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Design and Finite Element Modeling of Electro-Thermal Actuator for Biological Applications

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Abstract: This paper presents the designing, modeling and parametric analysis of V-shaped Electro-Thermal Actuator (ETA). The actuator was designed using aluminum alloy due to its advantageous electrical and thermal properties. A CAD model of an actuator was developed and its various geometrical parameters for example, length, width and angle, thermal input like temperature and electrical input such as voltage were analyzed to determine their effect on the displacement and stress of the actuator. The Finite Element Modeling of the actuator is performed in ANSYS Mechanical 14.5. The analytical model was developed by deriving governing equations. The model validation was achieved by comparing analytical and simulation results. The results show the output displacement of 20 μm along with 320 MPa stress at lower operating voltage of 0.1V. The actuator is in high demand for biological applications, such as the manipulation of cells and tissues.

Keywords: V-shaped Electro-Thermal Actuator, Parametric Analysis, Biological applications, Finite Element modeling, and Aluminum alloy

1. Introduction

In recent years, microactuators in microelectromechanical systems (MEMS) have undergone gradual development, resulting in various types of microactuators that offer a dynamic motion or static displacement and are utilized in numerous applications. Those applications are the micromanipulation of microchips, microbiological species, microstructures, and optical fiber. These MEMS-based microactuators are piezoelectric, electrostatic, electromagnetic, and electrothermal actuators. Potekhina and Wang reviewed that piezoelectric micro actuator produces high accuracy, and large force output but needs high actuation voltage and has small displacement. Electromagnetic micro actuator needs an external magnetic field, have large dimension, and delivers less output force. On the other hand, an electrothermal microactuator is a valuable element for MEMS due to its several advantages over other actuators. It is robust against moisture formation and produces a huge amount of force and displacement under a relatively less voltage [1]. There are various common types of the thermal actuator are analyzed: The Z-shaped thermal actuator, a pseudo-morph thermal actuator, and the chevron (V-shaped) thermal actuator. Kalaiarasi and Hosimin Thilagar [2] designed a COMSOL-based bimorph thermal actuator is designed. The actuator has been made of four layers of different materials, with rectangle beams, tapered beams, and with and without gold layers. The gold layer is the reason for the increased displacement. Since the actuation principle of this actuator is based on the asymmetric thermal expansion of different cross-sectional beams, it generates displacement in the form of a circular arc. However, the displacement is not limited in one direction ideally, can generate force up to some μN, as well as the sensitivity of the actuator is also low. Zhang et al. [3] compared a model of Z- and V-shaped electrothermal actuator has presented by developing analytical and FEA models. By varying one parameter of both actuators, a performance is investigated that V-shaped electrothermal actuator is superior to Z-shaped actuator because of its space saving specification and V-shaped produces large force and displacement. Hussein et al. [4] presented V- and Z-shaped electrothermal actuators for in-plane displacement by using FEA as well as analytical models. Elastic beam theory has been used, in which all modes of buckling were considered. V-shaped electrothermal actuators are widely used in biological applications such as manipulation of tissues and cells [5], biological materials characterization [6] and micro-assembly [7]. The electrothermal actuating systems are mainly used in micro grippers for these applications. For example, Yallew et al. [8] developed MEMS based electro-thermally actuated micro gripper for biological samples. A rotary capacitor sensor has used. FEA has been used to assess the design of microgripper. After that, Saba et al. [9] presented the design and analysis of a multi-jaw microgripper actuated by a single V-shaped thermal actuator. The microgripper has four jaws that can grip various sizes of biological species and their organelles. In microgripper, numerous thermal actuators can be used such as Voicu et al. [10] used SU-8, a biocompatible polymer for micromanipulation of two electro-thermally actuated microgrippers. The microgripper has two operating modes: normally closed and normally open. The results showed displacement of 40μm with the input current of 25Ma. Shivhare et al. [11] proposed a microgripper that uses two V-shaped electrothermal actuators. The model includes modifications such as converting free–free gripping arm into a clamped-free gripping arm and inclusion of the heat sinks in the shuttle. The proposed microgripper is modeled analytically and numerically using MEMS CAD tool CoventorWare. The results demonstrate the feasibility of fabrication. Yang and Xu [12] proposed Z-shaped electro-thermally actuated microgripper consisting of electrothermal force sensor. The purpose of the sensor is to sense the force which exerts in the right tip of the object to the Z- shaped thermal actuator. Selecting suitable material is another effective way to improve performance of an electrothermal actuator. Different types of material have been used in literature. For example, Joshi et al. [13] fabricated a model of V-shaped electrothermal actuator with metals silicon and gold. The displacement of 80.7μm is achieved at low input voltage of 4V. The fabrication method is done by utilizing double double-sided inductively coupled plasma etching technique generates maximum displacement with lower input voltage. Baracu et al. [14] fabricated an electrothermal actuator using the process of reactive-ion etching (RIE). The movement obtained by simulation through COVENTOR software was 12 μm for a voltage of 0.2 V and a current intensity of 257 mA. Saqib et al. [15] presented Finite element method (FEM) based V-shaped electrothermal actuator has designed by using electroplated nickel material. The design has been followed by economically available metal MUMPS, a micromachining process of electroplated nickel. Aluminum-based electrothermal actuators are commonly used because aluminum has a high thermal conductivity, which allows for efficient conversion of electrical energy into heat energy. Thangavel et al. [16] designed an electrothermal actuator by using aluminum as a structural material. The results showed minimum error of 0.3% by comparing analytical and FEA model of voltage vs. Temperature and voltage vs. displacement values. Jia and Xu [17] presented an optimal process that involves using the finite element method and genetic algorithm to maximize the displacement and output force and minimize the stress concentration for enhancing the performance of an electro-thermal micro-actuator.

Based on a literature review of the V-shaped ETA, it shows that there is a lack of comprehensive parametric analysis in the existing studies. Therefore, there is a need for further research to explore the effects of different design parameters on the performance of actuator. This study conducts a thorough parametric analysis of the V-shaped ETA, using a combination of theoretical and simulation methods. A V-shaped ETA utilizes Joule heating and thermal expansion to generate high displacement with optimum stresses produce within the beams of an actuator. The actuator has four beams, which are designed to increase the output displacement by varying its structural parameters such as length width and thickness and angle of a beam. The material used for the actuator is aluminum alloy, which has good conductivity and high thermal stability. The software ANSYS Workbench version 19.2 is used to create a 3D finite element model of the actuator. The numerical analysis is utilized to solve mathematical equations using MATLAB and validate the results by comparing the analytical and the theoretical results.

2. Designing and modeling of an actuator

The V-shaped ETA consists of four model V-shaped beams that are arranged in such a way that they stacked one above the other. The beams have a predefined initial angle with respect to its horizontal line to achieve the maximum displacement. Since four beams are utilized, the actuator can produce a larger displacement at a lower operating voltage. Because using more beams can increase the amount of displacement, as the deformation of each beam contributes to the overall motion of the actuator. The beams are placed between two conductive anchors, one of them is provided by voltage and other is grounded [5]. A central shuttle is attached between beams for allowing the coupling of the beams for a uniform motion. The Block diagram of an actuator is shown in figure 1. When a voltage is applied across the anchors, the current flowing through the beams generates heat, causing the resistance of the beams to increase. This increased resistance results in a further increase in temperature and a corresponding increase in resistance, leading to a self-heating effect. The self-heating effect causes the beams to deform and produce a displacement of the actuator.

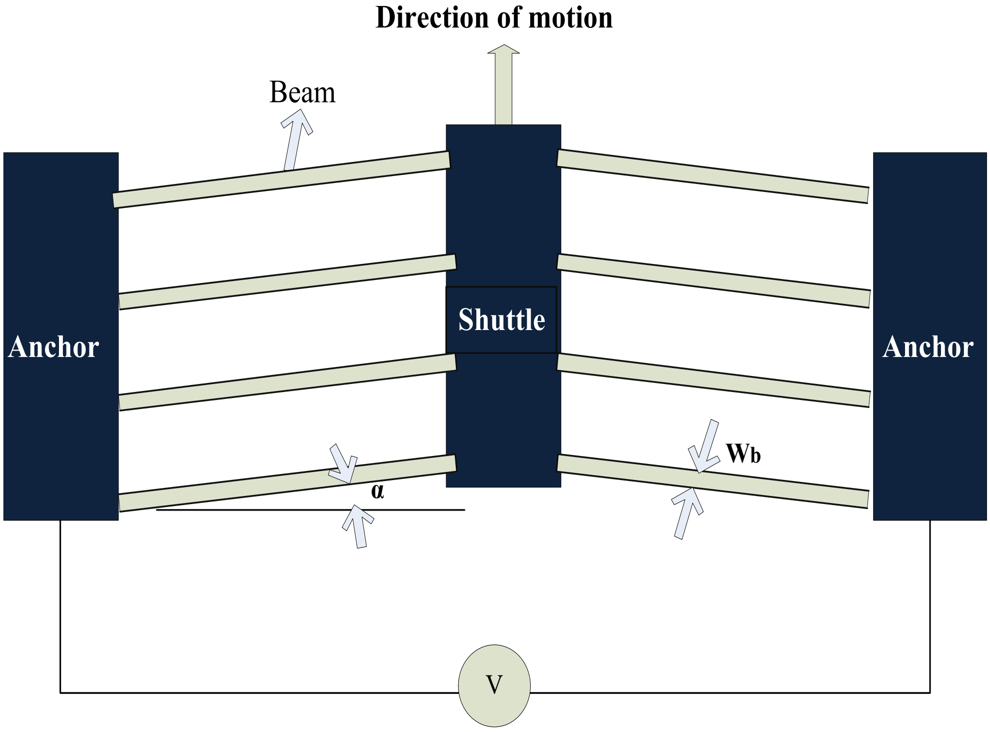

Figure 1. Block diagram of. V-shaped electrothermal actuator

3. Analytical Model

This section contains an analytical model of an ETA where the electrical, thermal, and mechanical behavior of a V-beam actuator is described by a combination of two analytical models, including: Electro-thermal model: describes the temperature distribution in the actuator and the relationship between the electrical power applied and the resulting temperature rise. The temperature distribution along the actuator beams can be determined by solving the heat transfer equation with the boundary conditions. Thermo-mechanical model: This model defines the mechanical behavior of the actuator and the relationship between the temperature, and the resulting deflection.

The structural parameters of a V-shaped ETA are defined by the dimensions of the V-shaped beam and the central shuttle as shown in fig. 2. Specifically, the dimensions of the beam are typically defined by varying its length (L_b), width (W_b), and overall thickness (t) of an actuator. The key structural parameters determine the deflection of an actuator when a voltage is applied. The dimensions of an actuator are shown in Table 1.

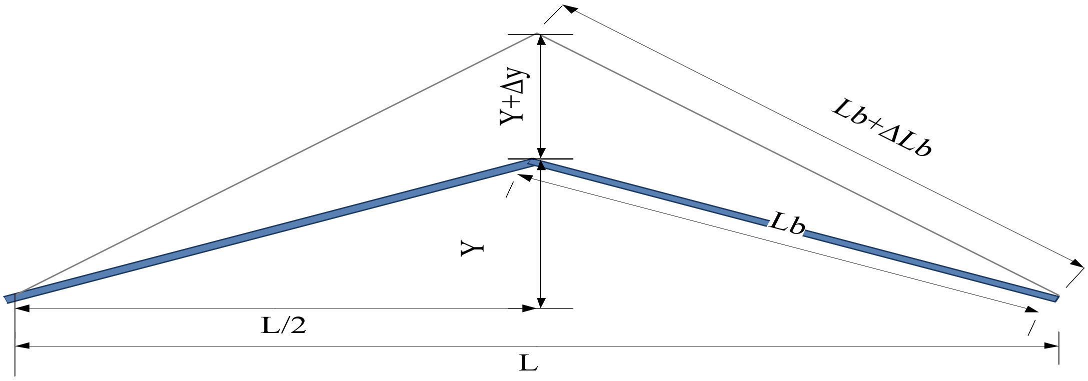

Figure 2. Geometric view of an actuator

Let L be the distance between the two anchors, L_b is the length of the beam and consider α is the angle between the horizontal and the line connecting to the anchor. Consider heat generated by the V-shaped ETA beam is either convectively transferred to the surrounding air or conductively transferred to the pillars, which remain at a constant temperature of 295K.

Table 1. Geometrical Parameters for the proposed electrothermal actuator

Design Parameters	**Values (µm)**
Number of beam in pairs(n)	4
Beam length(L_b)	335
Beam width (W_b)	5
Gap between the beams	60
Thickness(t)	10
Central Shuttle length(L_s)	300
Central Shuttle width(W_s)	75
Anchors length	300
Anchors Width	75
Angle of beam (α)	2°

The material properties of the V-shaped beam are significantly affecting the performance of the actuator. The material properties of aluminum alloy include thermal conductivity, coefficient of thermal expansion, Young's modulus, and Poisson's ratio are described in table 2. From figure 2, Pythagoras theorem has been used to estimate the vertical length Y as

$$Y = \sqrt{{L_b}^2 - \left(\frac{L}{2}\right)^2} \tag{1}$$

Similarly, the deflection in vertical distance (dY) can be determined as

$$dY = \sqrt{(L_b + \Delta L_b)^2 - \left(\frac{L}{2}\right)^2} - Y \tag{2}$$

The elongation of a differential segment of an actuator beam due to thermal expansion can be calculated using the coefficient of thermal expansion (α_T) and the change in temperature. The α_T is a material property that represents how much a material expands or contracts in response to a change in temperature. The change in length of a beam can be calculated using the formula:

$$dL_b = \alpha_T\,(T_d - Ts)dx \tag{3}$$

By integrating the differential elongation over the length of the beam, the total displacement of the beam is obtained as

$$\Delta L_b = \int_0^{L_b} \alpha_T (T_d Ts) ds \quad (4)$$

Where, ΔL_b is change in length of a beam of actuator, α_T is coefficient of thermal expansion, T_d is temperature distribution across the beam and T_s is surrounding temperature. The temperature distribution within a V-shaped electrothermal actuator beam can be modeled using the following equation:

$$T_d = Ae^{mx} + Be^{-mx} + Ta + \frac{g^m A_c}{h^* P} \quad (5)$$

Where, A and B are constants obtained by using boundary conditions, gm is volumetric generation, m is fin parameter, Ac is cross sectional area of beam (calculated as W*T) and P is the perimeter of beam By solving constants of equation 5, the temperature distribution within the beam can be determined. Now the value of temperature distribution (T) can be substitute in equation 4, it becomes

$$\Delta L_b = \int_0^{L_b} \alpha_T \left(Ae^{mx} + Be^{-mx} + T\alpha + \frac{g^m A_c}{h^* P} - T_s \right) dx \quad (6)$$

By solving definite integral the displacement will be obtained as

$$\Delta L_b = \alpha_T \left(\left(T_a - T_S + \frac{g^m A_c}{h^* P} \right) L_b + \frac{A}{m} \left(e^{(mL_B)} - 1 \right) - \frac{B}{m} \left(e^{(-mL_B)} - 1 \right) \right) \quad (7)$$

The electrothermal stress distribution within an actuator can be analyzed as

$$S_{th} = \alpha_T E \, (T_d - T_s) \quad (8)$$

Where, E represents Young's Modulus

From equation equations 2, 5 and 8 the distribution of temperature and stress, and displacement of single beam actuator are determined. The above analytical model is solved with the help of MATLAB program.

Table 2. Material properties used in analytical and simulation models

Properties	Values	Units
Thermal Conductivity	235	$W.m^{-1}.K^{-1}$
Resistivity	$2.6{\times}10^{-8}$	Ω.m
Coefficient of thermal Expansion	$23.1{\times}10^{-8}$	K^{-1}
Density	2710	$kg.m^{-3}$
Young's Modulus	77	GPa
Poisson's Ratio	0.3	--
Environment temperature (T_s)	295.15	K

4. Finite Element Analysis

In this section finite element analysis of a V-shaped electrothermal actuator is carried out. First, a 3D CAD model of an actuator is developed using structural material such as aluminum alloy. In figure 3, the flow chat contains two analyses. First part indicates the electrothermal analysis, for example input is voltage and its corresponding response is temperature. The second part specifies thermo-mechanical analysis of an actuator where temperature and boundary conditions (length, width, thickness and angle) are inputs and displacement, and stresses are their corresponding outputs.

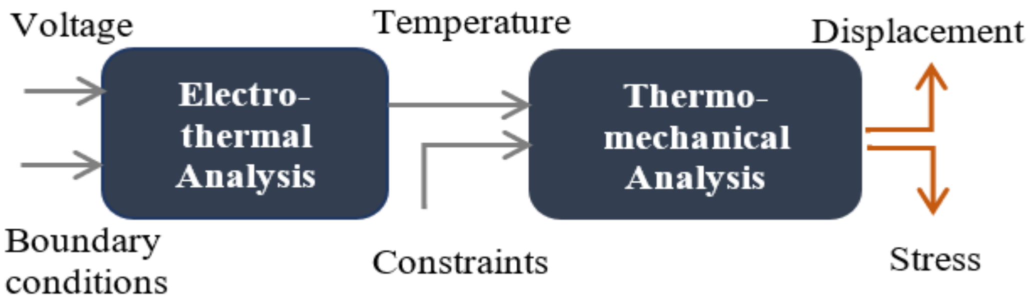

Figure 3. Flowchart of inputs and outputs of FEM based analysis.

The design and simulation of electrical, thermal, and mechanical behavior of an actuator is modeled by using ANSYS Workbench version 19.2. Figure 4, shows the simulation of an actuator with one beam where the first part indicates the temperature distribution within the beam, second part depicts deformation of the beam of an actuator, and finally stress analysis is presented in part c.

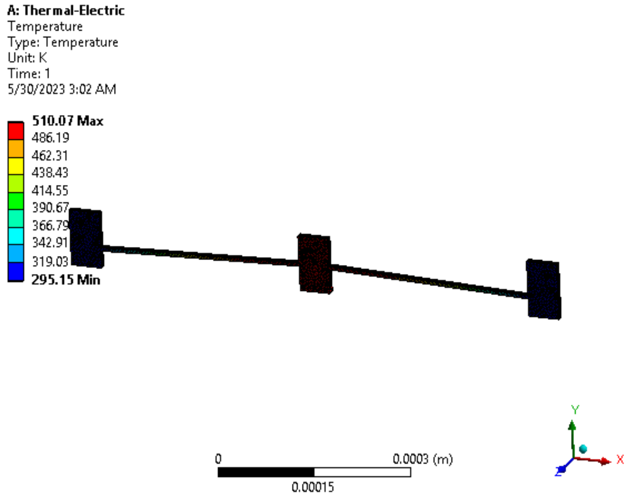

Figure 4. (a) Electro-thermal analysis of an actuator

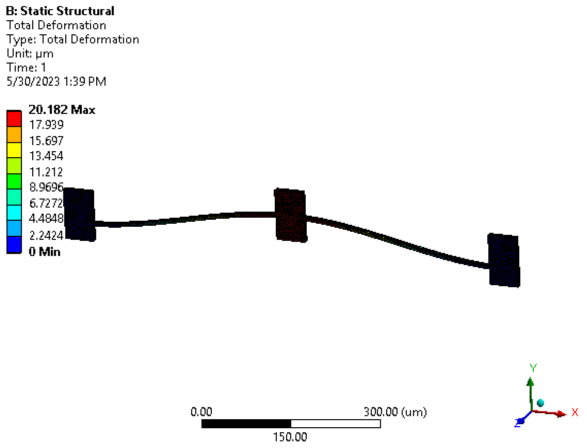

Figure 4. (b) Thermo-mechanical analysis of an actuator

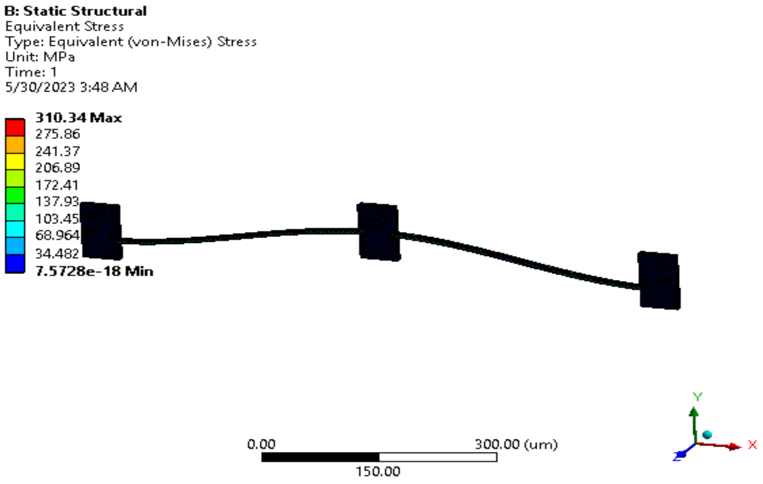

Figure 4. (c) Stress analyses within a single beam actuator

5. Parametric study

In this section a parametric study of ETA is discussed in both analytical and simulation models. Initially, structural parameter such as beam length is varied from 185μm to 335μm at the difference of 50 μm. The variation of width affects actuator's displacement and stress generation capabilities. The width is changed from 5μm to 20μm. Also, the displacement and stress are carried out at different values of actuator thickness from 10μm to 25μm. After that, a predefined angle of the beam is observed by changing its values from 2° to 8°. Only one parameter is varied at a time while keeping all other parameters constant to ensure accurate and reliable results. The Electrothermal parameters like voltage and temperature are also manipulated to get maximum displacement. The temperature on anchor points is set to 22°C (295.15K). The voltage is applied at one end of an anchor and is varied from 0.01 to 0.1V

6. Results and Discussion

This section covers the results of the V-shaped electrothermal actuator (ETA) analysis, which is conducted through both analytical and finite element methods. The achieved results for temperature distribution, displacement, and stress of the single beam ETA is presented in table 3. Figure 5, displays the analytical model and simulation results of temperature versus applied voltage, and the results from both models are consistent with each other. The relationship between the displacement and applied voltage at different lengths of a beam, as determined through both analytical and simulation methods, is shown in figure 6. The figure suggests that increasing the length of the beam results in a greater displacement of the actuator. This is because a longer beam is more flexible and has a lower bending stiffness compared to a shorter beam. Therefore, a longer beam can bend more easily, resulting in a greater tip displacement of the actuator. The consistency of results of both theoretical calculation and simulation can be noticeable.

Table 3. Comparison of the results for temperature, output displacement and stress of the proposed micro actuator

	Analytical results			**Simulation Results**		
Voltage	***Temperature***	***Displacement***	***Stress***	***Temperature***	***Displacement***	***Stress***
0.01	297.2	0.37	5.41	298.21	0.42	4.36
0.03	316	2.61	38.15	316.6	1.88	36.8
0.05	363.6	6.61	95.41	356.06	5.54	92.11
0.07	398.4	11.13	172.90	409.61	10.92	164.4
0.09	472	16	265.91	473.8	17	258
0.1	506	19	320.82	510.07	20.18	310.34

The width of a beam also plays a significant role, because wider beam will have a larger cross-sectional area, which will reduce the temperature gradient along the beam. As a result, the actuator will experience a smaller displacement. Figure 7 presents displacement voltage relationship at different widths of beam by using both analytical and FEA model. The analytical model and simulation results of displacement of a V-shaped ETA are not significantly affected by changes in the thickness of the beam. Figure 8 shows displacement as a function of voltage at the values of pre bending angle of a beam. The results indicate that a smaller pre-bending angle of a V-shaped electrothermal actuator beam can lead to higher displacement. However, using a small pre-bending angle can also increase the likelihood of buckling of the bent beams. Therefore, it is important to balance the desire for higher displacement with the need for structural stability and avoiding buckling. Figure 9 presents the analytical equations and simulation results of a stress as a function of applied voltage. It can be seen that maximum stress in the actuator is 320 MPa which is found to be less than the yield strength of an aluminum alloy (that is 700 MPa).

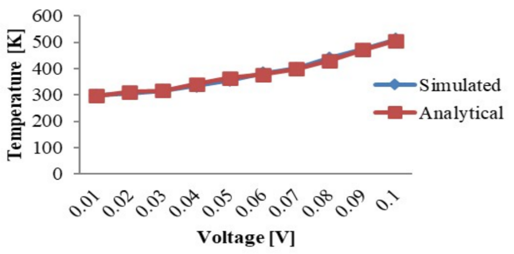

Figure 5. Temperature distribution within an actuator versus applied voltage (Lb = 335 μm, W=5 μm t=10 μm and *α* =2°)

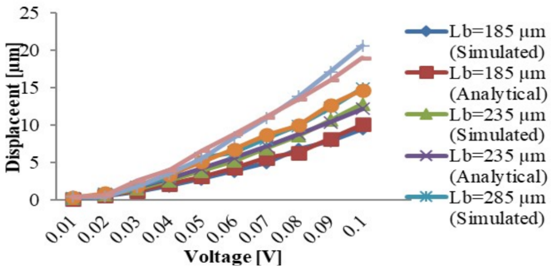

Figure 6. Output displacement for the corresponding values of input voltage at different lengths of beam (W=5

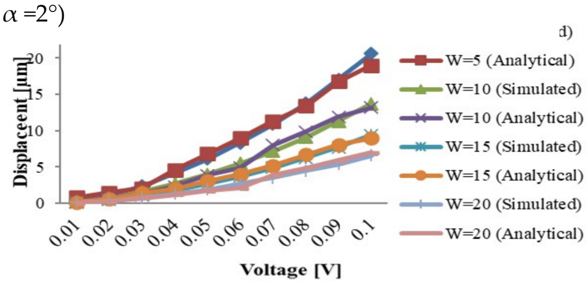

Figure 7. The output displacement versus input voltage at differ widths of beam (Lb=335 μm t=10 μm and *α*=2°)

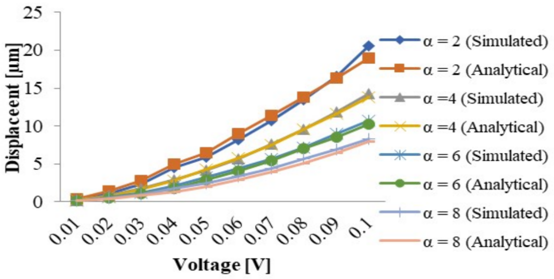

Figure 8. Displacement with respect to voltage at the values of pre-defined angle of a beam (Lb=335 μm, W=5 μm and t=10 μm)

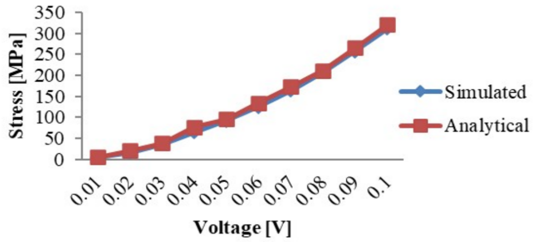

Figure 9. Output stress as a function of applied input Voltage (Lb=335 μm, W=5 μm t=10 μm and *α*=2°)

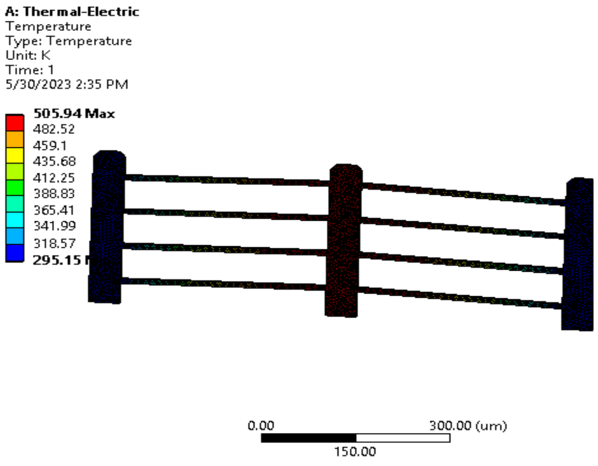

Figure 10. Output in-plane displacement in actuator applied voltage of 0.1V (Lb = 335 μm, W=5 μm t=10 and *α* =2°)

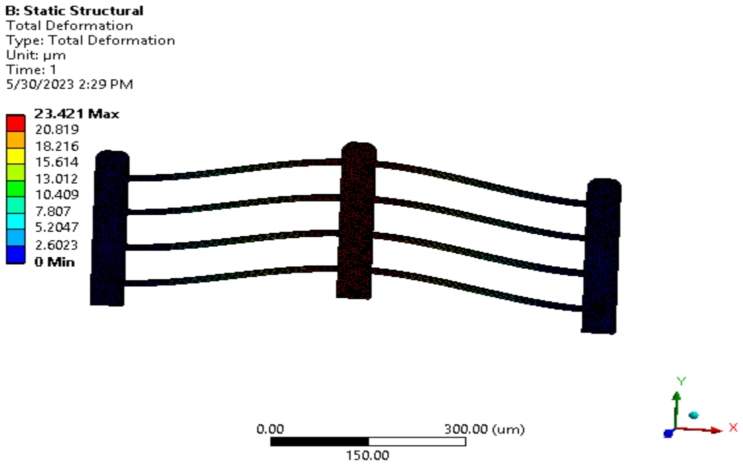

Figure 11. Output in-plane displacement in actuator for applied voltage of 0.1V (Lb = 335 μm, W=5 μm t=10 μm and *α* =2°)

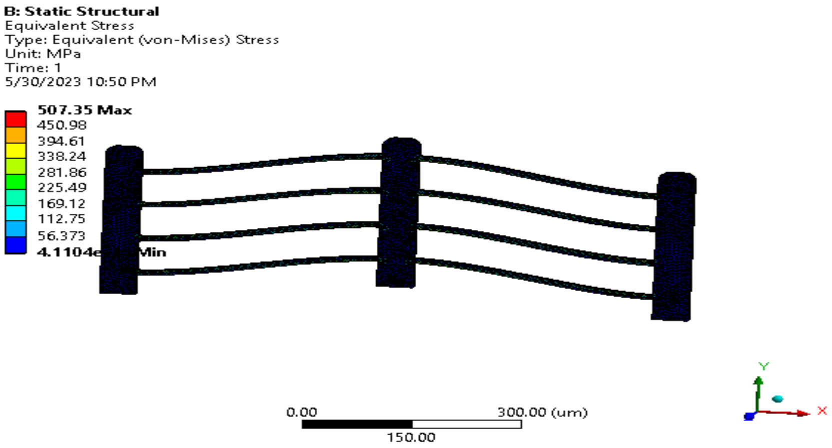

Figure 12. Electrothermal stresses within an actuator when applied input voltage is 0.1V (Lb = 335 µm, W=5 µm t=10 µm and α =2°)

The single beam actuator is now extended to a four beam because an actuator with four beams arranged in a parallel fashion and attached with a shuttle provides better results in terms of increment in displacement compared to a single beam arrangement. The simulation results in fig. 11, show that the temperature required for the four-beam actuator to achieve the maximum. displacement is 509 K which is smaller than that of single beam. Similarly, fig 12, explains that the four-beam actuator is capable of providing a displacement about 23µm for an applied voltage of 0.1 V, while a single beam actuator can only provide a displacement of 20µm for the same applied voltage. Additionally, in fig. 13, the maximum value of electrothermal stresses is 527 MPa which is still lower than the value of yield strength of aluminum alloy.

7. Conclusion

The paper is presented a comprehensive analysis of the design and modeling of a V-shaped electrothermal actuator. The actuator is designed to convert electrical energy into mechanical movement through the principles of thermal expansion and the joule heating effect. The use of aluminum alloy material as the structural material for the actuator was explored. The analysis was focused on various geometrical parameters such as length width thickness and angle of a beam, and thermal and electrical inputs to optimize the performance of the actuator for biological applications. The numerical simulation tool ANSYS Workbench version 19.2 was used for the parametric analysis and an analytical model has been developed by deriving governing equations through MATLAB. The validation of the model was achieved through the comparison of analytical and simulation results, which showed good agreement. The optimized design of the V-shaped ETA resulted in an output displacement of 20 µm and 320 MPa stress at a lower operating voltage of 0.1V, angle of 2°, length of 335µm, width of 5µm and thickness of 10µm, thereby improving its efficiency, reliability, and overall performance. Through the manipulation of a single-beam actuator, the simulation and theoretical methods were successfully employed, leading to the design and analysis of a four-beam actuator that exhibited a displacement increment of 2µm and a temperature reduction of 3K. Furthermore, it was discovered that the electrothermal stress remained below the maximum yield strength of the material. These significant findings of this study provide valuable insights into the design and optimization of electrothermal actuators for biological application.

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