Characterization and Development of Shape Memory Alloy Actuator for Pinch Valve Actuation

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Abstract

Pinch valves are used to control fluid flow by locating flexible tubing in a mechanism that pinches and releases the tubing to block and allow flow respectively. The present study deals with the design and characterization of a Shape Memory Alloy (SMA) spring actuator for this purpose. A SMA spring was designed based on the force needed to control the fluid flow. The Shape Memory Alloy actuator characteristics such as Current-Temperature, Force-Deflection and Temperature-Deflection were analyzed using Finite Element Analysis and the results were correlated with experimental results. A prototype valve was developed with the fabricated SMA spring actuator and the Current-Flow rate characteristics of the valve at different pressure ranges were determined which depicts the working of the pinch valve.

Keywords - Current-Temperature Model, Force-Deflection Model, Pinch valve, Shape Memory Alloy (SMA) Actuator, Temperature-Deflection Model.
1. Introduction

Pinch valve find application in areas of micro chemistry, drug delivery systems and micro fluidics [1]. The key advantages are the compatibility with different tubing materials, no contact with fluid and minimum pressure drop.

A Shape Memory Alloys (SMAs) are special metal alloys that are capable of recovering their original shape after being deformed through heating above the transformation temperature. This property is referred as Shape Memory Effect (SME). SMAs have been widely proposed as actuators, in fields such as robotics, biometrics and microsystems [2]. The focus of the present study is the design and characterization of a SMA spring actuator for actuating a pinch valve.

Shape memory alloys are offered as wires, tubes and strips, which provides different means of actuation for a required application. Among all the possible actuation solutions, the helical shape is one of the most frequently used, due to the number of parameters that can be adjusted, its ease of fabrication and its compactness [2]. The aim of this paper is to design and characterize a SMA spring actuator for a generic application such as pinch valve actuation, using various design parameters including stroke and force. The heat exchange of the SMA with air is also considered to efficiently manage the operation of the spring actuator.

2. Design of SMA actuator

In medical devices, SMAs has gained popularity due to their fatigue resistance and bio compatibility [3]. With the advantages of being a light weight technology and high power/weight ratio, SMAs are a viable alternative to conventional actuators. The simplest way to use a SMA for an actuator application is in the form of a wire. But the design has the disadvantages of having a small stroke and large recovery force. As a tradeoff between force and stroke, the SMAs can be designed to be used as actuators in the form of springs which will depend only on geometrical factors [4]. The following sections explains the use of SMA as a spring actuator for pinch valve application.

2.1 SMA spring mechanical modeling

2.1.1 Force-Deflection model

This section gives in detail the research work that has been carried out in the field of adapting SMA springs as actuators. A comprehensive review on the latest research work done in the field of SMA spring actuators was given by Adelaide
Nespoli et al. [5]. The review detailed the use of SMA spring actuators developed by T.Ishii [6], Jansen et al. [7], Pulnev et al. [8] and Donnellan’s improvement to the Stratasys Research and Applied Physics Laboratory mini actuator [9].

Alberto Bellini et al. [10] developed a SMA spring actuator for the operation of automobile tumble flaps. The actuator consists of two sets of SMA springs working as mutual antagonists to produce linear movement of an output shaft. Christopher G. Stevens [11] developed a SMA spring actuator based on conventional spring design and an Excel spreadsheet application was developed by him enabling an easy way to design SMA springs. Sonia Degeratu et al. [12] developed a Visual Basic application for the design of SMA spring actuators based on thermal analysis and conventional spring design. Igor Spinella and Eugenio Dragoni [13] compared the characteristics of solid and hollow SMA compression springs in which the spring design was based on conventional spring design. M Follador et al. [4] developed a general method for the design of SMA spring actuators which was also based on conventional spring design. The work of Sung Min An et al. [14], who developed a two-state static model for the development of SMA spring actuators differ from the conventional spring design. The work considered four different parameters namely SMA spring mean diameter (D), the wire diameter (d), the pitch angle (α) and the Number of helical coils (n). Based on this work, a similar model was developed for SMA compression springs and the Force-Deflection characteristics were determined. The equations used to determine the Force-Deflection characteristics of the SMA spring are given by Eq. (1) and Eq. (2).

\[
\frac{F}{G_a} = \frac{\cos^2 \alpha_i}{\cos^2 \alpha_f} \left( \frac{D}{d} \right) \sin (\alpha_i - \alpha_f) \left( 1 + \frac{n}{1 + \frac{D}{d}} \right)
\]

Where,
- \(F\) – Axial force (N)
- \(G_a\) – Shear Modulus at austenite phase (N/mm²)
- \(G_m\) – Shear Modulus at martensite phase (N/mm²)
- \(d\) – Wire diameter (mm)
- \(D\) – Mean diameter of the spring (mm)
- \(n\) – Number of helical coils in the spring
- \(\alpha_i\) – Initial pitch angle (degree)
- \(\alpha_f\) – Final pitch angle (degree)
- \(\delta\) – Deflection of the SMA spring (mm)
\( v \) – Poisson’s ratio

The verification of the developed model was done using three SMA springs of different specifications. The three sample Ni-Ti SMA springs had the austenite finish temperature of 90 °C, 55 °C and 65 °C. The SMA spring design parameters are tabulated in Table 1 and the springs are shown in Figure 1.

![Ni-Ti SMA springs](image)

**Figure 1.** Ni-Ti SMA springs taken for Force-Deflection model verification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of helical coils, n</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Diameter of wire, d (mm)</td>
<td>1.5</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Mean diameter of the spring, D (mm)</td>
<td>11.5</td>
<td>6.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Spring index, C</td>
<td>7.67</td>
<td>5.67</td>
<td>6.5</td>
</tr>
<tr>
<td>Initial pitch angle, ( \alpha_i ) (degree)</td>
<td>7.0</td>
<td>6.5</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The experiment was carried out with an apparatus consisting of a temperature chamber with a load cell placed inside as shown in Figure 2. The spring was compressed with a fine adjustment screw attached to a support frame around the load cell. The model results were compared with the experimental results and were found to be within 10% error and the plotted values are shown in Figure 3.
Figure 2. Schematic of the experimental setup to determine the Force-Deflection characteristics of the SMA springs.

Figure 3. Comparison of Force-Deflection plot for the sample springs at Austenite and Martensite Phases

From the results obtained in [15], it was found that the maximum force of 25 N is needed to close the silicon tube completely. But the spring was designed to exert a force of 33 N since the spring has to be used against a bias spring of 8 N.

2.1.2 Optimized SMA spring fabrication

Once the model was verified with three different SMA springs with different parameters, design of experiments was carried out with Taguchi Orthogonal Array. L27 array was used such that the different parameters chosen maximize the force. The optimized parameters of the SMA spring for the required force are tabulated in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of helical coils, n</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Diameter of wire, $d$</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Mean diameter of the spring, $D$</td>
<td>6.8 mm</td>
</tr>
<tr>
<td>Spring index, $C$</td>
<td>4.53</td>
</tr>
<tr>
<td>Initial pitch angle, $\alpha_i$</td>
<td>6.5°</td>
</tr>
<tr>
<td>Shear modulus, $G_a$</td>
<td>23.90 GPa</td>
</tr>
<tr>
<td>Shear modulus, $G_m$</td>
<td>9.56 GPa</td>
</tr>
</tbody>
</table>

Commercially available Ni-Ti SMA wire of 1.5mm diameter was purchased with 65 °C austenite start temperature. Two sample SMA springs were fabricated using a spring winding machine based on the design. The springs were then shape trained in a furnace at 400°C for 1 hour for obtaining better dimensional properties.

The Force-Deflection values of the designed SMA spring was found and compared with FEA and the conventional design results. The results were improved and the error percentage was reduced from an average of 15% to 3.5% in the austenite phase and from 12.5% to 3.5% in the martensite phase. The results are plotted in Figure 4. With the results obtained, it is observed that the model can be used to determine the force-deflection characteristics of any SMA spring with different design parameters.

3. **SMA Spring Electrical Model**

The actuation of the SMA actuators can be achieved by methods such as passing electric current, exposing the SMA to thermal radiation and external heating by a wire. The different heating methods are illustrated in Figure 5.
Among the three actuation methods, the heating by passing electric current is commonly used as the method is simple and direct. The SMA spring was actuated by passing electric voltage through it. As the electric voltage is passed through the SMA spring, the spring gets heated up due to the Joule heating effect.

The current-temperature characteristics of the SMA spring was found experimentally using a thermocouple and a DC power supply. Once the SMA spring was connected to the power supply, the display showed values of current and voltage as 2.01 A and 0.31 V respectively due to the resistance of the SMA material. The current value was then increased and the corresponding temperature values were noted until the austenite finish temperature (75°C) of the SMA spring material. The results of the experiment were plotted and the corresponding governing equation was found using the polynomial curve fit. The results are shown in Figure 6.

The resistance of the SMA material was also found from the ratio of voltage and current at various temperatures and the value is 0.149 ohm.

Based on this resistance, the resistivity of the SMA material was calculated from Equation (3) and was found to be 0.0021 ohm-mm for a wire length of 130mm.
4. SMA Spring Thermal Model

Thermodynamic properties of heating and cooling cycles are a critical point in the design, both for the power consumption and for the frequency of the activation cycles [4]. In this design, the heat transfer is dominated by convection, since the wire is surrounded by air. The heat transfer coefficient of the SMA spring is calculated using the equation given in [4], which is denoted by Equation (3),

\[ h = \frac{I^2 \rho}{2\pi r^4(T - T_a)} \]  

Where,
- \( h \) – Heat transfer coefficient (W/mm\(^2\) 0°C)
- \( I \) – Input current (A)
- \( \rho \) – Resistivity of the SMA wire (ohm-mm)
- \( r \) – Radius of the SMA wire (mm)
- \( T \) – Target temperature (°C)
- \( T_a \) – Ambient temperature (°C)

The SMA spring attained the austenite finish temperature at a voltage and current value of 0.63 V and 4.11 A respectively. Based on the current value, the heat transfer coefficient was calculated from Equation (3) as 9.5E-5 W/mm\(^2\) 0°C for a room temperature of 30 °C.

The specific heat of the SMA material was obtained from the supplier’s technical data sheet which is 836 Joule/kg 0°C. The power supplied to the spring was calculated from the current and voltage values needed to make the SMA spring reach the austenite finish temperature and was found to be 2.6 Watts. In order to obtain the heating and cooling time, a 3D current-thermal-structural analysis was carried out in MSC Marc package.

The SMA spring was modelled with tetrahedral elements and the number of elements was 31622. A fixed boundary condition was applied to end of the spring and the other end of the spring was left free to allow the spring to deflect. The convection to the air was applied to the SMA spring as a film coefficient with the calculated ‘h’ value. A fixed voltage of 0.63V is applied to nodes at the fixed end and a fixed voltage of 0V is applied to the nodes at the free end. The input voltage was applied in terms of a square wave with 8 seconds ‘ON’ time and 32 seconds ‘OFF’
time. An initial temperature of 30 °C was applied to all the nodes. The finite element model used for the analysis is shown in Figure 7. The results of the analysis show that the time taken for the SMA spring to attain complete transformation and to cool down to martensite finish temperature as 7.6 seconds and 30.8 seconds respectively.

5. Temperature Deflection Characteristics

The SMA deflection spring at various temperatures is an important factor in the design of the actuator since it depicts the actuation of the actuator inside the valve. The SMA spring actuator is actuated by passing electric voltage through the spring. As the Current-Temperature characteristics were previously discussed, the deflection at various temperatures were noted from finite element analysis done previously. The SMA deflection spring at various temperatures were experimentally determined with the setup as shown in Figure 8. The SMA spring was attached to a plunger whose other end is attached with a bias steel spring. The SMA plunger along with the SMA spring and bias spring are fixed in a metal frame with a hole in one side for enabling the plunger to be fixed inside. Electrical connections were made to the SMA spring through connecting wires. The temperature rise in the SMA spring was monitored using a thermocouple. The current input to the SMA spring was varied from zero to 4.11A and the corresponding temperature and deflection values were noted using the thermocouple and LVDT respectively.

Three trials were taken for the deflection values and the deflection and temperature values were then compared with the FEA results that are tabulated in Table 5. The compared results are well within 10% error. The SMA spring was designed to produce a force of 33 N at a stroke of 3.5 mm. But the experiment
showed that the spring was capable of producing only 3.1 mm deflection which results in a drop in force produced by the spring.

![Experimental setup for determining the Temperature-Deflection values of the SMA spring]

Figure 8. Experimental setup for determining the Temperature-Deflection values of the SMA spring

![Table 5. Comparison of Temperature-Deflection results from FEA and experiment]

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Temperature(°C)</th>
<th>Displacement(mm)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEA</td>
<td>Experiment</td>
<td>FEA</td>
</tr>
<tr>
<td>2.5</td>
<td>40.72</td>
<td>38.38</td>
<td>0.72</td>
</tr>
<tr>
<td>3.0</td>
<td>48.30</td>
<td>48.71</td>
<td>1.30</td>
</tr>
<tr>
<td>3.5</td>
<td>60.25</td>
<td>59.93</td>
<td>2.10</td>
</tr>
<tr>
<td>4.0</td>
<td>72.38</td>
<td>72.04</td>
<td>3.06</td>
</tr>
</tbody>
</table>

6. Design of a prototype valve

The characteristics of the SMA spring such as Force-Deflection, Current-Temperature and Temperature-Deflection were discussed in the previous sections. With these results of the SMA spring, an actuator was developed to squeeze the silicone tube selected for experiment previously at a pressure range of 0.2 to 2.0 bar with air as the flowing medium.

The SMA spring is made to push a small plunger attached with a bias spring. The purpose of the bias spring is to bring back the SMA spring to its compressed position once the power supply to the spring is cut off. When activated, the SMA spring pushes the plunger overcoming the bias spring force thereby squeezing the silicone tube which in turn controls the flow of fluid inside the tube. For the prototype, the casing which holds the SMA actuator was made of commercially available Teflon due to its easy machinability and high temperature resistance. The plunger was made of Aluminum and the bias spring was made from spring steel. A
A grub screw was mounted at the top of the casing to provide pre-adjustment to the silicone tube. The exploded view of the entire actuator is shown in Figure 9.

![Exploded View of the Prototype Valve](image1)

Figure 9. Exploded view of the prototype valve

The function of the SMA actuator was tested using the experimental apparatus as shown in Figure 10.

![Experimental Apparatus](image2)

Figure 10. Experimental apparatus for testing the prototype valve.

The air supply from the compressor was fed to the flow control valve. The flow control valve was then connected to the prototype pinch valve with SMA actuator. The other end of the silicone tube was connected to a flow meter to measure the flow rate once the valve is actuated. Initially the pressure and flow rate were set as 0.2 bar and 0.2 l/sec. The actuation of the valve was achieved by raising the current...
value from 0 to 4A. The valve was expected to provide a deflection with the required force as shown in Table 5. The flow rate was monitored as the current value was increased. The result is plotted in Figure 11.

![Current-Flow rate Plot](image)

Figure 11. Current-Flow rate plot of the prototype valve

### 7. Results and discussions

The current work dealt with the design of a SMA actuator for the actuation of a pinch valve. The maximum force required to close a 4mm silicone tube at a pressure of 2 bar with air as the flow medium was found to be 25 N. This force was predicted using FEA and compared with the experimental results. Based on the force required, a SMA actuator was developed with SMA spring as the actuating device.

The SMA spring actuator was designed to provide a force of 33 N with a deflection of 3.5 mm since it has to act against a bias spring of 8 N force which was used to return the SMA spring to its original compressed position once the actuation is complete. But the SMA spring was able to produce a deflection of about 3.1 mm only at the maximum actuation temperature.

Force-Deflection, Current-Temperature and Temperature-Deflection characteristics of the SMA actuator were determined using both FEA and experiments. The results were compared and was found to be within 10% deviation. The current and voltage needed to actuate the SMA actuator was found to be 4.11 A and 0.63 V respectively. With these values, the heating and cooling time of the SMA actuator was found to be 7.6 and 30.8 seconds respectively which determines the power consumption and frequency of actuation of the actuator.

A prototype valve was developed with the SMA actuator. The Current-Flow rate values at a pressure of 0.2 were found for the valve. Even though the actuator
produced a deflection of 3.1 mm and a force of 33 N, full closure of the silicone tube was not achieved. Further studies will be made to achieve full closure of the tube using the SMA actuator.

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9. References


