached to. Furthermore, the “original shape” of the SMA can be manipulated via annealing, or applying heat and then cooling the material in order to remove internal stresses, the alloy to a desired shape so to modify the SMA for one’s own purposes, be it the need for a certain shape, size, pull-force, etc.

SMAs are used as actuators in a number of engineering applications. One application is in Bioengineering, where SMA plates with a trigger temperature at body temperature are attached to two ends of a broken bone to impart a constant force on both ends of the bone toward each other to speed up healing. [2] Other applications include early warning shut-off systems in fire security and water flow systems, where SMA’s can be used to trigger a shut off mechanism as soon as it experiences a certain amount of heat [4]. The parameters that will determine the effectiveness of each shape in any given application will be the maximum pull force the shape can achieve as well as the time it takes to achieve that pull force. Currently, SMAs are used in a variety of settings, and a variety of shapes, but little has been done to optimize the shapes used for different applications [2]. The purpose of this experiment would be, therefore, to better inform what shapes of SMAs would be more suitable for any given engineering application that they may be used for.

In order to study the effectiveness of various shapes of SMA wires as actuators, five shapes different shapes were researched: elliptical spring, circular spring, triangular spring, 2D sinusoidal wave, 2D square wave. The pull force of these shapes over time in response to a constant input current will be tested using DC power supply and a force sensor to actuate SMA wire and measure its pull force. The raw data received from this experiment will be a constant current versus time graph that will be coupled with a time-dependent force response from which the transfer function between the constant input current and the force response of the SMA can be found. The steady state force output, or the maximum pull force that the wire achieves, to settling time, or the time it takes for the pull force to reach the steady state value, of various shapes will be used as a metric to assess the effectiveness of various shapes in different applications. This is because while in some applications a lower settling time is needed, such as when SMA’s are used to trigger safety mechanisms, other cases may require a higher steady state force.

BACKGROUND

SMAs exhibit two main distinct phases with different crystal structures and properties. These phases are dependent on the temperature of the SMAs; the high Temperature phase is known as Austenite, while the low temperature phase is known Martensite. While Austenite has a generally cubic crystal structure, Martensite's structure is more tetragonal or monoclinic. Martensitic transformations occur when shear lattice distortion occurs within the lattice structure of the alloy. [1] This causes variances in the orientation direction of the martensitic crystal, resulting in two forms of Martensite: twinned Martensite, or a combination of random martensitic variants, and detwinned Martensite, which is a reoriented version of Martensite in which a specific variant is dominant. These orientations are modeled in figure 1 below [1].

PHASE TRANSFORMATIONS

The unique quality of interest in SMAs here is their ability to undergo reversible phase transformations from Austenite to Martensite and back when exposed to an external catalyst, which is heat, or, in the case of this experiment, the heat caused by the current flowing through the wire. There are four important temperature boundaries associated with the phase transformation of an SMA. During a forward transformation from Austenite to Martensite in which the material is cooled, the Austenite begins to transform into twinned Martensite at a specific temperature Ms, and goes on to complete the transformation at a final temperature Mf. [3] A similar phenomenon occurs in the reverse reaction in which the material is heated, where the material begins converting back into an Austenitic structure at a certain temperature As and then becomes a complete Austenite at a final temperature Af. [1].

THE SHAPE MEMORY EFFECT

Furthermore, it is also possible to detwin martensite at low temperatures when a mechanical load is applied, resulting in a detwinned martensitic state. Following this deformation, if a heat is then applied to the material above the As temperature, it will return to a austenitic state, having a complete shape recovery. [3] A cooling of the SMA following this transformation will result in the formation of twinned martensite, with no indication of past deformation. This ability to "remember" its original shape after heat is applied, depicted in Figure1 below, is known as the shape memory effect.

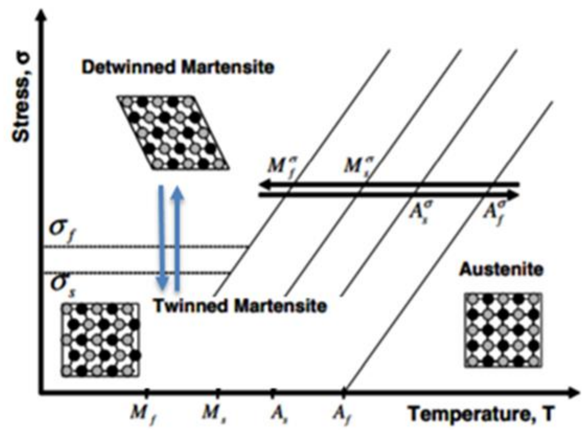

Figure 1: The blue arrows represent the detwinning of an SMA in the martensitic state under an applied stress. The black arrows represent the shape memory effect in which the Martensite is heated and transformed into an Austenite followed by it being cooled and reverting back to its martensitic state [2]

ENGINEERING APPLICATIONS

SMAs are especially appealing for many active engineering applications as they are much more light weight and have much less power consumption than conventional actuators. For many applications in which relatively low forces are needed for active response or feedback, SMA's can be used as a low cost, efficient alternative as they are reliable and multifunctional. Engineers have used SMAs to solve complex engineering problems in a variety of fields ranging from aerospace and naval to surgical instruments and medical implants and fixtures. [2] The use of SMAs is especially becoming more abundant in the medical field, where Nitinol, the alloy tested in this experiment, is mostly used. Nitinol contains roughly 50% Nickel and 50% Titanium regularly. [1] Compositional variances, however, to this ratio can result in major alterations to the operating characteristics of the material. Often in the medical field this alloy is made to have a slightly greater nickel composition, resulting in superelasticity, or an elastic, reversible response to an applied stress. [1] As less invasive procedures become more favorable in medicine, better quality Nitinol and Nitinol fabrication techniques are needed.

Testing the effects of the physical shape of the SMA and the current applied to it provides, therefore, more insights as to what shapes and power ranges are optimal for various applications. Due to the cost of shape setting and limitations of force output, however, non-conventional shapes are often refrained from, and more conventional shapes such as straight wires, ribbons, and springs are used [5]. In the case of this experiment, the focus is on springs, and in particular extension springs, shown in Figure 2 below.

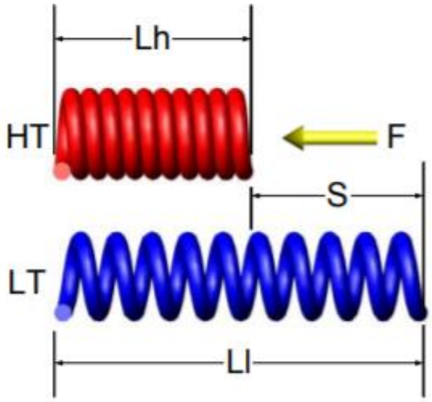

Figure 2: Shape Memory Alloy extension spring actuation [5]. Lh is the length of the spring when heated, LI is the initial, unheated length of the spring, and S is the stroke of the spring. F is the force with which the spring contracts.

ACTUATION METHODS

The two methods of actuation for SMAs are thermal and electrical actuation. Due to the temperature dependent phases mentioned in section 2.1, thermal activation is intuitive in the way it activates the SMA. This, however, is hard to implement as it requires a heat-controlled chamber in which the SMA functions in order to be able to activate and deactivate the SMA on control. This can not only be costly and inefficient, but also provides an added time delay for actuation due to heating and cooling times [5]

Electrical activation can, therefore, be a more useful method when incorporating SMAs in engineering applications. Due to the high resistivity of SMAs caused by their metallurgical composition, they can be heated by passing a current through them [5].

FIRST ORDER RESPONSES

The following is a fit equation for a first order response:

$$f(t) = a * e^{-\frac{t}{\tau}} + c \quad (1)$$

where a, τ, and c are controlled constants, is applied over the data set to find each shape's exact first order force response.

The relevant parameters when determining which shape to use in any given engineering application is the settling time, Ts and the steady state force, Fss. These can both be calculated from the generalized first order response equation 1 as derived in equation 2 and 3.

$$T_s = 4 * \tau \quad (2)$$

$$F_{ss} = f(t) = c \quad (3)$$

The steady state pull force and the settling time are illustrated graphically in Figure 3

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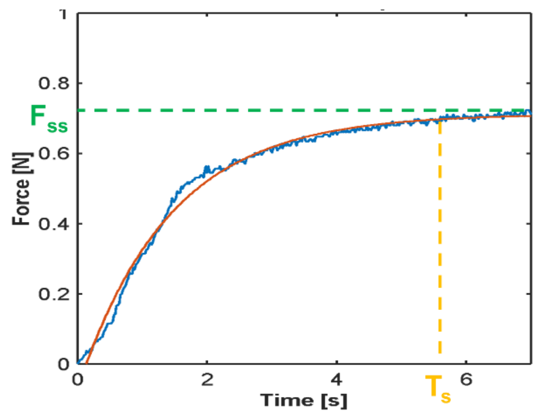
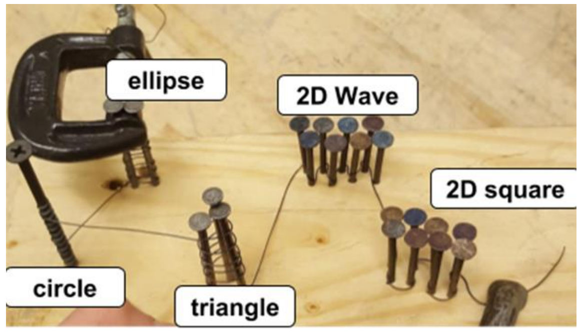


Figure 3: Steady State force and Settling time overlaid over a first order response.

These fit parameters will be especially useful further on section 4 in order to properly compare each of the shapes tested in this experiment using relevant parameters.

EXPERIMENTAL DESIGN

Untrained, Cold Drawn 0.5 mm diameter Nitinol wire purchased from Kellogg's Research Labs was used for the purpose of this experiment. To program the wire to the remember the test shapes when heated via a current passing through it, the wire was wrapped around nails that were positioned in a way to secure the wire in the test shape position. After annealing with propane blow torch flame until the wire burned a dull red along its entire length, the wire was unclamped and the separate shapes cut apart from one another.



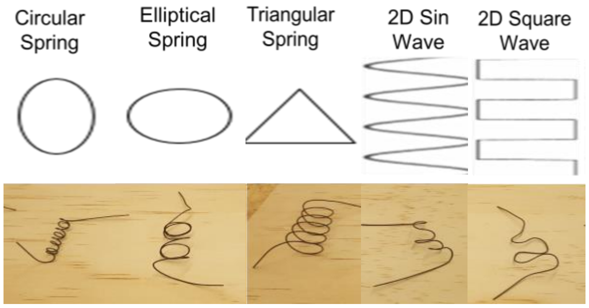


Figure 4: From left to right different patterns of nails can be seen in the wood board with the Nitinol wrapped through these orientations in order to secure it in the various shapes that are tested in this experiment. After clamping, a blow torch was used to anneal the wire to each of the shapes. All shapes are cut to the same length of 1 inch.

The shapes in Figure 4 were chosen in order to bring insight on possible correlations between two dimensional and three dimensional shape responses as well as how shapes with distinct edges and corners, such as the triangular spring and the square wave, respond compared to shapes without. To determine the response time-dependent pull force of the Nitinol wire in response to a constant step input current, each wire shape was inserted into the circuit shown in Figure 5 and clamped to the force sensor and a fixed end.

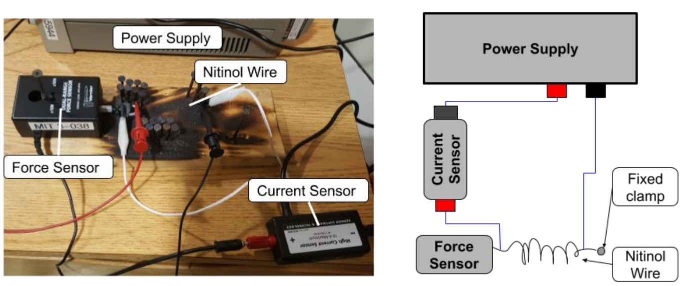


Figure 5: On the left is a photograph of the experimental setup and on the right is the corresponding diagram. On the diagram, the Power Supply, Current Sensor, and Force Sensor are represented by grey boxes. The wires connecting the circuit are represented in blue and the Nitinol wire is represented in black. The red terminals represent positive and the black represent negative in the circuit

For three trials of each test shape the Nitinol wire was stretched out and then clamped with one end to a Vernier Dual-Range Force Sensor, which has a .01 N resolution ±10N range, on one end and a fixed peg on another using electrically insulated alligator clips. This allowed for the measurement of the pull force of the wire once the current was sent through it. The circuit seen in Figure 5 on the right illustrates how the Agilent E3610A power supply, which was chosen due to its range of 3 Amps, is connected through the Vernier High Current Sensor, with a resolution of 4.9 mA and a ±10 A range, to each end of the Nitinol wire. After setting the power supply to the 2.55 ± .005 A, the power supply was turned off and the circuit was connected. The power supply was then turned on in order to resemble a step input for the current, and both the current input and the time-dependent force response was recorded using a Vernier LabPro, which has a maximum sample rate of 5 kHz when two sensors are connected to it.

In order to electrically activate the SMAs as described in section 2.4, a step input current of 2.55 Amperes was applied to the circuit shown in Figure 5, which can be modeled as the Heaviside step function in Figure 6.

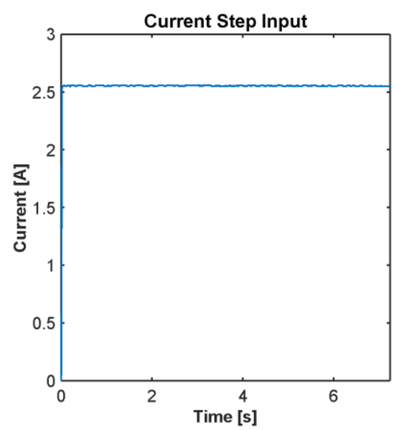


Figure 6: Heaviside step input of current that is applied to every SMA shape at 2.55 Amperes

RESULTS AND DISCUSSSION

TIME DEPENDENT FORCE RESPONSE

The time-dependent output force is then fit with a first order time response as seen in Figure 7. As there is no previous literature to dictate what order time response would be best suitable for SMA reactions, a first order response was chosen due to the fact that the actuation of the SMA depends on the heat applied to it, and the unsteady heat transfer equation for the wire with a current flowing through it is a first order response.

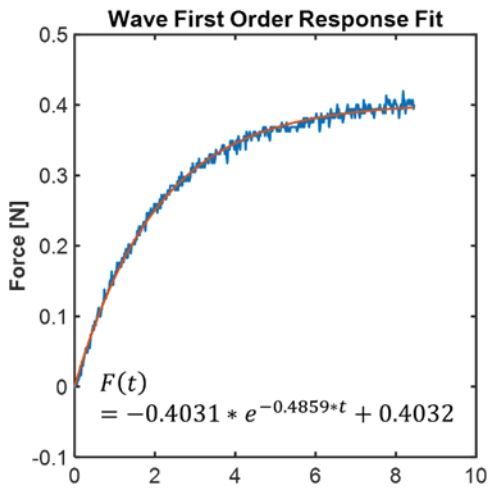


Figure 7: First order fit in red overlaying blue preliminary raw data of the SMA actuation.

The fit equation for this data was therefore equation 1 from section 2.5. The values for equation 1's constants and their uncertainties can be found in Table 1, and the full equations for each shape can be found overlaid on each graph in Figure 8.

Table 1: The constants that define the time-dependent force response for each shape are labeled with their absolute uncertainties. All of the values found were found to be statistically significant.

Shape	a	τ	c
2D sinusoidal wave	-0.4031 ± 0.0025	2.058 ± 0.0320	0.4032 ± 0.0015
2D square wave	-0.4751 ± 0.0109	0.8805 ± 0.0401	0.3999 ± 0.0039
3D circular spring	-0.7828 ± 0.0082	1.418 ± 0.0315	0.7125 ± 0.0035
3D elliptical spring	-0.834 ± 0.0121	1.085 ± 0.0435	0.9211 ± 0.0091
3D triangular spring	-0.1858 ± 0.0031	1.404 ± 0.0415	0.1718 ± 0.0009

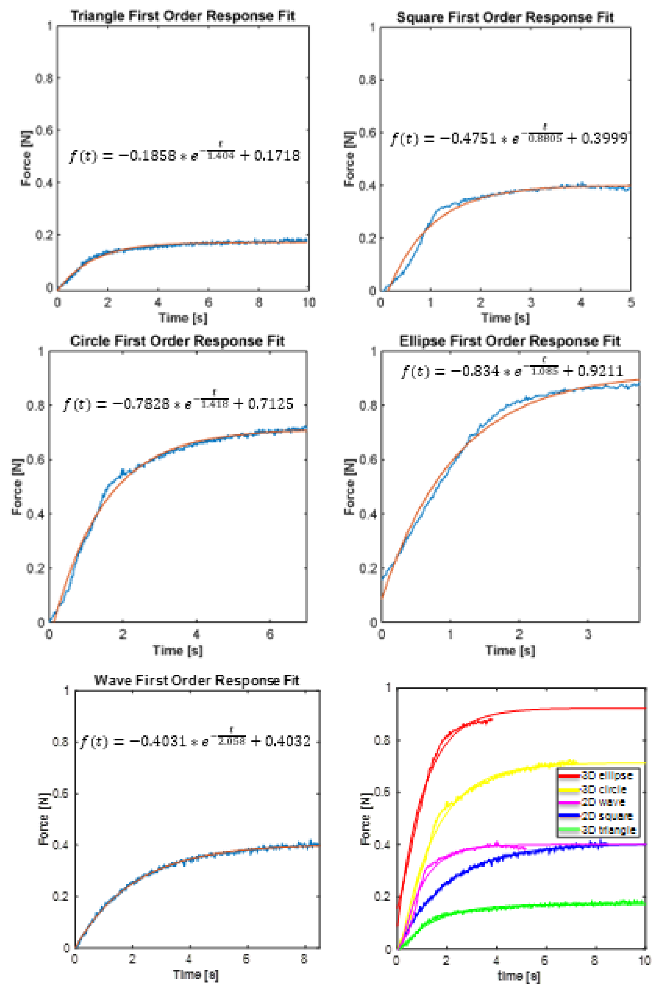


Figure 8: Each plot, labeled with the shape of wire that it represents (3D triangular spring, 2D square wave, 3D circular spring, 3D elliptical spring, 2D sinusoidal wave), depicts the time dependent for response in Newtons. The graph in e) depicts the comparison between the fits for each shape.

SHAPE DETERMINATION

The settling times and steady state force values for each of the shapes can be seen in the Shape Determination Chart in figure 4.3, in which each shape is marked with a square.

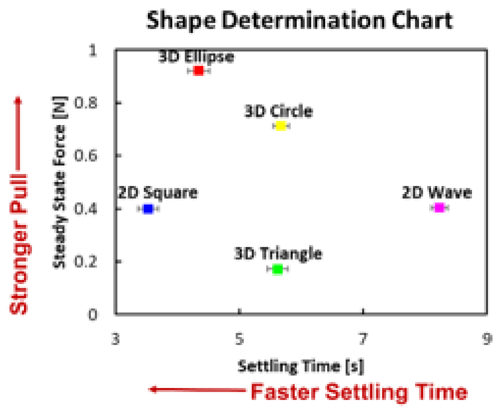


Figure 9: comparison between the steady state force values for every SMA shape and the settling times for the shapes.

The comparison chart depicted in figure 4.3 provides for an ease of comparison between the five different SMA shapes tested between their relevant parameters (steady state force value, settling time). For the shapes used in this experiment, the shape with the largest steady state force was the 3D ellipse, with a value 5.4 times greater than the shape with the lowest pull force, the 3D triangle. Furthermore, the shape with the shortest settling time was the 2D square, with a value 2.3 times smaller than the shape with the longest settling time, the 2D wave. Lastly, there was no apparent correlations found between 3-Dimensional and 2-Dimensional shapes and the force response by which they pulled or organic and inorganic shapes seemed to have the highest pull force at more than 2 times their 2D or inorganic counterparts.

POSSIBLE LIMITATIONS

Only one type of SMA was used throughout this experiment, specifically a thin Nitinol wire with constant thickness. Other types of SMAs may therefore have different characteristic responses when actuated. Furthermore, only compression springs were investigated in this study, and SMAs may have different responses when used as expansive actuators (measuring the push force of the SMA) rather than contractive actuators, as studied within this experiment.

Another possible limitation is that only five shapes were studied, which is not extensive nor does it encompass the vast array of possible shapes and orientations for different engineering applications.

CONCLUSIONS

SMAs are used in a wide array of applications from camera apertures to medical devices to safety trigger mechanisms, and for each of these applications there are different parameters that the SMA needs to achieve in order to be suitable. The shape of the SMA is, therefore, a parameter that one can adjust based on specific application, as it has a large effect on the relevant parameters in relation to SMAs, the steady state force and the settling time.

The comparison of these parameters will allow for more informed decisions on what shape of SMA to use when applying them in various engineering applications. If a short settling time is necessary, for instance, a 2D square wave should be used rather than any other shape. If a higher pull force, however, is required, then using a 3D ellipse would be more optimal. In order to find the proper shape for the application, one can use the steady state force to settling time ratio of each shape and find which shape is closest to the ratio needed for your application.

If, for instance, we look back at the engineering applications mentioned in section 2.3, we might realize that if we wanted to use a SMA for the purpose of providing a constant, high pull force over an extended period of time to pull two parts of a bone together, then Fss matters and Ts does not. For this case, a 3D circle or 3D ellipse may be used. If, however, Fss does not matter and Ts does, as in the case of a fire safety mechanism where the trigger mechanism must activate as soon as possible, then a 2D square or 3D ellipse may be used to optimize your shape application.

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