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FINITE ELEMENT STUDIES OF TRIPLE ACTUATION OF SHAPE MEMORY ALLOY WIRES FOR SURGICAL TOOLS

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BACKGROUND

Since the early discovery in 1951 [1], shape memory alloys (SMAs) have been used in design and development of several innovative engineering systems. SMAs' unique characteristics have introduced unconventional alternatives in design and development of advanced devices. SMA's field of applications has covered many areas from aerospace to auto industries, and medical devices [2]. During the past couple of decades, scientists have suggested material models to predict the SMA's shape memory effect (SME) and its superelastic behavior. The superelastic characteristic of SMAs (its capability to exhibit a large recoverable strain) has been widely used to develop innovative products including biomedical implants such as stents, artificial heart valves, orthodontic wires, frames of indestructible spectacles, etc. However, its actuation capabilities, known as SME, hasn't been thoroughly expanded. The number of products privileging from SMA's SME behavior has been very limited. The reason relies on the SMA's complex material properties that depend on the stress, strain and temperature at every stage of actuation as well as the material's processing and the thermomechanical loading history.

In the past couple of decades, research studies have been done to utilize the SME behavior of SMAs and provide actuator alternatives in design and development of medical devices that require a precise manipulation at their tip to navigate inside the patient's body. These devices could be used in diagnostic and therapeutic procedures such as colonoscopy, suturing, and laparoscopy. Additionally, SMs have been suggested to be used in navigating devices in procedures such as peripheral artery diseases, coronary vasculature: stents and angioplasty.

In a recent study, SMA wire was used to actuate a brachytherapy [3] needle for an enhanced placement of radioactive seeds inside prostate to kill cancerous cells locally. In another study, an active MitraClip locator device [4] was designed with SMA actuations for percutaneous transcatheter mitral valve repair system.

When a SMA wire is used as an active actuator of a system, the stress, strain, temperature path that the SMA will go through is not always known. Thereby, an incomplete phase transformation is probable, and thus a non-consistent actuation behavior. Obtaining a consistent and reliable actuation remains a challenge in design and develop of SMA activated systems.

In depth understanding of SMA's phase transformation process during actuation is necessary to accurately predict its behavior in active surgical tools. It also helps controlling the motion, and path planning of their end effector. For this purpose, we designed a system with triple SMA wires to obtain a 3D manipulation. By means of this system the amount of stress, strain and temperature, that SMA wires are subject to, could be easily altered to characterize the wires. While experimental data is obtained, a finite element model was developed for evaluation purposes. An optimization study by Konh et al. [5,6] showed the significance of having an accurate material model for SMAs for design purposes. Terriault et al. [7] modeled both the nonlinear elastic modulus and the hysteresis of SMAs in ANSYS. The limits of this approach were related to the difficulties in defining a custom material models of SMA materials. The main scope of this work is to propose a finite element model of the active device that privileges from a reasonably accurate SMA material function. This modeling approach is intended to help incorporate SMA actuators into medical devices.

METHODS

2.1 Experimental setup

The experimental setup (shown in Fig. 1) was designed and built with two circular discs (D=30mm) with three hooks to attach the SMA wires. The top side was fixed to a rigid frame and the lower side was hanged by three SMA wires (purchased from Dynalloy Inc., Tustin, CA) with diameter and length of 0.29 and 100mm, respectively.

The SMA wires were connected to the hooks at 16mm from the center. For a proper actuation, SMA wires must be pre-stressed prior to applying the electric current. To set a desired pre-stress on the wires a total mass of 100g was applied to the lower disc. This weight creates 4.95MPa of stress on each wire. Joule heating method was used to heat the actuators using a programmable power supply with an ON-OFF switch to facilitate the actuation of each wire. To prevent damaging the actuators, the current was kept under 0.7A. The corresponding voltage across the wire raised to max of 1.3V at 0.7A. To measure the deflection of the disc, image shots were captured using a Canon EOS 6D digital camera with a Canon EF 24-105mm f/4L IS USM Lens. The deflection angle was then calculated by processing the images using ImageJ software.

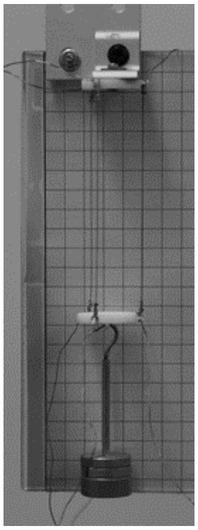
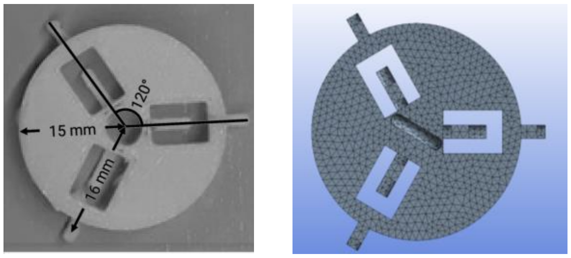


Fig. 1. Experimental setup: two 3D printed discs, top disc is fixed to the frame and a 100g weight is attached to the lower disc to apply a certain stress on three hanged SMA wires.

2.2 Finite element model

Figure 2a displays the 3D printed discs with 120-degree angle spacing and diameter of 15mm. The generated mesh for finite element analyses is shown in Fig. 2b. Hexagonal, adaptive coarse elements were used to model the geometry similar to the experimental setup.



(a) (b)

Fig. 2. Design of the disc: (a) 3D printed part, and (b) generated mesh for finite element analyses.

A total number of nodes and elements of 75,2016 and 48,136 were used in the model, respectively. Six contact regions were defined to bond the SMA elements with the disc. A fixed support constraint was applied on the top face of the disc that was attached to the frame. A constant pressure was applied to the lower disc to create 4.95MPa of initial stress on each SMA wire. Initial temperature of the wires was set to 22˚C. To calculate deflection during the 10s of heating, a transient solution was adopted with overall 20 time steps: min and max time step of 0.1 and 0.5s, respectively, and the step end time of 10s. The large deflection option was turned on for a better convergence. Thermal loading condition was applied to one of the SMA wires to heat it gradually from room temperature (22 ˚C) to 32˚C in 10s. It was assumed that a complete phase transformation could be achieved when the SMA's temperature is raised by 10˚C. The SME of SMAs was represented by a thermal expansion material model. A negative coefficient of $-0.005C^{-1}$ was set on SMAs to obtain 5% of strain within a 10˚C temperature rise.

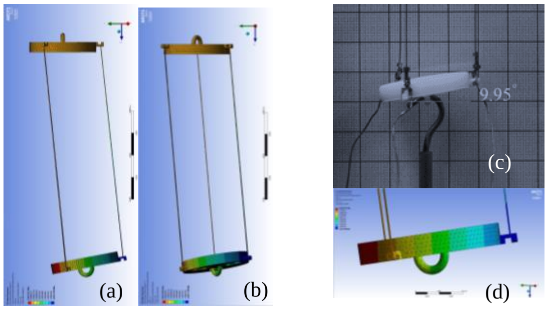


Fig. 3. (a) & (b) FEA representation of the deflected disc. Comparison between the tilted angle: (c) experimental result, and (d) FEA prediction.

Results

Two angular views of the disc's final deflection, actuated by one wire, is shown in Fig. 3a and b. Figure 3c shows a typical image that was captured for experimental evaluations. The deflection of the disc was calculated by processing 24 images captured during 10s of operation. Finite element prediction for the directional deformation in z-axis is shown for the disc in Fig. 3d.

Figure 4 compares the deflection of the disc predicted by finite element analyses and the experimental data. The vertical displacement of the node located at the point of contact between the wire and the disc was chosen as reference for comparison. A contraction of 5.1mm was observed on SMA wire when actuated, which corresponds to 5.1% of strain. The overall deflection of 5.39 and 5.46mm was predicted by FEA and experimental results, respectively. The FEA predicted the final deflection with a high accuracy while was unable to capture the nonlinear behaviour of the SMAs because of the adopted simplified linear material model. The model worked well to predict the deflection, however the amount of stress on the wires were not trustable.

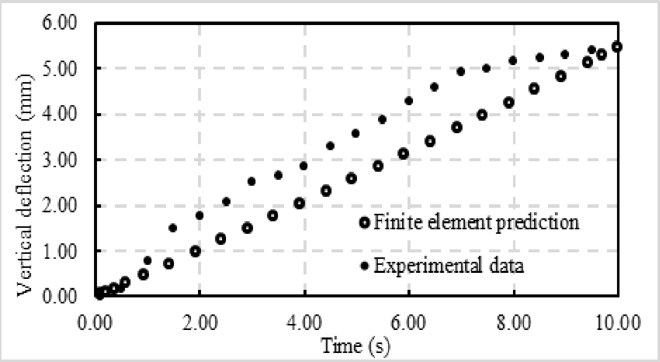


Fig. 4. Vertical disc deflection predicted by finite element analyses compared with experimental results.

INTERPRETATION

This study describes a material model for SMAs that could be used to predict the final deflection of an active structure with triple SMA actuator. This study is very useful to understand the characteristics and behavior of SMA's material and predicting the deflection and changes in wire length under various loading conditions. This study also could be used in development of any future control algorithms to realize a 3D movement, positioning of SMA's, and their path planning.

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