SMA Powered Non-Magnetic Actuator

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Abstract

Our project is aimed to model an SMA based bipennate muscle actuator based on Kanhaiya et. al. [2022]. This integration of SMA wires with biological pennate muscles offers a superior power-to-weight ratio and finds applications across diverse fields, from building controls to precise drug delivery systems. The model makes use of the prominent Liang and Rogers model for Shape Memory Alloys for the constitutive equations along with basic heat transfer and kinematics equations.

1 Introduction

Actuators are essential components in various mechanical systems, driving controlled motion for a wide range of applications. Shape memory alloys (SMAs) play a crucial role in building robust actuators, as highlighted in the paper. SMAs offer unique properties such as shape memory effect and high actuation energy density, making them ideal for actuation applications. Bipennate muscles are a type of muscle architecture wherein muscle fibers are arranged on both sides of a central tendon at an oblique angle, resembling a feather-like structure. This unique arrangement allows for a higher total muscle force generation compared to parallel fiber muscles within the same cross-sectional area.

By leveraging SMAs in actuator design, we introduce a novel non-magnetic hierarchical actuator powered by SMA-based bipennate muscle. This innovative approach combines the advantages of pennate muscle from biological systems with the exceptional characteristics of SMAs to deliver significantly higher actuation forces and reduce overall weight, showcasing the potential of SMAs in advancing actuator technology. Specifically, using widely popular models for SMAs, we try to study the dependence of various state variables on time and the amount of force and stroke our model is able to generate.

2 Literature Review

→ After conducting a detailed literature review of the paper by Kanhaiya et. al. [2022], the following are our findings:

2.1 Background on SMAs and Bipennate Muscles

2.1.1 Introduction to Actuators:

- Actuators play a vital role in facilitating controlled motion within mechanical systems, serving as essential components for various industrial and manufacturing applications.
- Traditional actuators, such as hydraulic and pneumatic systems, are commonly utilized but face challenges related to maintenance, complexity in design, and high operational costs, prompting the exploration of alternative solutions.

2.1.2 Advantages of Shape Memory Alloys(SMAs) in actuator design:

- Shape Memory Alloys (SMAs) are a class of smart materials known for their unique properties, including the ability to recover their original shape after being subjected to high temperatures, making them ideal for actuation applications.
- The high power-to-weight ratio of SMAs sets them apart from conventional actuator materials, offering a promising avenue for developing more efficient and compact actuation systems.

2.1.3 Inspiration from Bipennate Muscle Architecture:

- Bipennate muscle architecture, observed in mammalian muscle structures like the triceps surae complex and quadriceps femoris, features muscle fibers arranged obliquely on both sides of a central tendon, enabling a higher total muscle force output within a given cross-sectional area compared to muscles with parallel fiber alignment.
- The geometric complexity and functional advantages of bipennate muscles serve as a source of inspiration for the innovative hierarchical actuator design proposed in the study, aiming to harness the biomechanical efficiency of natural muscle structures.

2.2 Proposed Model

2.2.1 Proposed Hierarchical Actuator Design:

- The research introduces a novel hierarchical actuator design powered by SMA-based bipennate muscle, combining the exceptional properties of SMAs with the structural benefits of bipennate muscle architecture to enhance actuator performance.
- By arranging SMA wires in a bipennate configuration, the actuator aims to achieve significantly higher actuation forces, up to 150 N, while simultaneously reducing weight by approximately 67% compared to existing SMA-based actuator designs.
- The mathematical model governing the SMA-based bipennate actuator includes equations describing the behavior of SMA wires under varying conditions, such as stress, strain, temperature, and martensite volume fraction, to predict the actuator's performance accurately.
- The model makes use of the phase transformation property of SMAs which leads to contraction of the SMA wire leading to a net stroke and force generation.

The model equations are mentioned in the methodology section of the report.

2.2.2 Key Findings and Experimental Validation:

- The mathematical model developed for the hierarchical SMA actuator allows for the customization of design parameters and provides insights into critical factors influencing actuator performance, enabling a deeper understanding of the actuation mechanism.
- Experimental validation of the actuator includes muscle force output measurements and thermal imaging experiments to analyze the actuator's behavior under varying input voltages and temperature fluctuations, offering valuable insights into the actuator's operational characteristics.

The physical model is given below:

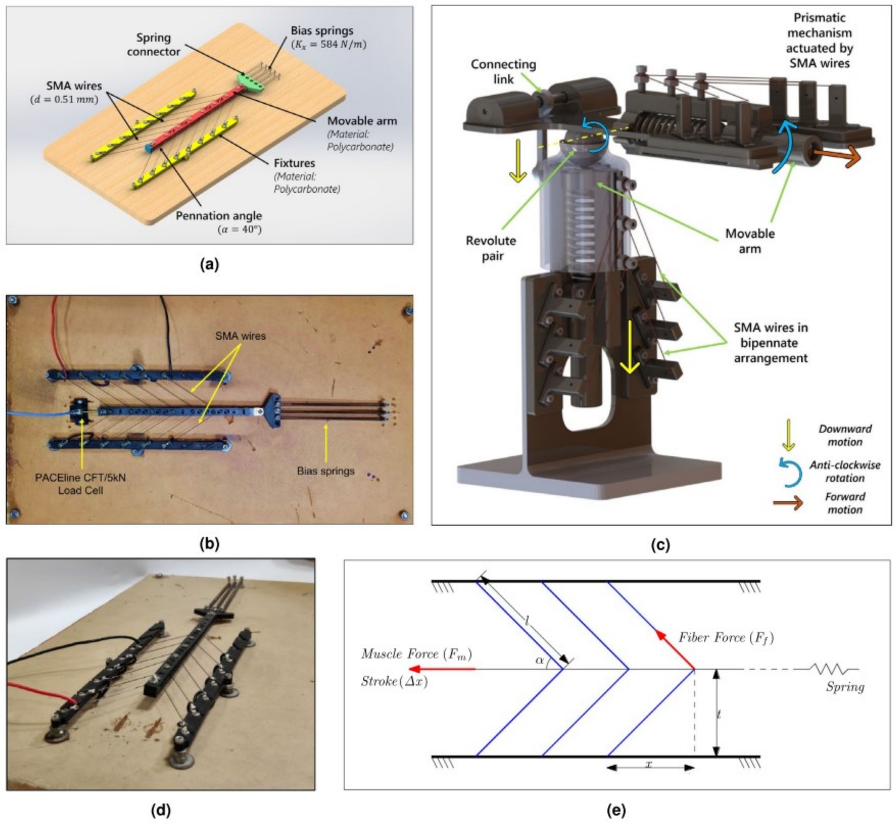

Figure 1: Physical Model. Adapted from Kanhaiya et. al. [2022]

2.3 Summary

- The integration of SMAs with bipennate muscle architecture in hierarchical actuators represents a significant advancement in actuator technology, offering enhanced performance, efficiency, and versatility for a wide range of applications.

- The developed actuator holds promise for applications spanning from building automation controls to precise drug delivery systems, showcasing the potential of biomimetic design principles in engineering innovative actuation solutions.

3 Methodology

Our model is divided into 5 sub-models namely :

1. Heat Transfer Model
2. Phase Transformation Model
3. Dynamics Model
4. Kinematics Model
5. Constitutive Model

The equations for the respective are given below:

1. Heat Transfer Model :

$$m_{wire}c_p\dot{T} = \frac{V_{in}^2}{R_{ohm}} - A_c h_T(T - T_\infty) + m_{wire}\Delta H\dot{\xi} \tag{1}$$

2. Phase Transformation Model:
   - Reverse Transformation (Martensite to Austenite)

$$\xi = \frac{\xi_M}{2}[cos[a_A(T - A_S) + b_A\sigma]] \tag{2}$$

   - Forward Transformation (Austenite to Martensite)

$$\xi = \frac{1 - \xi_A}{2}[cos[a_M(T - A_M) + b_M\sigma]] + \frac{1 + \xi_A}{2} \tag{3}$$

3. Dynamics Model:
   - The net stroke produced is given by:

$$\Delta x = \frac{l_0(1 - \epsilon)[n\sigma A_{cross}cos\alpha - K_x x_0]}{nA_{cross}[\sigma sin^2\alpha - E(1 - \epsilon)cos^2\alpha]} \tag{4}$$

   - The net force produced is given by:

$$F_m = nF_f cos\alpha - K_x(\Delta x + x_0) \tag{5}$$

4. Kinematics Model:

$$\dot{\epsilon} = \frac{(\dot{\Delta x})cos\alpha}{\sqrt{l_0^2 - 2l_0(\Delta x)cos\alpha}} \tag{6}$$

5. Constitutive Model:

$$\dot{\sigma} = E(\dot{\epsilon} - \epsilon_L\dot{\xi}) + \theta_T\dot{T} \tag{7}$$

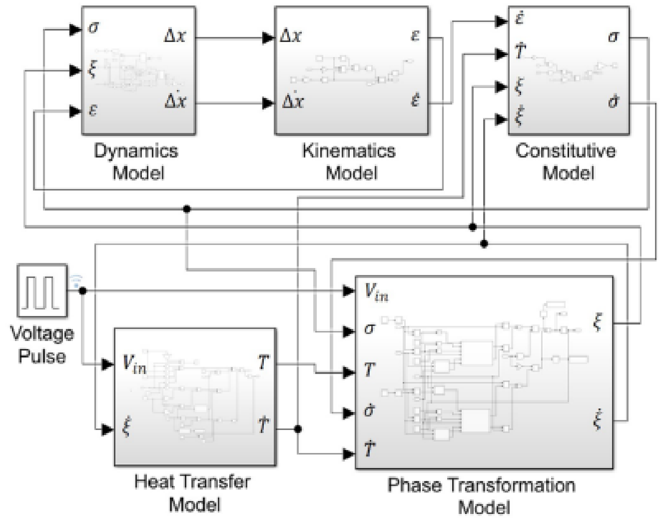

Figure 2: Adapted from Kanhaiya et. al. [2022]

A few of the assumptions used while modelling are:

- The cross sectional area of the wires remains fairly constant.
- The stroke of the actuator is much smaller than the length scale of the wires.
- There are no frictional losses in the entire system. This leads us to neglect the heat loss due to friction in the heat transfer model.

The variables in our control are input Voltage V_{in} and time t. The input voltage is kept at 7V for 8 sec which marks the heating of the SMA wires. For the rest of the cycle, it is kept at 0V for 7 sec to mark the cooling phase. Time stepping schemes such as the explicit Euler and RK methods are tried for solving the system of ODEs. The order in which the above equations are computed is given in the Simulink block diagram above.

The entire code of the model is ready. The results of the model are discussed in the result analysis section.

4 Results

4.1 State Variables Vs Time

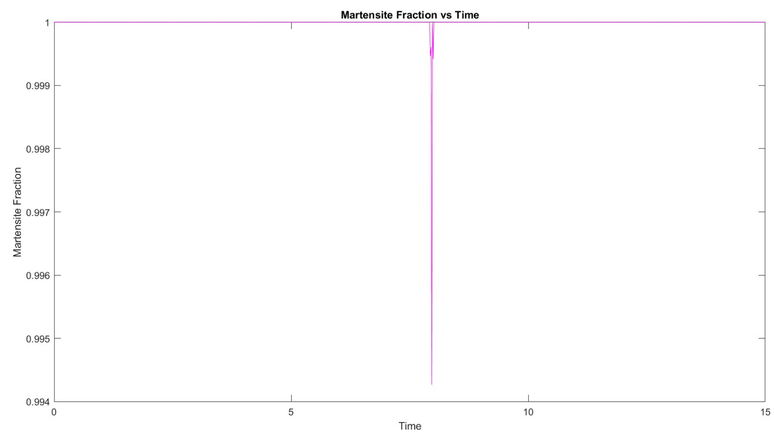

Figure 3: Martensite Volume Fraction Vs Time

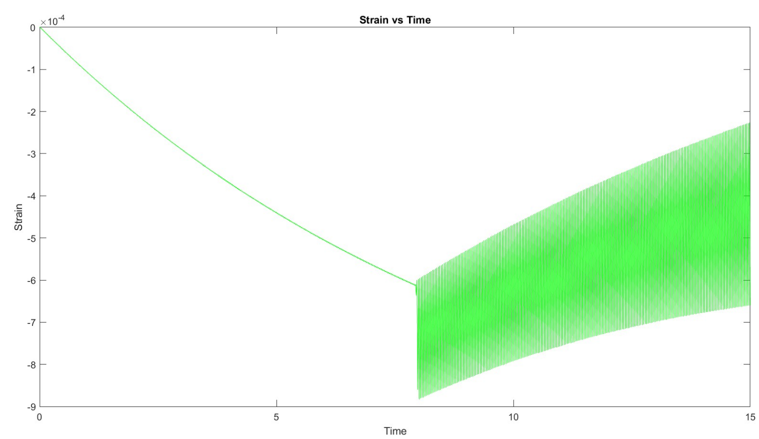

Figure 4: Strain Vs Time

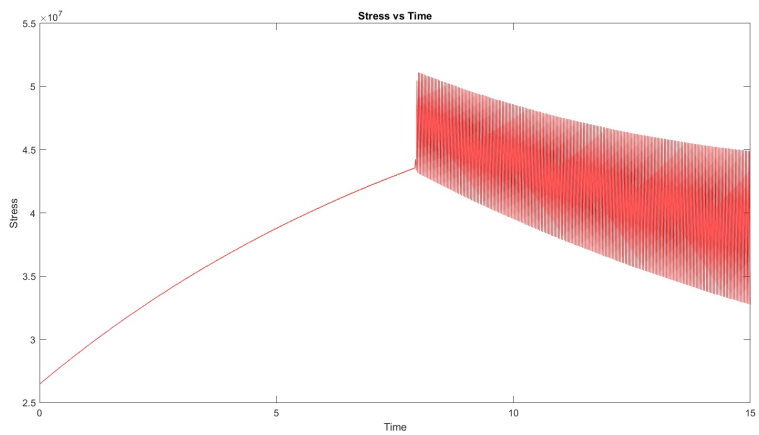

Figure 5: Stress Vs Time

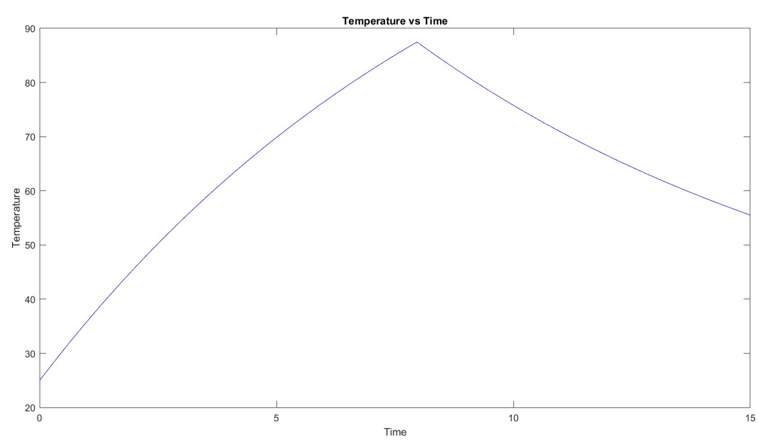

Figure 6: Temperature Vs Time

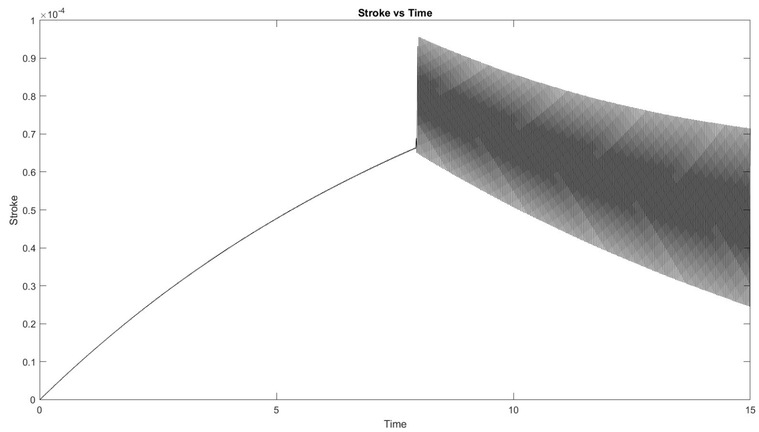

Figure 7: Actuator Stroke Vs Time

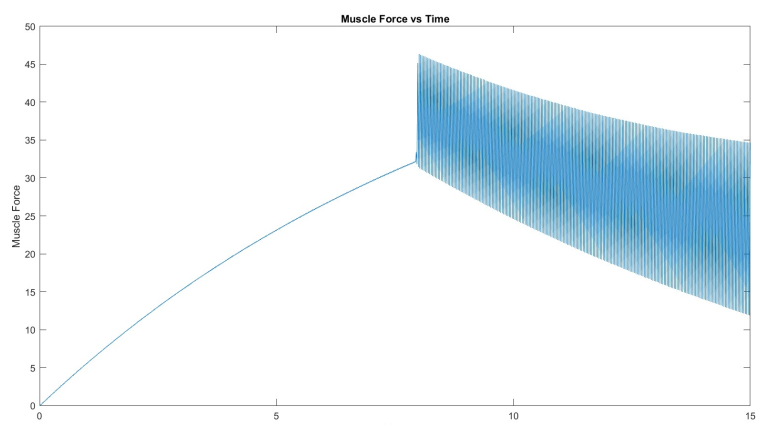

Figure 8: Muscle Force Vs Time

4.1.1 Result Analysis

- It can be observed that the stroke of the actuator increases as heating prolongs.
- Once the temperature is sufficiently high to exceed the Austenite start temperature, we observe that the transformation causes rapid fluctuations in the state variables. The reason for these fluctuations is the highly coupled set of model equations and the non linear nature of these equations.
- Once the cooling phase begins upon turning off the voltage supply across the wires, the oscillations persist. This is due to the fact that the state variables at the end of the heating phase are already corrupted and thus influence the model's behaviour thereafter.
- However, we see that there is sudden jump in the actuator's output force and stroke produced. This is in accordance with our predictions and the paper's results.

5 Scope for improvement

- We can try to apply the Brinson's model instead of Liang and Rogers for better accuracy.
- The changing cross sectional area and length of the wires could be incorporated in the model.
- The initial conditions of the state variables have been assumed in the model. These assumptions may cause misleading results.
- Frictional effects may be significant and thus need to be incorporated into the model for better accuracy.

References

Yashaswi Sinha Bishakh Bhattacharya Kanhaiya et. al., A. Sri Harsha. Design and development of non-magnetic hierarchical actuator powered by shape memory alloy based bipennate muscle. *Sci Rep 12, 10758*, 2022.