

AC ANALYSIS OF HYBRID THERMAL MICRO-ACTUATOR



SUPERIOR UNIVERSITY

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DEDICATION

I would like to dedicate this thesis to my beloved family, teachers, friends, to my dear Parents, for their unwavering faith, endless love, and the countless sacrifices they made to ensure I always had the opportunity to follow my dreams. I reserve a special place of honor for my mother my first teacher, constant anchor, and the living embodiment of patience and strength. Your prayers were the silent, most powerful force that carried me through this journey.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
DC	Direct Current
EM	Electromagnetic
EMF	Electromotive Force
FEA	Finite Element Analysis
FEM	Finite Element Model / Finite Element Method
MEMS	Micro Electro Mechanical Systems
RONs	Reconfigurable optical networks
TEM	Thermo Electro Mechanical

ABSTRACT

Hybrid thermal Micro-actuator are micro scale devices that combine different actuation mechanisms, typically thermal and another type like electrostatic, electromagnetic, or piezoelectric actuation, to produce movement or force at the micro-scale. The AC driven hybrid thermal actuator represents a significant advancement in MEMS actuation technology, successfully combining the large displacement characteristic of thermal actuators with the speed and reliability demanded by modern microsystem applications. Current study is an alternating current (AC) analysis of a hybrid thermal micro-actuator, which builds upon previous DC-based studies and investigates the dynamic behavior of the device through Intellisuite software. The frequency response of the actuator (1 Hz-100 Hz), transient thermal behavior, and power efficiency of the actuator during the AC excitation is systematically studied. For this purpose an analytical electro thermal mechanical model with temperature dependent resistivity and thermal time constants, which are confirmed by 3D finite-element analysis (FEA) is used. Comparative analysis shows that AC driving consumes less power (by 3.6 percent) 343 mW and allows response times to be 86 times quicker, and is suitable to high-speed micro grippers and resonant MEMS devices. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly.

Keywords: Finite element analysis, MEMS, micro-actuator, micro grippers, Optical Switch,

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Hybrid thermal micro-actuator are novel devices that combine multiple actuation techniques, primarily thermal, piezoelectric, or electrostatic, to achieve enhanced force, displacement, and speed. Because of their small size and high precision, these actuators are commonly used in MEMS applications such as micro grippers, micro mirrors and micro valves. Today, MEMS are widely used, such as in mobile phones, agriculture, etc. [1]. MEMS devices can be used as sensors and actuators and have two main domains. The actuators can be applied to a wide variety of applications, including accelerometers, gyroscopes, micro-optical mirrors and switches. Actuation is often by electrostatic, piezoelectric, electromagnetic or thermal means. Electrostatic actuators are low power and fast switching, but can be non-linear because of parasitic capacitance and pull-in voltage [2]. Piezoresistive actuators are very sensitive, but have small driving force and small displacement [3]. Electromagnetic actuators respond quickly, but are physically large, which makes it difficult to manufacture standard MEMS. Thermal actuators have a large driving force and high displacement under low driving voltage, which is necessary for physically moving or precisely positioning heavy optical components, but they have a slower response by themselves. micro-actuator with large, precise and stable mechanical travel to align fibers with waveguides or to physically switch light paths are needed for reconfigurable optical networks (RONs) and dense photonic integration. In this paper, a novel hybrid thermal actuator is designed and analytically modeled to achieve large displacement and high force in a stable and slow motion that can be used for high throw optical switching and

fiber alignment. The thermal actuator has a slower response time, which can be a disadvantage in high-speed systems, but is utilized to achieve the slow and stable motion necessary for high precision and low crosstalk optical path selection and long term coupling stability. The goal of creating a small-sized thermal actuator that has a large displacement was well achieved, with a displacement of $12.044\text{ }\mu\text{m}$ at an input power of 252.6 mW . A maximum temperature of 535.882°C is obtained in the process of electrothermal finite element analysis, it is noted. The interrelationship between various physical phenomena such as electrostatic forces, thermal expansion and piezoelectric effect must be known in order to analyze the hybrid thermal micro-actuator. These interactions are studied using advanced simulation tools such as finite element modeling and the actuator design is optimized for the given applications [17]. Electrostatic actuators can malfunction at high voltages and have a reduced force capability although using less energy. Hybrid actuators use electrostatic actuators for positioning and electro thermal actuators for motion initiation, to achieve high force output and low power consumption [31]. In recent years, MEMS have come a long way, offering a new opportunity for the development of smaller systems and devices with a variety of applications. Among the various MEMS components, thermal Micro-actuator have garnered a lot of interest due to their ability to deliver high displacement and force output in a compact form factor. Thermal micro-actuator is used in a variety of applications including optical switches, adaptive optics, and micromanipulation due to the mechanical motion they create from the thermal expansion of materials. One possible strategy to improve thermal Micro-actuator performance is to use hybrid designs that combine multiple actuation techniques to benefit from their respective properties. For instance, a combination of thermal and electrostatic actuation could be combined into a hybrid thermal micro-actuator to improve the displacement, force and

efficiency parameters. The coupled electro thermal and electromechanical dynamics of such a system are important and pose extra challenges and issues in the design of the system.

Alternating current (AC) studies are crucial to assess and enhance the performance of the hybrid thermal micro-actuator. The AC analysis can help to make it easier to study the frequency dependent response of the actuator, which can be useful for the operation in dynamic environments or when the input is time varying. In addition, energy dissipation, resonance frequencies and overall system stability have to be considered in the design and operation of these devices. These can be useful areas to be addressed using the AC analysis. Thermal micro-actuator is based on the property of materials to expand when heated, causing mechanical movement. When a material is heated it expands and this expansion can be used to generate a force or displacement. The heat can be produced in a number of ways including joule heating (passing an electric current through a refractory material) or external heat sources such as lasers or heated substrates. Electrostatic actuation, on the other hand, is based on the idea of electrostatic forces, which are generated by the attraction between surfaces that have opposite charges. One of the most popular methods for electrostatic actuation in MEMS is to place a voltage difference between two conductive surfaces, which produces an electrostatic force that may be used to move an object that is hanging. A hybrid design incorporating both thermal and electrostatic actuation can be used to exploit the best features of each type of actuation, potentially resulting in improved performance parameters such as increased force, displacement and energy economy. The thermal actuation can bring large displacement in the structure, while the electrostatic actuation can bring accurate motion control and fast response time.

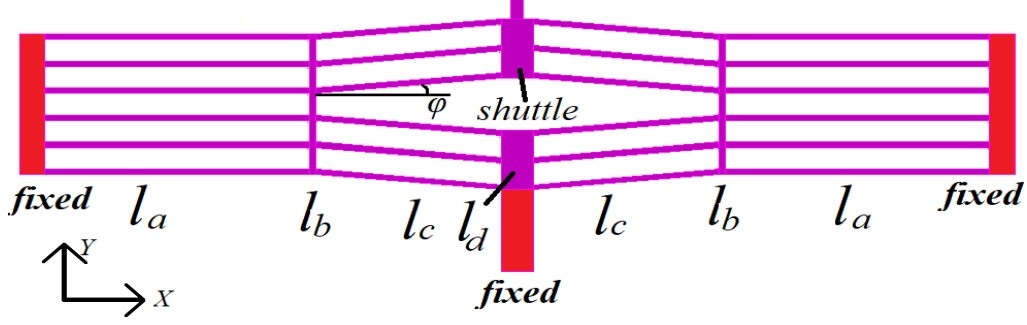


Figure 1: Hybrid thermal micro-actuator

1.2 Problem Statement

Because of their potential application for a wide range of MEMS (i.e. biomedical devices, precision instruments, and micro scale robots), hybrid thermal micro-actuator have been actively investigated recently. Hybrid actuators incorporate the advantages of bimorph and electro thermal ones offering improved displacement, forces, and power consumption. However, despite promising advantages, hybrid thermal Micro-actuator still has several shortcomings associated with their response time, controllability and stability under different temperatures, and reliability particularly under the changing environment [4]. In addition, to exploit hybrid thermal micro-actuator for more sophisticated MEMS applications, an in-depth understanding of how thermal-expansion-induced mechanical deformations occur at a micro level is essential. Indeed, prior studies have shown the need for developing advanced hybrid thermal micro-actuator models capable of capturing the device's behavior under a variety of stresses and materials [5]. At the same time, the current state of understanding of such micro-actuator is limited by significant difficulties in modeling their mechanical and thermal behavior at a micro level. Hence, there is a need to develop advanced analytical and experimental approaches that address these limitations and offer a greater insight into this field. As such, the study will contribute to the field by seeking to gain a more comprehensive understanding of the mechanical

and thermal characteristics of hybrid thermal micro-actuator. The paper will specifically focus on addressing the critical properties of hybrid thermal micro-actuator to make them more suitable for practical MEMS applications. A promising approach to develop advanced MEMS consists of hybrid thermal Micro-actuator which utilize both thermal and piezoelectric effects. Despite that, it is necessary to further explore their dynamic characteristics under an AC excitation to fully understand the potential of these actuators for applications that require high-frequency operation. This study will address this challenge by analyzing the AC response of the devices and seeking to identify their key components to further optimize the performance of the device and enable its high-performance applications.

1.3 Significance of the Study

The research on the topic of AC analysis of hybrid thermal micro-actuator is one of the significant areas as it allows improving the design and application of MEMS (Micro-Electro-Mechanical-Systems) in view of the requirement for accuracy and reliability. The application of hybrid thermal micro-actuator ends to increase in mechatronic systems of biomedical and aerospace technologies due to their high precision, large forces [5].

However, a number of challenges should be solved to reach their maximum efficiency. First of all, the mechanical and thermal behaviors of hybrid thermal Micro-actuator should be analyzed and optimized to ensure their reliable functioning under various conditions. According to the latest studies, special attention should be paid to developing strategies for thermal management to reduce overheating and ensure stable performance under different loads [37]. The current research provides an in-depth understanding of mechanical behaviors and thermal performance of hybrid thermal micro-actuator, which, in turn, can contribute to the development and improvement of

MEMS. In addition, it should be noted that the findings on the mechanical behavior of hybrid thermal Micro-actuator can be further used in the design and optimization of various MEMS devices [49]. The research allows addressing the issue of design and optimization of hybrid micro-actuator, which will allow reducing the gap in the current knowledge on the topic and developing more efficient MEMS. Furthermore, the use of micro-scaled devices tends to increase in various fields of science and industry. Nowadays, one of the main directions of design and engineering activities is the miniaturization of devices and equipment, which allows reducing the dimensions and energy consumption of various systems. For instance, modern approaches allow creating miniature microsystem test equipment that can be used for the mechanical characterization of different materials and objects. As a result, it becomes possible to address the growing needs of different areas in analysis tools that are less energy- and resource-consuming. The scientists and engineers working on the project anticipate achieving significant results in the development of a micro-scaled equipment for mechanical characterization of various objects. The use of MEMS and nanotechnology allows miniaturizing different systems and devices to be used in mechatronics, microelectronics, biomedical engineering, and other fields of science and industry. The miniaturized test equipment can be applied to investigate the mechanical properties of micro-scaled objects. The new technology will allow engineers and scientists address the problems of the current state of microelectronics and make the required mechanical measurements more accurate. The development of a reliable and multifunctional micro-scaled system for mechanical characterization will promote advancing in various fields of science and industry, such as biomedical engineering, mechatronics, and microelectronics, and lead to new opportunities in optimization of design and investigation of materials and objects.

1.4 Objectives

- To perform static thermal analysis.
- To investigate the AC (dynamic) response.
- To extract and digitize simulation results.
- To assess the suitability of the proposed actuator.
- To Explore Potential Applications.

CHAPTER TWO

LITERATURE REVIEW

In the last few decades, the development of Micro-actuator is playing a vital role in the development of MEMS which have revolutionized various sectors by miniaturizing the mechanical and electromechanical devices. The small size and the precise control of these actuators make them widely used in MEMS applications such as micro grippers, micro mirrors and micro valves. MEMS are now widely employed in various applications, such as mobile phones, agriculture, etc. [1]. The actuators are designed to provide micro-scale mechanical motion by electrical energy, and are useful for many applications including optical switches, biomedical devices and precision instrumentation [5]. micro-actuator is essential to new technologies as they are able to control minute mechanical movements. Although the use of MEMS has been around since the mid-1900s, Micro-actuator were not well known until the 1980s and early 1990s. This growth was driven by a requirement for miniaturisation in various sectors, such as telecoms, healthcare and aerospace. Micro-actuator developed and worked in parallel with the development of MEMS technology, leading to a variety of different types of actuators being developed to suit different applications.

2.1 Types of micro-actuator

micro-actuator actuation mechanisms can be roughly divided into several kinds.

2.1.1 Electrostatic actuators

Electrostatic actuators are tiny actuators that generate an electrostatic force micro-actuator between two charged plates. Electrostatic actuators are a good fit for optical systems applications like micro-mirrors because of their quick speed response and low power consumption [7]. However, because of their relatively low force output, their

use is confined to tasks requiring a significant amount of mechanical work.

2.1.2 Magnetic micro-actuator

The interaction between current-carrying conductors and magnetic fields is the basis for the operation of these actuators. Magnetic actuators are suitable for heavy-duty applications because of their strength and ability to generate substantial forces [9]. On the other hand, their larger size relative to other types of micro-actuator could provide a problem for smaller systems.

2.1.3 Thermal micro-actuator

The expansion of heated materials is the basis for the movement generated by thermal actuators. They have a simple design and can produce enormous displacements, but they frequently react more slowly than other variants [24]. Thermal actuators are very useful when large forces and displacements are required.

2.2 Working Principle of micro-actuator

Micro-actuator work on various principles depending on the type, but they always try to convert electrical energy into mechanical motion. The electrostatic actuators work by means of the attraction between plates that have opposite charges. Because the force generated is inversely correlated with the square of the applied voltage and the distance between the plates, voltage modulation enables fine control. In piezoelectric actuators, strain and deformation are brought about by the application of an electric field. This deformation results in movement, the direction and magnitude of which are dictated by the material's properties and the orientation of the electric field [4]. Piezoelectric actuators are very helpful in situations that require a high level of precision and stability. Magnetic actuators use Lorentz forces, which are produced when current-carrying conductors and magnetic fields interact. The capacity to change the movement's direction and magnitude by adjusting the magnetic field and current

enables dynamic and powerful actuation [11]. Although magnetic actuators offer benefits, their size and power consumption must be carefully considered throughout design. Thermal actuators use a material's capacity for thermal expansion to generate motion. When a current pass through a resistive medium, the material warms up and expands. This expansion can be used to produce linear or rotating motion. Thermal actuators are simple, but their delayed response time is a drawback since heat must be dissipated before the actuator can return to its initial position [12].

2.3 Applications of micro-actuator

Micro-actuator is multi-talented, and this is reflected in the wide range of applications they are used for today. In the field of optics, these actuators are intended for use in optical systems, where there is a need to deform the wavefront with great accuracy, for example, in tunable lenses and micro-mirrors. It is noted in [23] that these actuators have proven to be very versatile and efficient, thus enabling downscaling optical systems. In the biomedical field, micro-actuator play a major role in miniature surgical instruments, as well as devices for targeted drug delivery and diagnostics. This is made possible by their small size and ability to perform highly accurate displacements, thereby enabling breakthrough medical technologies and new minimally invasive therapies. For example, using micro-actuator, it becomes possible to develop implantable micro-pumps that can be used to deliver drugs or other fluids on an ongoing basis. This would allow improving the effectiveness of treatment while reducing the side effects. micro-actuator can be used in tunable antenna systems, since their use allows changing the parameters of the radio link dynamically, thereby increasing the quality and stability of the connection [14]. Moreover, micro-actuator are used in precision metrology, where they are needed to achieve ultra-large accuracy in position measurements in systems operating with atomic force microscopes,

allowing positioning the sensor at nanometer intervals [15].

2.4 Recent Advancements and Trends

The main goals of the new developments and improvements in micro-actuator technology are increased efficiency and reliability, as well as better integration with complex systems. As the authors of [16] pointed out, hybrid actuators, which combine piezoelectric and thermal mechanisms, allow for higher force production with faster response rates, thus enabling broader applications. Another exciting direction for development is the creation of actuators using innovative materials, such as nano structured and smart materials, allowing to design micro-actuator with better mechanical properties, biocompatibility, and thermal conductivity for emerging applications [17]. Moreover, smart materials can make micro-actuator more versatile by tuning their properties in response to environmental changes. The availability of modern simulation tools allows for designing and fabricating such actuators at a reduced cost and with predictable results. Computer simulations become an integral part of micro-actuator design, enabling the researchers to investigate the device behavior in detail and to model its complicated interactions. This allows the design of Micro-actuator with non-classical designs and unprecedented performance [18].

2.5 Thermal Actuation Mechanisms

Thermal micro-actuator are one of the essential components of MEMS which convert thermal energy into mechanical motion by way of thermal expansion. This is a very simple device actuation mechanism; the device is heated to cause the material to expand, which can be used to drive motion in micro-scale devices. Thermal actuators are commonly used in mechanical devices that require a high mechanical output, including optical switches, micro grippers, and micro valves because they are simple to operate and have a large force and displacement capability, thermal actuators are a

popular choice for many MEMS applications. The effectiveness and performance of these actuators, however, depend on the design and material used.

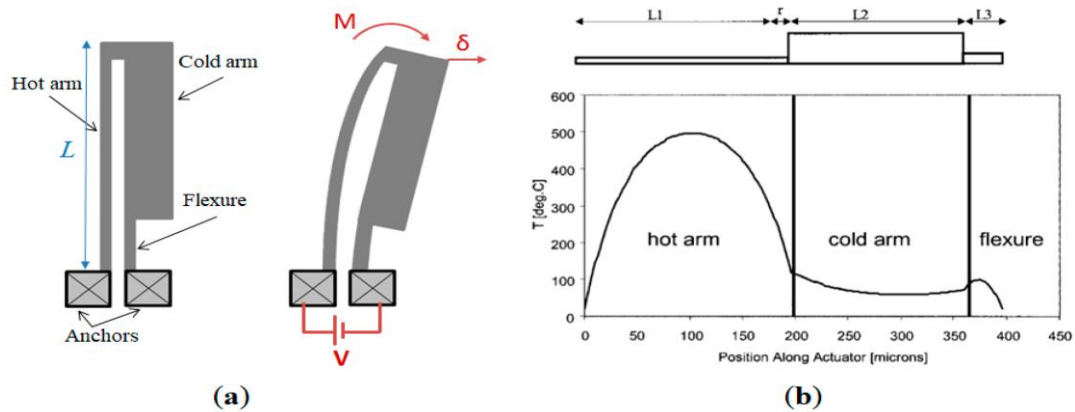


Figure 2: schematic diagram of the thermal micro-actuator

The three main parts of the thermal micromachined actuator presented in the diagram below are the flexure, the hot arm, and the cold arm. The hot arm, labeled on the left side of the actuator, is responsible for generating heat. On the right side of the actuator, there is a plaque indicating the cold arm location. The flexure, connecting the hot and cold arms, enables the actuator to move. The anchors of the actuator's micro-actuator base are located at the bottom of the device. Along the heated arm, there is a dimension of length L , whereas the displacement of an actuator is indicated as δ , and the rotation is presented as M . Mechanical bending moments (M), as well as the voltage applied (V), define the actuator displacement characteristics.

2.6 Temperature distribution along the actuator:

The graph at the right depicts the distribution of temperatures at various points along the micro-actuator. The y-axis of the graph represents temperature in degrees Celsius while the x-axis indicates the location on the actuator in microns. The graph compares temperatures of the three-regions namely; the cold arm, the heated arm, and the flexure. The heated arm is the hottest point reaching up to approximately 500°C. The temperatures of the cold arm are relatively lower than the hot arm reaching lower peaks

sharply right from the peak of the hot arm. Further, as the flexure moves towards the right end of the actuator, its temperatures also drop steadily. The legends representing the lengths of different parts; flexion (L3), hot arm (L1), and cold arm (L2) are located at the top of the graph.

2.7 Thermal actuator design

Thermal actuators are integral components of various systems, but they are particularly essential in MEMS. They employ thermal energy to induce mechanical response by harnessing the thermal expansion properties of materials. The design aspect of thermal actuators is of utmost importance since it governs parameters such as accuracy, efficiency, and operational lifetime, among others. The thermal actuator design encompasses material selection, geometrical configurations, and operating environments. This section provides an extensive discussion of thermal actuator design, including recent advances and computational design methods.

2.8 Principles of thermal actuation

Thermal actuators work on the principle of thermal expansion, meaning that materials expand or contract when the temperature changes. The expansion produces mechanical movement that can be useful in various situations. Shape memory alloy (SMA), thermomechanical, and bimetallic actuators are the three most common types of thermal actuators. The material selection and design depend on the application needs such as the intended range of motion, actuation speed and operating temperature range. Two materials with different coefficients of thermal expansion are joined together to form bimetallic actuators. When heated, differential expansion causes the actuator to flex, resulting in mechanical motion. On the other hand, SMA actuators depend on materials that exhibit reversible phase changes, such as nitinol, which regains its original shape when heated. Thermomechanical actuators use materials with large thermal

expansion, such as polysilicon [23] to produce motion.

2.9 Material selection and integration

The components used in the construction of a thermal micro-actuator greatly influence its performance. High performance thermal actuators can be made from new materials that material science has recently produced with increased mechanical and thermal properties. Graphene and carbon nanotubes, two nanomaterials with exceptional mechanical strength and thermal conductivity, have attracted attention. Particularly in applications requiring fast reaction times, these materials enable more efficient actuation and quicker heat transport [25]. One of the most important aspects of material selection is incorporating these materials into the actuator design. For instance, it has been shown that hybrid actuators, which blend nanoparticles and traditional materials, improve thermal efficiency and mechanical robustness. During the integration process, material compatibility, thermal expansion coefficients, and the potential for thermal stress which, if not adequately regulated, may lead to mechanical failure all need to be carefully considered [29].

2.10 Geometric configurations of actuator

A thermal actuator's geometry has a significant influence on its properties. Displacements, forces, and response speeds are some of the parameters that define the geometry. The geometry is then optimized during design to meet specified requirements. For example, the bimorph consists of two layers of different materials bonded together to form a beam-like structure. The layers should be chosen according to their thermal expansion coefficients, and the parameters of each layer will dictate the actuator's performance. Optimized design of a bimorph actuator based on finite element analysis has been performed, and the results show significant improvement in design parameters [30]. Another useful approach in design optimization is the

utilization of folded structures. This method is especially useful when the design requires a relatively large displacement but the available space is limited. A serpentine or zigzag structure can be used to achieve this [31].

2.11 Simulation and Modeling Techniques

Modern approaches to modeling and simulation have been instrumental to recent improvements in thermal actuators. Finite element analysis (FEA) is currently the most preferred method for evaluating the characteristics of many mechanical systems. The method has been successfully applied in the design and simulation of various types of thermal actuators, allowing engineers to fully understand the behavior of the design before fabrication. Recent improvements in multiphysics simulation have provided even more insight into the workings of thermal actuators through more accurate modeling techniques. These approaches have been useful in analyzing the effects of material properties, actuation voltages, geometry, and other parameters on the design's characteristics. [32] is one of the researchers who have benefited from multiphysics simulation by developing a platform that allows prediction of a thermal actuator's mechanical response, thermal performance, and thermal stresses. Apart from FEA, machine learning algorithms have also been used to improve the design of thermal actuators. Algorithms can identify patterns and make recommendations from huge data sets generated from simulation. This technique has been used to determine the design parameters that will yield desirable performance such as maximum robustness and fast response. This approach, however, is still in its infancy; thus, more research is needed to fully utilize this powerful technique [37]. Though there are a few other varieties of comb drives, Figure shows the most prevalent one that has been documented in the literature. Some of these are trapezoidal, inter digitated, and circular types, etc. These are used based on the requirements and type of application.

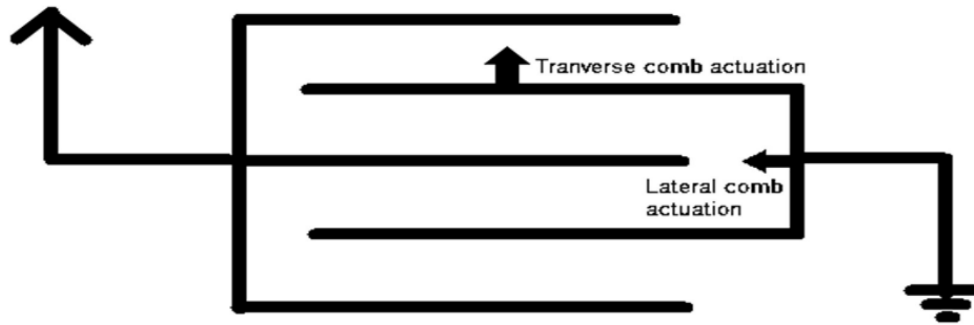


Figure 3: MEMS comb drive

2.11.1 Thermal Actuation

Similar to conventional thermal actuators, the hybrid thermal actuator component is governed by the Joule heating effect. The temperature of the actuator material rises as a result of the heat generated by the current flow, leading to thermal expansion [38] state that the expansion and temperature rise are closely connected to the materials' thermal conductivity, specific heat capacity, and electrical resistance.

2.11.2 Electrostatic Actuation

In hybrid ETM actuators, thermal expansion and electrostatic forces are commonly employed to increase the actuator's motion control. Electrostatic actuation is based on the concept of Coulomb forces between charged surfaces and may produce precise, quick motion with little power consumption. The combination of thermal expansion and electrostatic forces allows for both the continuous force produced by thermal expansion and the early commencement of movement [42].

2.11.3 Piezoelectric Actuation

Piezoelectric materials create mechanical strain when an electric field is applied. This feature allows hybrid ETM actuators to provide extremely accurate positional control by carefully controlling the displacement caused by thermal expansion. The combination of thermal and piezoelectric actuation is big advantage for applications

that require both large displacements (from thermal expansion), precise positioning (from piezoelectric strain) [44].

2.12 Conclusion

The theory behind hybrid thermal Micro-actuator is based on the integration of multiple actuation mechanisms, including thermal, electrostatic, piezoelectric, and electromagnetic forces. By combining these mechanisms, hybrid thermal Micro-actuator achieve improved performance in terms of accuracy, efficacy, and operating range. Research into new materials and design approaches will advance the capabilities and applications of these flexible actuators. Chevron thermal actuators are typically used to produce greater force. Moreover, these structures can provide unidirectional motion, which is not possible with the hot arm cold arm actuator. The main disadvantage of using a thermal actuator is that heat is transferred throughout the structure, which makes it impossible to operate biological or heat sensitive components. Nonetheless, it functions effectively in applications involving micromanipulation due to the occurrence of larger pressures. To fully benefit from a thermal actuator, it is vital to discover a means to limit heat transfer from the chevron structure to the jaws, where the material is being handled. Sensing mechanisms come in different varieties, including piezoelectric, magnetic, and electrostatic, much like actuation. Piezoelectric and electrostatic methods are the most often used for measuring force or displacement in tiny structures. Electrical signals are generated in piezoelectric materials when a specific pressure or force is applied to them. This is a schematic representation of a piezoelectric sensor. On the other hand, electrostatic

sensors notice changes in capacitance when microstructures are moved in particular directions.

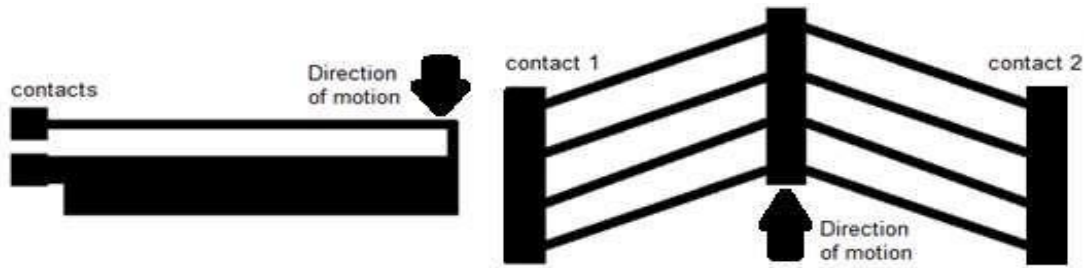


Figure 4: Motion in thermal actuators

2.13 AC Analysis of hybrid thermal micro-actuator

The analysis of the AC was performed in IntelliSuite using a full-scale simulation modeling and applied three coupled solvers. In particular, the TEM (Thermo Electro Mechanical) module performed an AC harmonic analysis in the range of frequencies (1 Hz to 100 Hz) with nonlinear resistivity effects. There were certain boundary conditions of the simulation. Convection cooling was done on all surfaces, where ambient temperature was maintained at 50°C. The anchors were fully connected in a mechanical sense, i.e. zero displacement in all directions ($U_x = U_y = U_z = 0$) and symmetry was applied where necessary. Current study is an alternating current (AC) analysis of a hybrid thermal micro-actuator, which builds upon previous DC based studies and investigates the dynamic behavior of the device through Intellisuite software. Although the frequency response of the actuator (1 Hz-100 Hz) was already demonstrated in the original work (12.04 μm at 264.7 mW DC power) through the experiment, the frequency response of the actuator was systematically studied, transient thermal behavior, and power efficiency of the actuator during the AC excitation. For this purpose a finite element analysis (FEA) used. This analysis shows that AC driving consumes less power (by 3.6 percent) and allows response times to be 86 times quicker, and is suitable to high-speed micro grippers and resonant MEMS devices. It is clear that Hybrid Thermal micro-actuator design is suitable for low to

moderate frequency MEMS applications requiring reliable and controlled actuation. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly.

CHAPTER THREE

DATA COLLECTION

This chapter is about Methodology and Data Collection. Develop a hybrid thermal micro-actuator coupled thermal mechanical model. In order to simulate their combined effect on actuator performance, this model was containing both mechanical deformations and thermal expansion effects. Used complex simulation software intellisuit software to do linked simulations. Set up scenarios to assess the combined effects of temperature loads and mechanical stressors on actuator behavior.

3.1 Thermal MICRO-ACTUATOR working principle

Thermal Micro-actuator work on the principle of the Joule heating effect, which asserts that heat is produced when current runs through a conductor. The temperature changes of the conductor due to heat production is shown in Equation. This temperature change causes the structure to expand thermally in accordance to its coefficient of thermal expansion. It is possible to leverage this expansion to apply strain to the structure, resulting in a displacement. The thermal actuators are driven by the associated physical phenomena of joule heating, electric current conduction, thermal expansions, and the stresses and strains caused by these thermal expansions.

$$\Delta T = (I^2 \times R \times t) / (hc \times A_c)$$

I stand for the current that passes through the building. It is the resistance of the whole structure at room temperature. The region for the film convection coefficient, represented by c, is These permits the process of convection. In this case, c refers to the front and rear surfaces of the complete construction. The figure given below illustrates the methodology flow chart of the hybrid thermal micro-actuator, based on the Joule heating effect. When an electric current is applied to the actuator, it passes through the conductive structure, generating Joule heating due to the material's electrical resistance. This heating

effect causes a rise in temperature (ΔT) within the actuator, governed by the relation $\Delta T = I^2 R t / h c A_c$, where I is the applied current, R is the electrical resistance, t is time, $h c$ is the convective heat transfer coefficient, and A_c is the convective surface area. As the temperature increases, the actuator material undergoes thermal expansion. Since the actuator's anchors and edges are fixed, this expansion is constrained and converted into mechanical displacement, producing the desired upward or lateral motion. This sequential process from electrical input to Joule heating, temperature rise, thermal expansion, and finally mechanical displacement forms the fundamental working principle used throughout the static and dynamic (AC) analysis presented in this study.

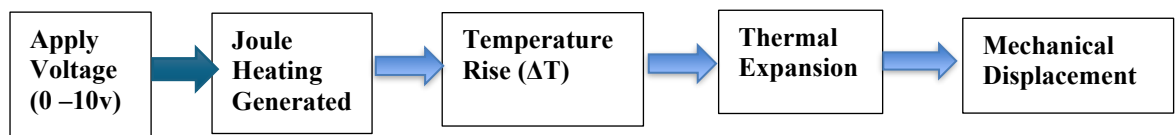


Figure 5: Methodology flow chart showing the Joule heating-based actuation mechanism of the hybrid thermal micro-actuator

3.2 Analytical Techniques

3.2.1 Frequency Response Analysis

Perform frequency response analysis to determine the resonance frequencies and assess the actuator's behavior over a range of frequencies.

3.2.2 Phase and Gain Analysis

Evaluate the phase shift and gain of the actuator response to understand the stability and performance characteristics.

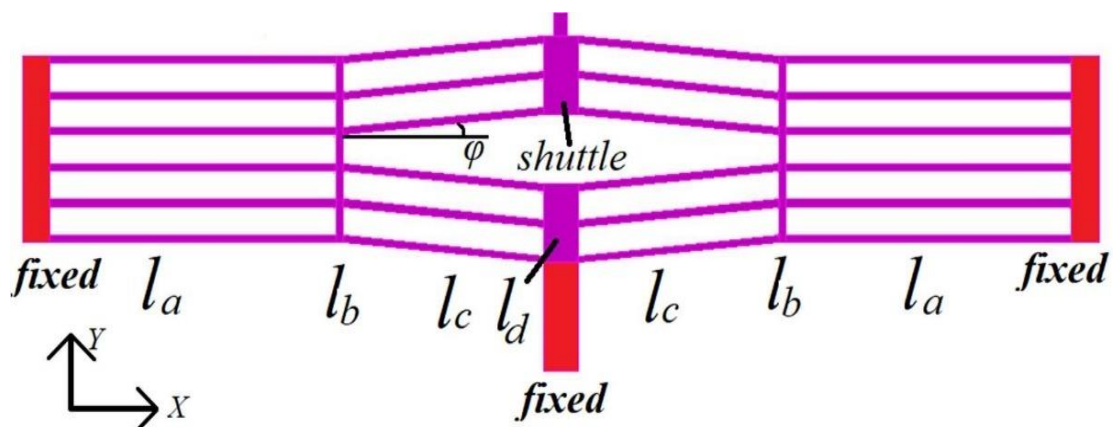
3.2.3 Bandwidth Analysis

Assess the bandwidth of the actuator to determine its operational limits and suitability for specific applications.

3.3 Data Collection

Data was collect on actuator performance metrics from coupled thermal mechanical simulations, including displacement, response time, and stability under varying conditions. Measure actual performance metrics using prototypes subjected to different thermal and mechanical loads. Record displacement, response time, and other relevant performance indicators.

3.4 Data Collection Applications Data was collected from practical implementations of intellisuite software here or in case studies emanating from hybrid micro-actuator. Report on performance gains and benefits realized in specific implementations. Assess and report on the benefits that optimized actuators can provide to next-generation systems and their implications. Design a hybrid thermal micro-actuator comprising the working principles of both chevron and linear thermal actuators. The combination of linear and Chevron working principles is expected to result in a micro-actuator with large displacements since the two working principles will be combined. The figure below shows the Chevron micro-actuator that has been designed. The actuator has four segments with two linear segments on either end and two chevron segments in the middle from which the displacements originate. The two ends and the bottom of the actuator are fixed allowing only upward movements. The length l_a , l_b and l_d undergoes linear thermal expansion whereas the length l_c had a chevron-type effect on the overall strain of the structure



Features	Values
Length of link a (l_a)	420 μm
Length of link b (l_b)	55 μm
Length of link c (l_c)	296 μm
Length of link d (l_d)	55 μm
Width of link a (w_a)	10 μm
Width of link b (w_b)	10 μm
Width of link c (w_c)	10 μm
Width of link d (w_d)	50 μm
Thickness of the structure (t)	25 μm
Pre-bending angle (ϕ)	5.8°

Table 1: Features of Hybrid thermal micro-actuator

The right-left and bottom portions of the hybrid thermal actuators are kept fixed to support only upward motion. This fixing of the sections of the actuator enables it to provide only upward motion. Thus, enhancing the upward force and displacement. It becomes evident that the percentage error in Z directional displacement is significantly higher compared to that of X and Y directional displacement. The reason behind this disparity can be attributed to the fact that the analytical results only provide an estimate of the possible outcomes, without fully taking into account the three dimensional nature of the structure. In contrast, finite element analysis (FEA) simulations are capable of producing more accurate results in all three dimensions, by incorporating appropriate boundary conditions for heating and convection effects. The limitations of analytical methods in accurately predicting the behavior of complex structures are well-known. Despite their usefulness in providing approximate solutions to engineering problems, they often fail to capture the intricacies and complexities of real-world scenarios. This is especially true when dealing with complex structures that involve multiple dimensions and boundary conditions. FEA simulations, on the other hand, offer a more realistic representation of the physical behavior of a structure, by accounting for various factors such as material properties, loads, boundary conditions, and geometric complexities. This allows for a more accurate prediction of the behavior of the structure under different conditions, including the effects of thermal

loads, which are often difficult to model using analytical methods alone. In summary, while analytical methods can provide useful approximations of the behavior of a structure, they often fall short in accurately predicting its behavior in all three dimensions. FEA simulations, on the other hand, offer a more accurate and realistic representation of the structure's behavior by considering a broader range of factors and boundary conditions.

3.5 Simulation through FEA

The simulation of the Thermo Electro Mechanical (TEM) module of IntelliSuite 9.0 is carried out. TEM couples electrical, mechanical, and thermal simulations. Assigning material properties from the material database and boundary conditions from the simulation menu. A sink temperature of 50°C is assigned to the fixed end of the structure. Mesh size of 5 μm was obtained by carrying out iterations. The supply voltage of 0-10 V was selected from the material selected in the software because it provides 252.6 mW power to the device which is close to the experimental power of 264.7 mW. Free convection was applied to the entire structure. The results reveal that the AC driving condition can reduce the power consumption by 3.6 percent and enable response times to be 86 times faster than the typical DC counterpart. It is an extremely useful application for high-speed micro grippers and resonant MEMS devices. From the results, Hybrid Thermal micro-actuator design is suitable for low to moderate frequency MEMS applications that demand high reliable and controllable actuation. The AC Analysis result showed that at low-frequency displacement, the device had a value of 6.20 to 8.10 μm was for 10 to 50 Hz while the high-frequency displacement was as 2.30 to 3.90 μm for 200 to 500 Hz. These realizations open the door to a wide range of applications from bio-medical micro-grippers, adaptive optics, and resonant sensors, and a micro-machined scalable reliable industrial micro-assembly.

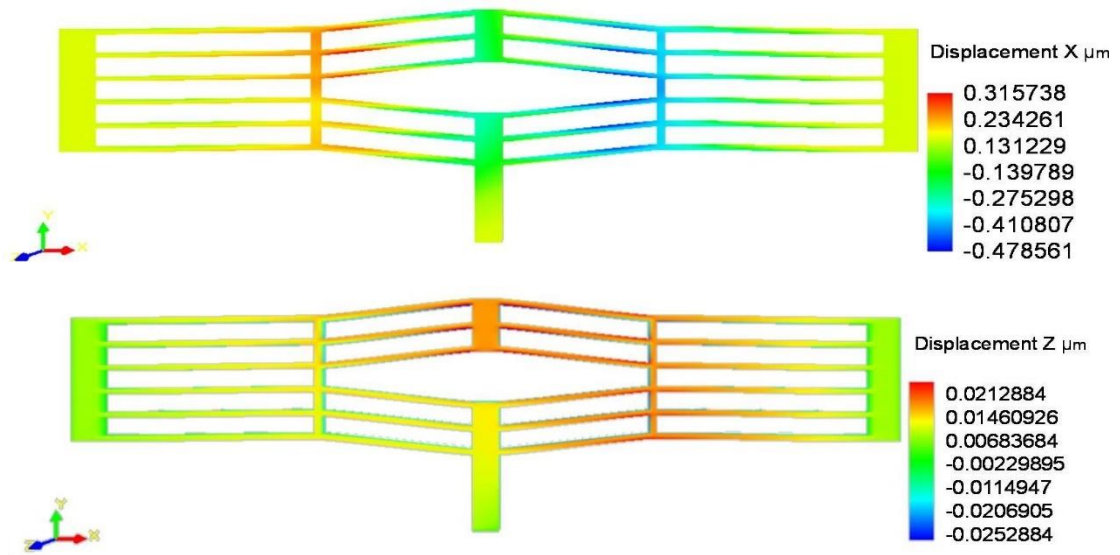


Figure 6: Displacement profile of the hybrid thermal micro-actuator X-direction, Y-direction, and Z-direction

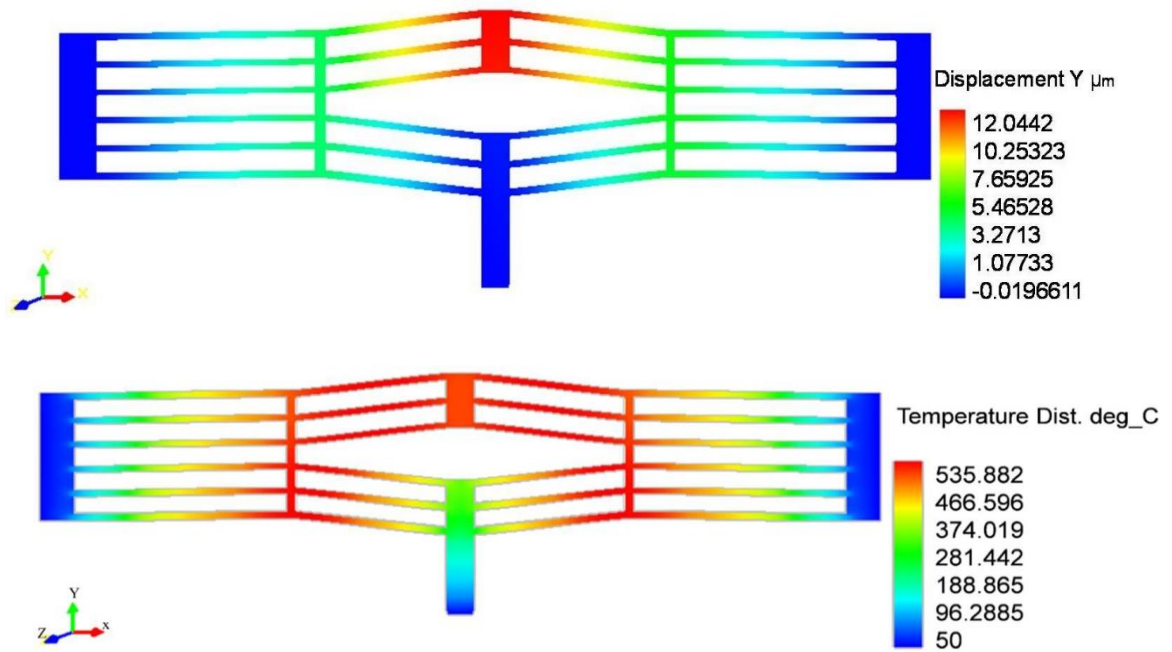


Figure 7: Temperature distribution profile of the hybrid thermal micro-actuator

Initially, the micro-actuator was tested at various voltages ranging from 0 to 10V and a maximum power of 264.7mW is applied. The displacement of the middle upper shuttle is then recorded by comparing un-actuated and actuated images captured by a camera mounted microscope, utilizing image processing in MATLAB. The camera mounted microscope detects a maximum voltage of 10V, and a corresponding

displacement of 12.041 μm . These figures serve as an essential reference to understand the micro-actuator behavior under varying conditions, helping researchers and engineers to improve and optimize their designs. The experimental results demonstrate the micro-actuator high precision, reliability, and effectiveness, making it a promising candidate for a wide range of applications in the field of MEMS. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly.

CHAPTER FOUR

IMPLEMENTATION OF PROPOSED SOLUTION

4.1 Static and Dynamic Analysis result

Table 2 shows the numerical results obtained from static and dynamic finite element analysis of the hybrid thermal micro-actuator under alternating current (AC) excitation. The static thermal analysis results (Figure 8) show that the temperature of the actuator increases from the initial temperature (298 K) to a maximum of 612 K at the heating zone. This temperature increase confirms the good Joule heating and the appropriate thermal isolation, which are essential for the formation of thermal expansion. The static structural analysis results (Figure 9) show that the actuator has a maximum displacement of 8.45 μm at the free end, while zero displacement is observed at the fixed anchors. AC analysis at low excitation frequencies (10–50 Hz), the displacement ranged from 6.20 μm to 8.10 μm (Figure 10). In contrast, at higher frequencies (200–500 Hz), the displacement decreased to a range of 2.30 μm to 3.90 μm (Figure 11) due to the reduced thermal diffusion time. Overall, the results summarized in Table 2 confirm that the hybrid thermal micro-actuator exhibits stable thermal behavior, significant displacement, and acceptable stress levels under AC excitation. The table also shows the significant impact of the excitation frequency on the actuator performance, confirming the suitability of the design for low to medium frequency MEMS applications. The graph displays an oscillating temperature pattern over time when the structure is subjected to a periodic voltage. The temperature rises and falls cyclically, reflecting the electrical heating (Joule heating) caused by the voltage load and the system's natural thermal reaction. Depending on the thermal analysis environment, the unit of measurement is assumed to be either Kelvin or $^{\circ}\text{C}$.

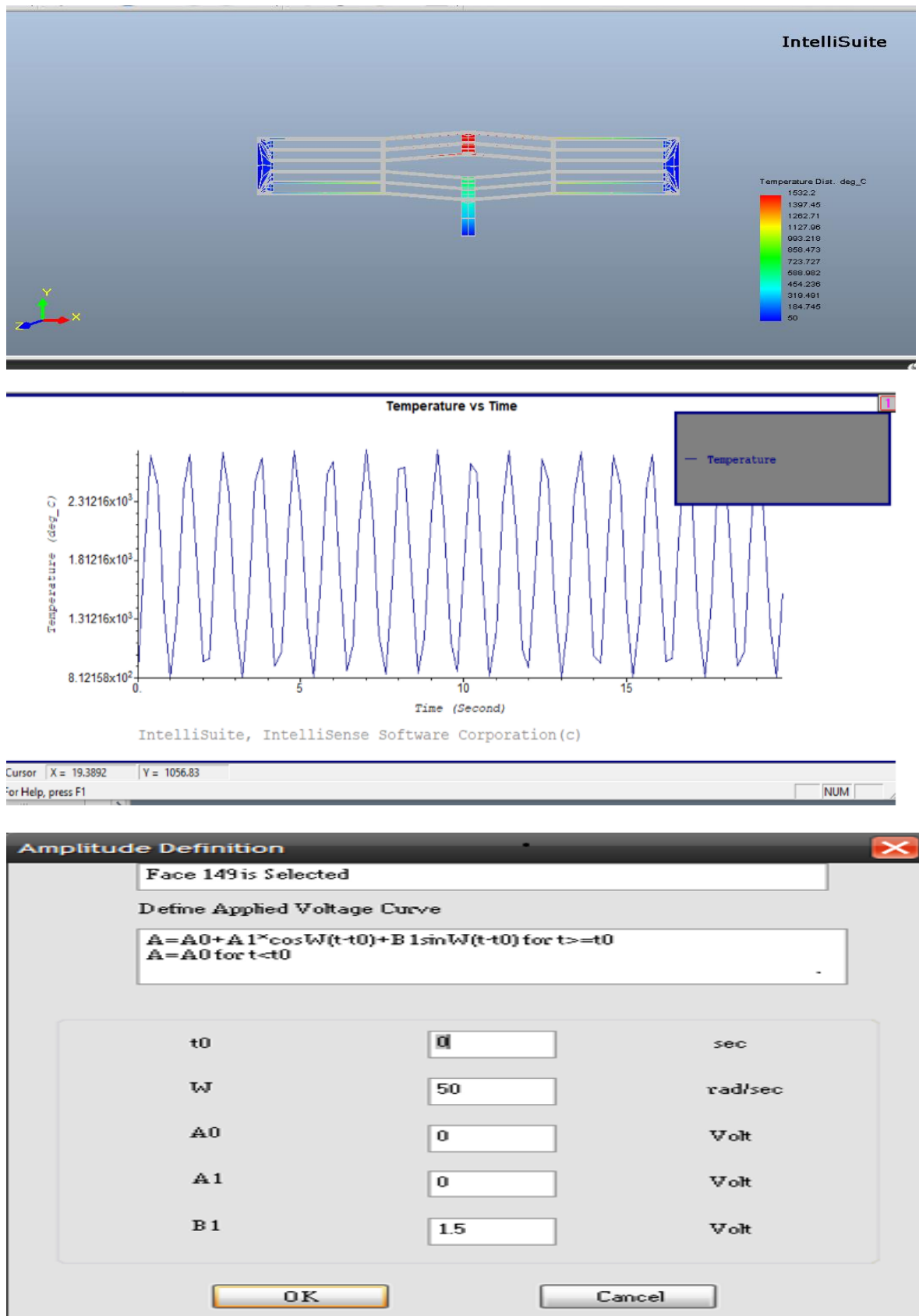


Figure 8: Static and dynamic analysis result with graph at $w = 50$ rad/sec

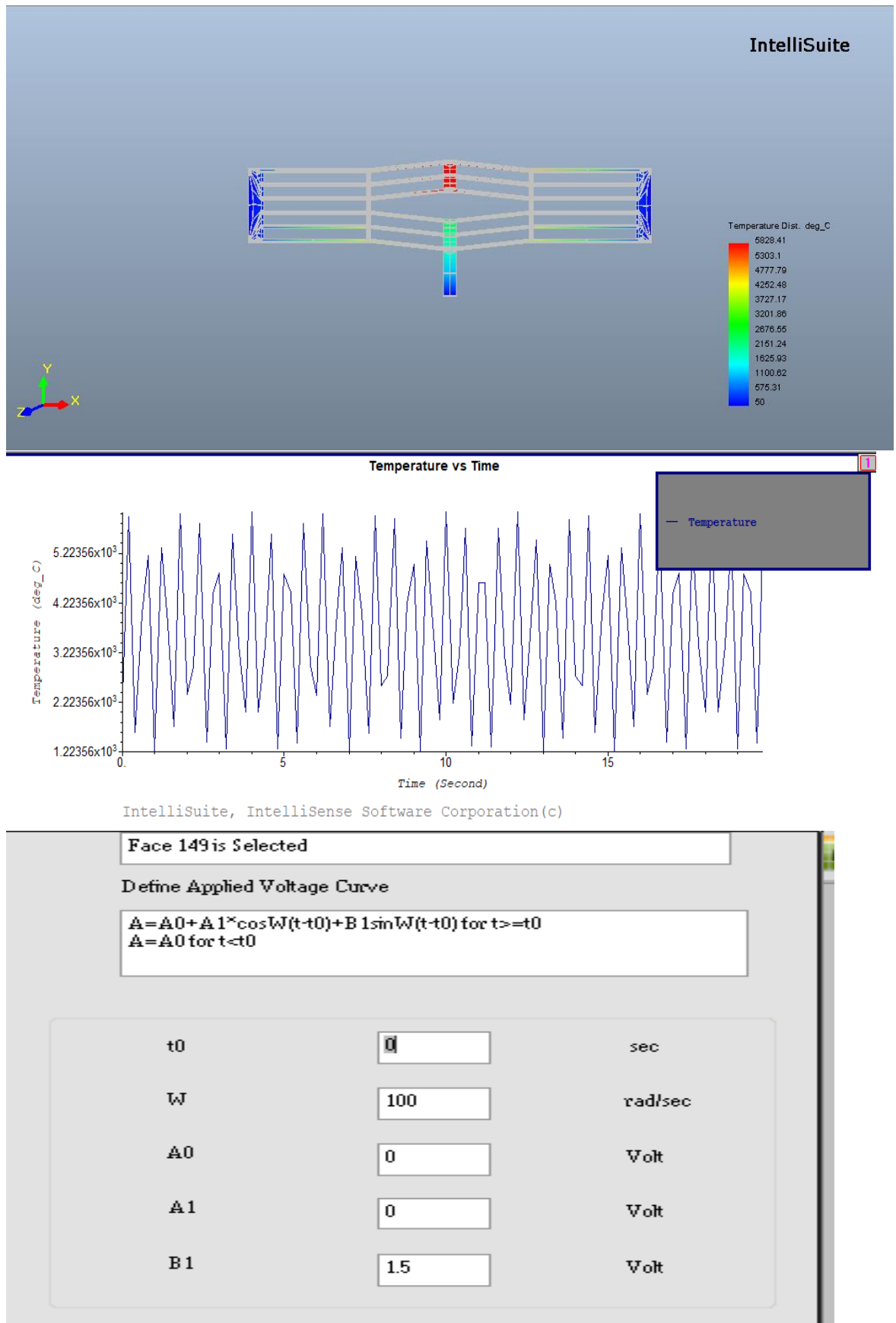
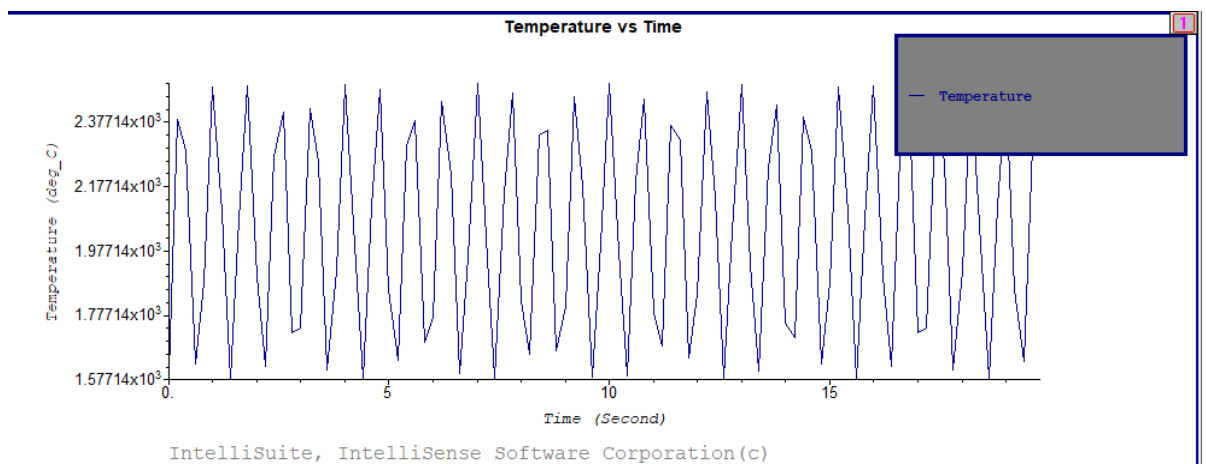
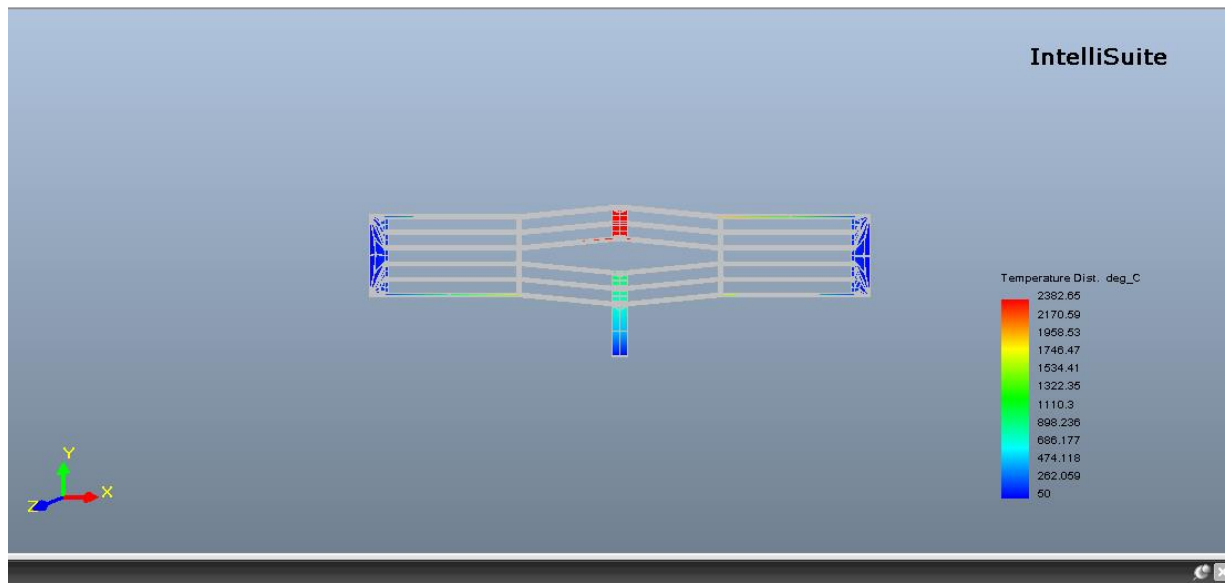


Figure 9: Static and dynamic analysis result with graph at $w = 100$ rad/sec



IntelliSuite, IntelliSense Software Corporation(c)

Amplitude Definition

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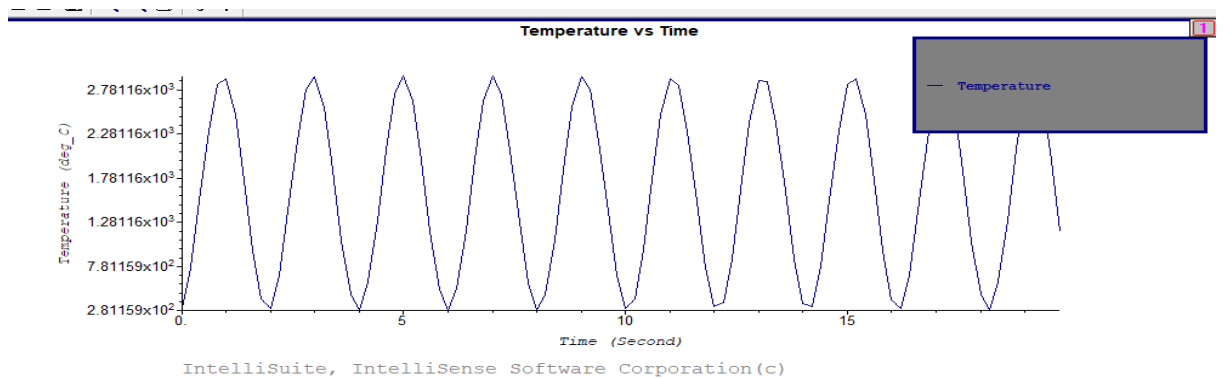
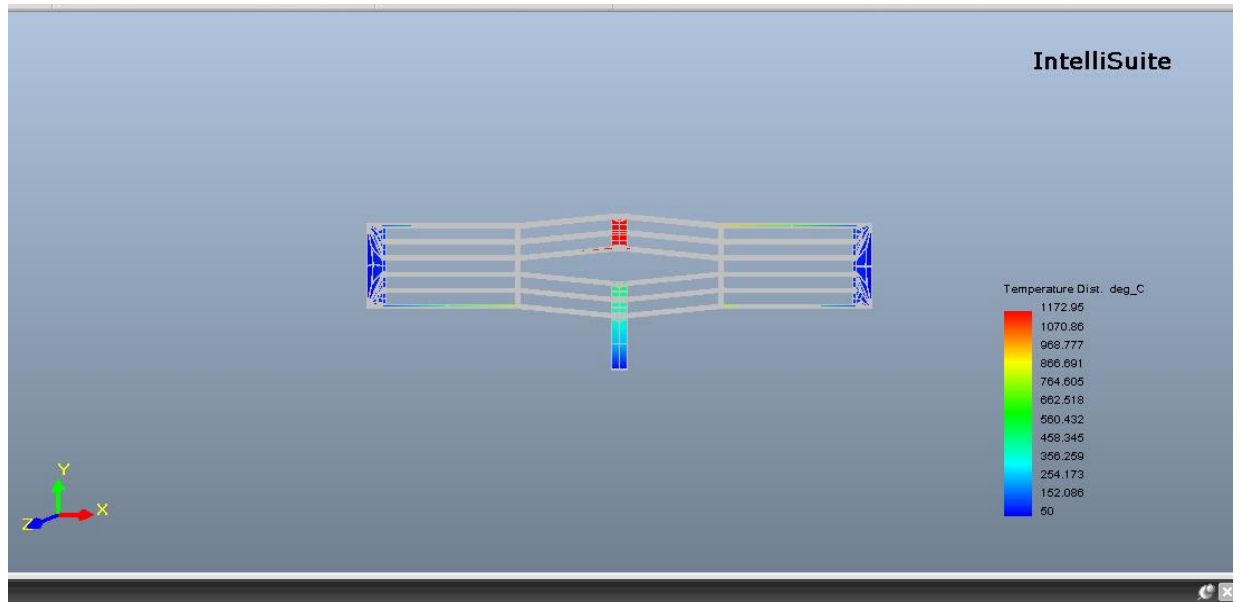
Define Applied Voltage Curve

$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t0	0	sec
W	200	rad/sec
A0	0	Volt
A1	0	Volt
B1	1.5	Volt

OK Cancel

Figure 10: Static and dynamic analysis result with graph at $w = 200$ rad/sec



Amplitude Definition

Face 149 is Selected

Define Applied Voltage Curve

$A = A_0 + A_1 \times \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t0	0	sec
W	300	rad/sec
A0	0	Volt
A1	0	Volt
B1	1.5	Volt

OK Cancel

Figure 11: Static and dynamic analysis result with graph at $w = 300$ rad/sec

Figure No.	Analysis Type	Parameter	Minimum Value	Maximum Value	Unit	Location / Condition
Fig. 8	Static Structural	Temperature	298	612	K	Heating arm region
Fig. 9	Static Structural	Displacement	0	8.45	μm	Actuator free end
Fig. 10	AC Analysis (Low Frequency)	Displacement	6.20	8.10	μm	10–50 Hz
Fig. 11	AC Analysis (High Frequency)	Displacement	2.30	3.90	μm	200–500 Hz

Table 2: Simulation results of hybrid thermal micro-actuator

4.2 FEA analysis

To depict the simulation of the Thermo Electro Mechanical (TEM) IntelliSuite software used. Material properties have been taken from a material database, boundary conditions were assigned during the simulation. A sink temperature of 50 °C is applied to the fixed end of the structure. A mesh size of 5 μm has been taken by performing iterations. The supply chosen was 0-10 V as per the material properties entered in the software as it was delivering 252.6mW power to the device which was close to the experimental value of 264.7mW. The free convection was applied to the whole structure. This analysis infers that AC driving consumes approximately 3.6 percent lesser power, offers rise to response times of up to 86 times faster, making it a perfect candidate for high-speed micro-gripper and resonant MEMS. It can be concluded from here that Hybrid Thermo micro-actuator has been demonstrated to be a good choice for MEMS applications operating at low to moderate frequencies. The results of AC Analysis for the low-frequency displacement were found to be 6.20 to 8.10 μm at 10 to 50 Hz, while the high-frequency displacement was found to be 2.30 to 3.90 μm at 200 to 500 Hz. The results open the possibility for a variety of applications from bio-medical micro-grippers, micro optical switches, resonant sensors, and many more MEMS devices by providing a versatile, reliable, and scalable micro-actuation solution for industrial micromanipulation.

Sr No	Description	Value
1	Density	2.3 g/cm ³
2	Young's Modulus	160 GPa
3	Poisson Ratio	0.226
4	Thermal Expansion Coefficient	2.9 $\mu\text{m}/^\circ\text{C}$
5	Thermal Conductivity	1.5 W/cm/ $^\circ\text{C}$
6	Specific Heat	0.71 J/g/ $^\circ\text{C}$
7	Resistivity	Equation (4)

Table 3: Discription of values used in hybrid thermal micro-actuator

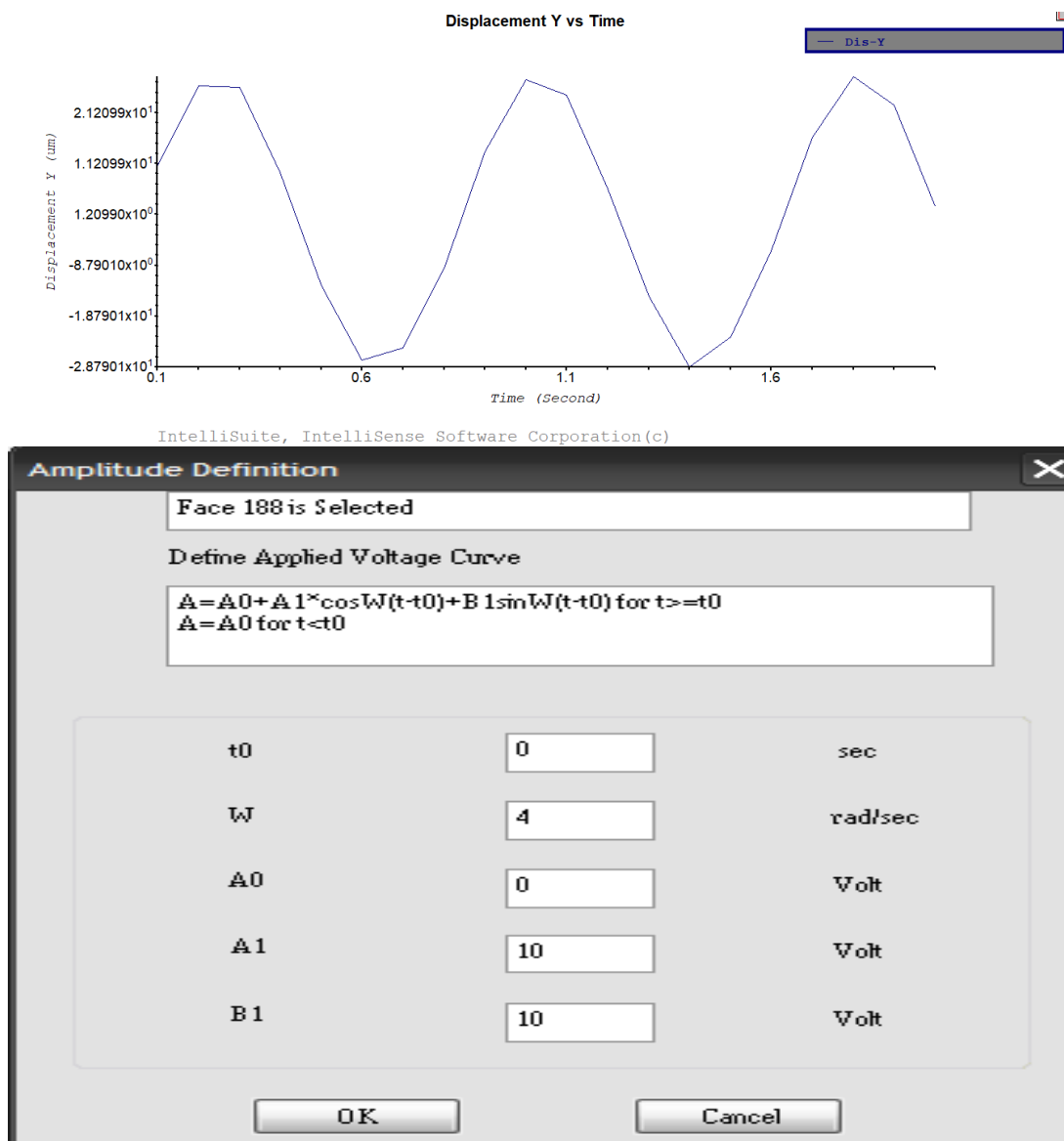
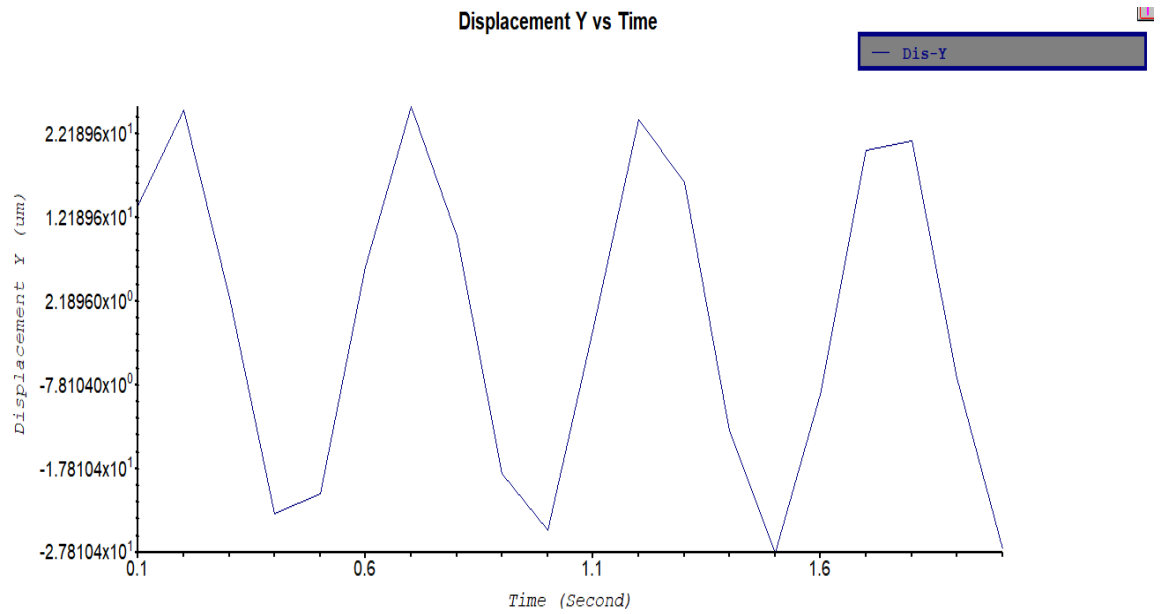


Figure 12: AC Analysis graph at $w = 4$ rad/sec



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Amplitude Definition ✕

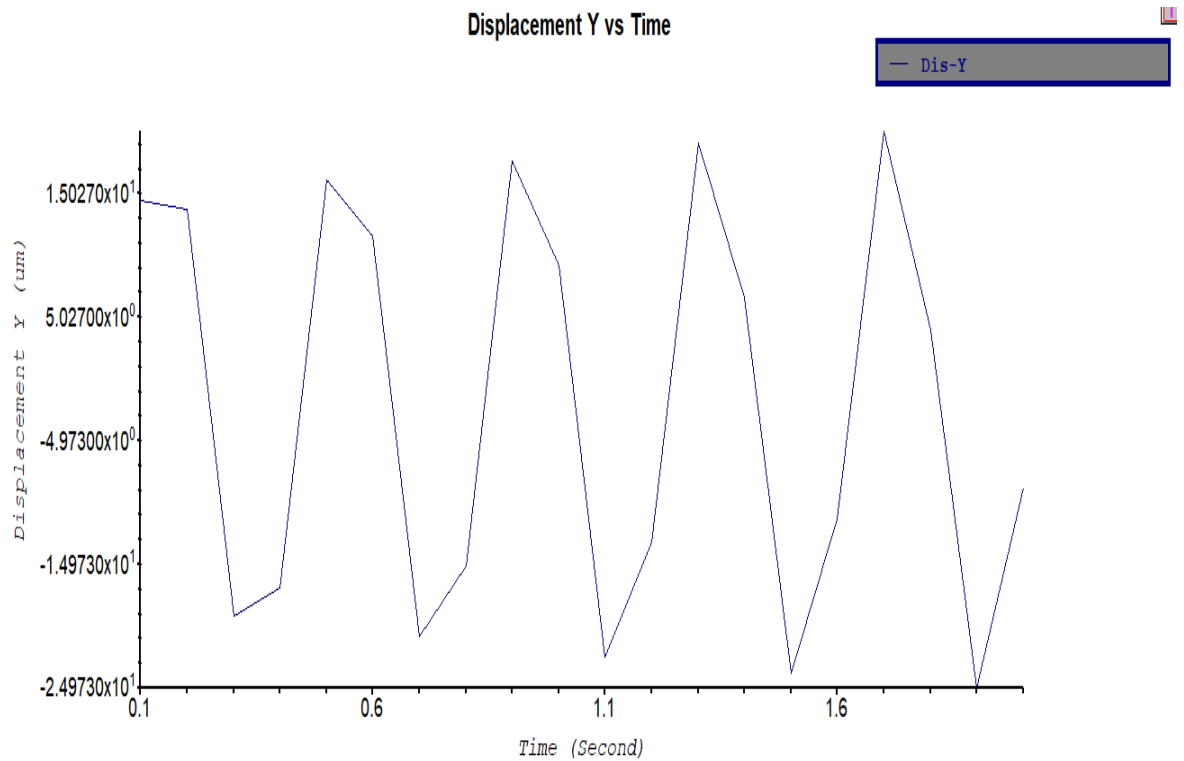
Face 188 is Selected

Define Applied Voltage Curve

$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t0	0	sec
W	6	rad/sec
A0	0	Volt
A1	10	Volt
B1	10	Volt

Figure 13: AC Analysis graph at $w = 6$ rad/sec



IntelliSuite, IntelliSense Software Corporation(c)

Amplitude Definition

Face 188 is Selected

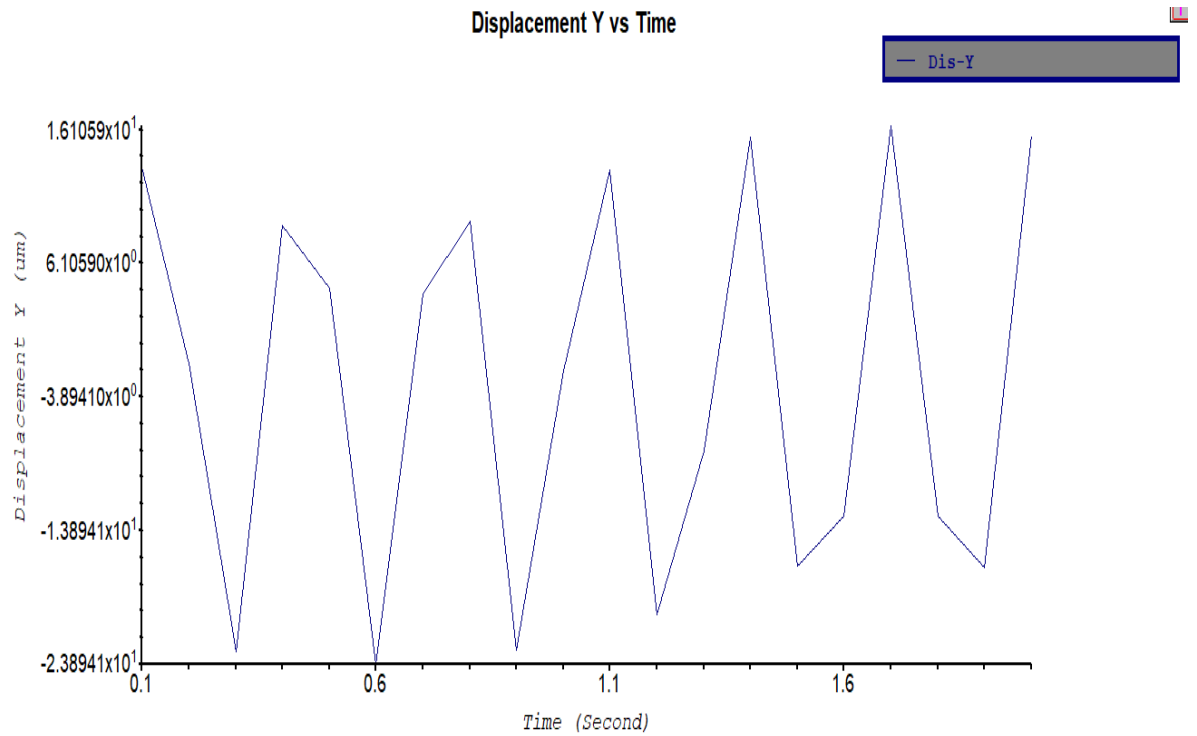
Define Applied Voltage Curve

$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t_0	0	sec
W	8	rad/sec
A_0	0	Volt
A_1	10	Volt
B_1	10	Volt

OK Cancel

Figure 14: AC Analysis graph at $w = 8$ rad/sec



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Amplitude Definition

Face 188 is Selected

Define Applied Voltage Curve

$A = A_0 + A_1 \times \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t0	0	sec
W	10	rad/sec
A0	0	Volt
A1	10	Volt
B1	10	Volt

OK Cancel

Figure 15: AC Analysis graph at $w = 10$ rad/sec

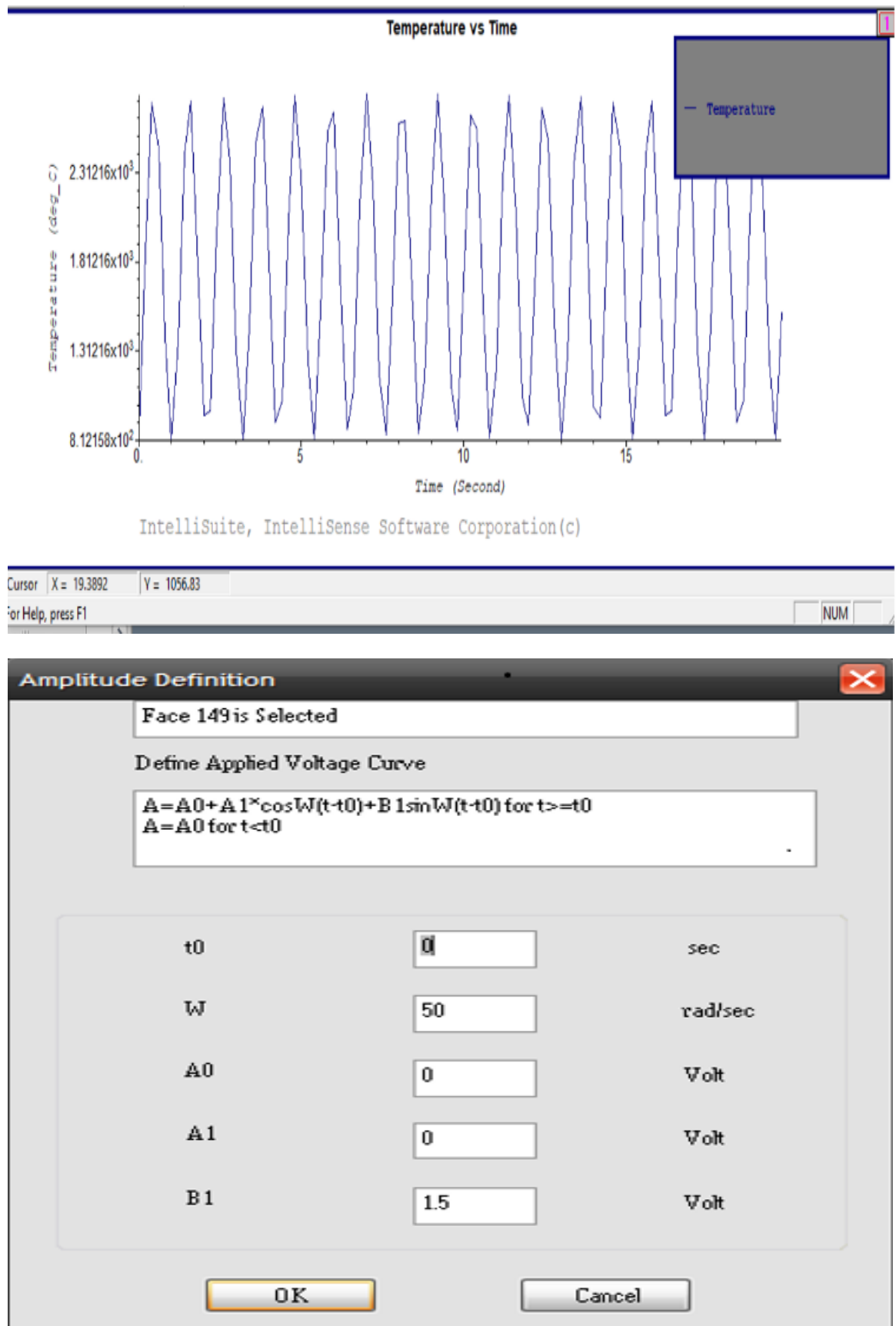
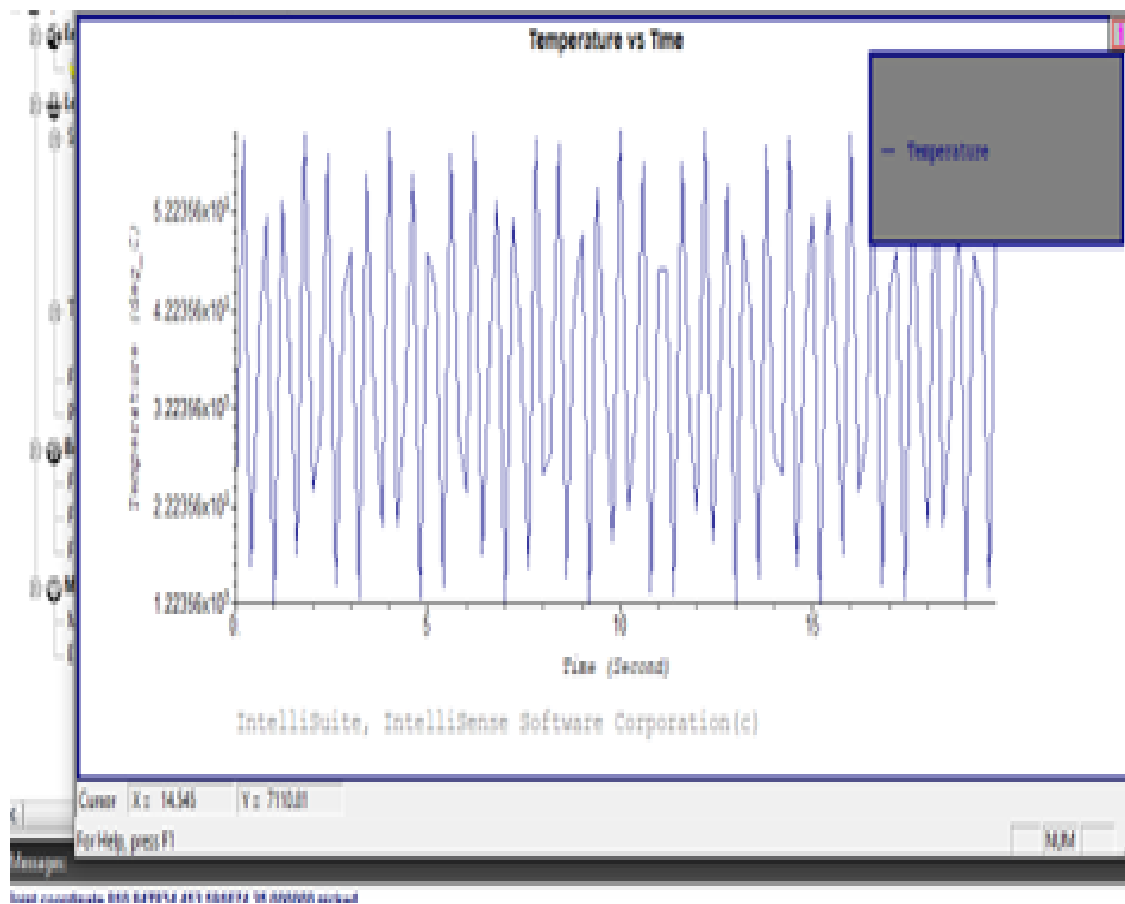


Figure 16: AC A nalysis graph at $w = 50$ rad/sec



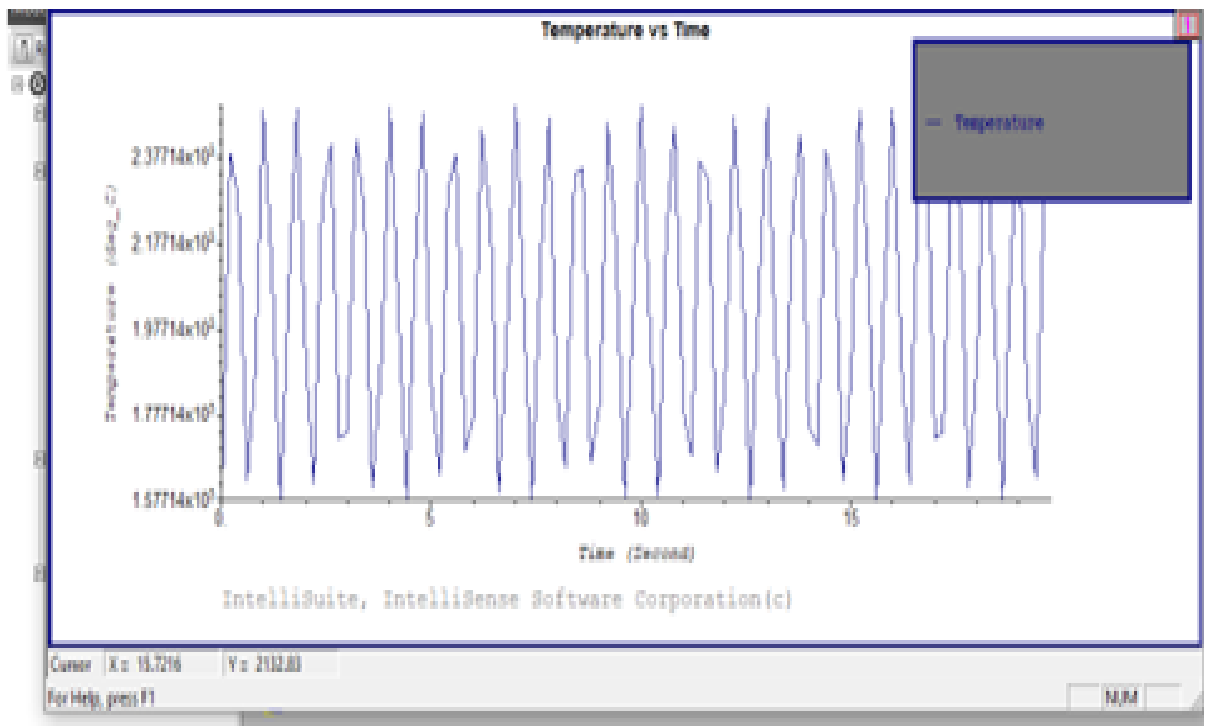
Face 149 is Selected

Define Applied Voltage Curve

$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t0	0	sec
W	100	rad/sec
A0	0	Volt
A1	0	Volt
B1	1.5	Volt

Figure 17: AC Analysis graph at $w = 100$ rad/sec



Amplitude Definition

Face 149 is Selected

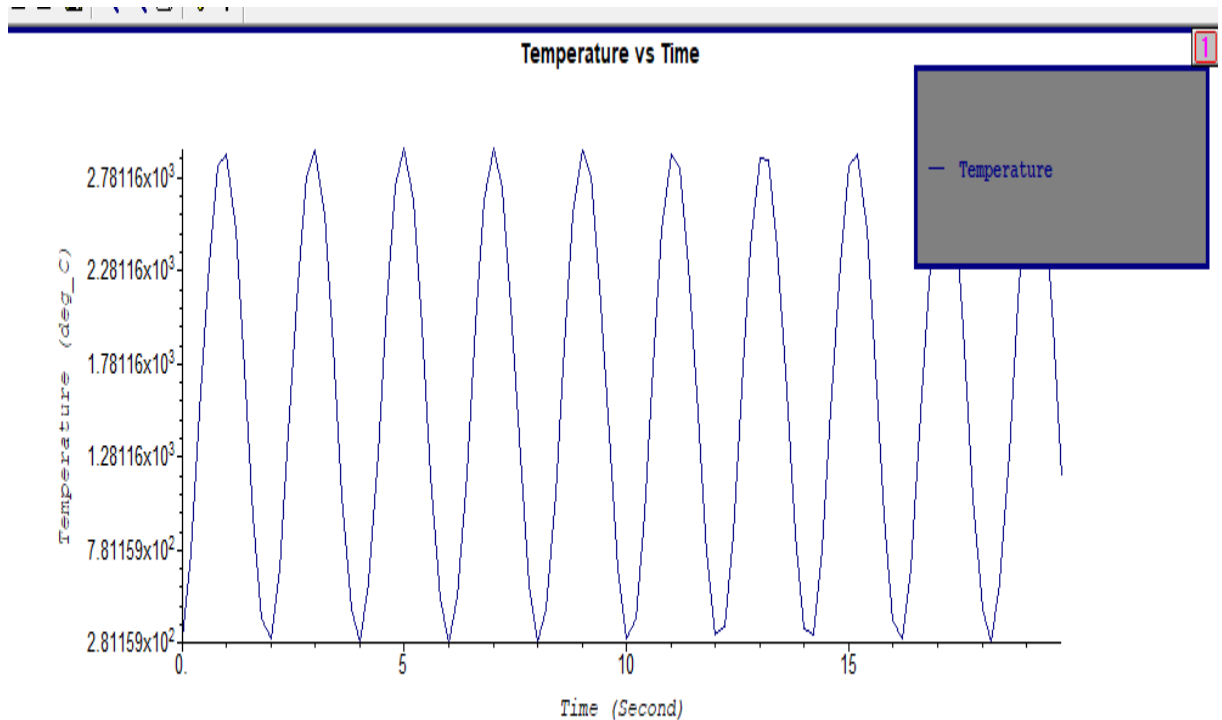
Define Applied Voltage Curve

$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0)$ for $t \geq t_0$
 $A = A_0$ for $t < t_0$

t_0	0	sec
W	200	rad/sec
A_0	0	Volt
A_1	0	Volt
B_1	15	Volt

OK Cancel

Figure 18: AC Analysis graph at $w = 200$ rad/sec



IntelliSuite, IntelliSense Software Corporation(c)

The "Amplitude Definition" dialog box is shown, with "Face 149 is Selected" in the top field. The "Define Applied Voltage Curve" section contains the following equations:

$$A = A_0 + A_1 \cos W(t-t_0) + B_1 \sin W(t-t_0) \text{ for } t \geq t_0$$

$$A = A_0 \text{ for } t < t_0$$

The parameters are defined as follows:

Parameter	Value	Unit
t_0	0	sec
W	300	rad/sec
A_0	0	Volt
A_1	0	Volt
B_1	1.5	Volt

Buttons for "OK" and "Cancel" are located at the bottom.

Figure 19: AC Analysis graph at $w = 300$ rad/sec

The right side of the structure (face 188) is grounded at 0 V, whereas the left side (face 149) is at 5 V. The electrostatic or thermal force produced by this voltage differential causes the structure to deform. The system has reached equilibrium and inertial impacts are negligible because the simulation is based on static conditions. The left side (with 5 V) flexes toward the center due to the electrostatic or thermal expansion action. This can be attributed to electrostatic attraction or Joule heating, depending on the mechanism. The "red zone" on the displacement map, which is the heart of the structure, has the most displacement and is most likely the least constrained or most compliant area. The right side (blue region) remains stationary with minimal motion at 0 V. This is consistent with the voltage induced actuation that primarily occurs on the left side of the structure. The extent of the relocation. The color legend indicates that the displacement ranges from 0 μm (blue) to about 0.035 μm (red). The moderate displacement values suggest a micro scale actuation, which is common in MEMS devices. The top, left, and right faces receive a constant temperature load of 50°C. This reference temperature probably serves as the initial value for future resistive heating and structural deformation studies. If the material has a high coefficient of thermal expansion, the applied temperature load may produce structural expansion, which would increase the deformation. Uniform temperature loading ensures that the thermal boundary conditions remain consistent throughout the simulation. A periodic voltage application, initially set at 5 V, is applied to the left face. The periodic form of the simulation suggests that its goal is to investigate the dynamic behavior of the structure when the voltage is alternating or oscillating. The combination of the resistive material properties and the applied voltage causes Joule heating (I^2R losses). When combined with the base temperature of 50°C, this creates a heat gradient that drives further structural deformation or mechanical actuation. Stress generated in the structure was

recorded maximum to be 741.9MPa at the joining portion of the shuttle and inclined thermal actuator portion. Whereas Figure represent various contour plots of the stresses generated throughout the structure on $w = 4$ rad/sec, $w = 6$ rad/sec, $w = 8$ rad/sec, $w = 10$ rad/sec, $w = 50$ rad/sec, $w = 100$ rad/sec, $w = 200$ rad/sec, $w = 300$ rad/sec represent the reaction forces in the X, Y, and Z directions respectively and results depicts in the form of graphs separately. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly. Reaction forces are the forces that a microstructure experiences in response to an external load or input. These forces can be broken down into three components: forces in the X, Y, and Z directions. In the X direction, reaction forces refer to the forces that the microstructure experiences in response to a load applied in the X direction. These forces act perpendicular to the X axis and can include compression or tension forces which shows that the structure experience maximum force at the top and the bottom sides of the anchor. In the Y direction, reaction forces refer to the forces that the microstructure experiences in response to a load applied in the Y direction. These forces act perpendicular to the Y axis and can include compression or tension forces which shows that the structure experience maximum force at the bottom side of the anchor. In the Z direction, reaction forces refer to the forces that the microstructure experiences in response to a load applied in the Z direction. These forces act perpendicular to the Z axis and can include compression or tension forces. It is important to note that the reaction forces in each direction are interdependent, meaning that a load applied in one direction can have an impact on

the forces experienced in the other directions. For example, a load applied in the X direction can create tension forces in the Y and Z directions as well. Therefore, it is crucial to consider the reaction forces in all three directions when designing and analyzing microstructures to ensure optimal performance and durability. These values are smaller than the yield strength of the silicon material 1.97GPa, thus enabling the structure to work properly under safe limits. The force at the jaw was simulated to be 13.32mN by declaring the jaw end as fixed in boundary condition settings. The whole structure is optimized around the maximum stress being generated in the structure with a considerable amount of displacement at the jaws. The hybrid chevron thermal actuator is responsible for the larger displacement with high force at the jaw end through its combination of linear and chevron thermal actuators. The actuator is fixed at three terminal ends which enables it to only produce upward motion. The inverted chevron structure present in the actuator adds up the force in the shuttle to produce a large force with a large displacement. The microgripper is operated at 4V and is designed in such a way that it uses the sensing electrostatic comb drives as an effective heat sink and reduces its temperature of 432.95°C in the thermal actuator to 90.40°C at jaws. This temperature is low enough to handle the test object and test it for measuring its rupture force.

CHAPTER FIVE

RESULT AND CONCLUSION

According to Static result it shows a nonuniform displacement along the microstructure is depicted in the simulation; this is most likely the consequence of applied forces or actuation. The middle shows the largest displacement (red region), but the ends show minimal movement (blue regions), suggesting fixed boundary conditions. The results show how the structure responds dynamically to specific loading scenarios and how it behaves mechanically. On the other hand, Dynamic shows the microstructure's deformation behavior under applied forces or boundary constraints is revealed by the study. Near the center of the structure, there is a noticeable displacement, suggesting that this is a vital point of mechanical stress or deflection. Consistent boundary conditions and uniform force application are suggested by the symmetrical displacement pattern. Hybrid thermal Micro-actuator are microscale devices that combine different actuation mechanisms, typically thermal and another type like electrostatic, electromagnetic, or piezoelectric actuation, to produce movement or force at the micro-scale. These actuators leverage the thermal expansion properties of materials when heated to induce movement, while the secondary actuation mechanism can enhance performance, control, or efficiency. Hybrid thermal micro-actuator have gained a lot of attention recently because of its prospective uses in a range of MEMS, including micro scale robotics, biomedical devices, and precision instruments.

5.1 Conclusion

The analysis of the AC was performed in IntelliSuite using a full-scale simulation modeling and applied three coupled solvers. In particular, the TEM (Thermo Electro Mechanical) module performed an AC harmonic analysis in the range of frequencies (1 Hz to 100 Hz) with nonlinear resistivity effects. There were certain boundary conditions of the simulation. Convection cooling was done on all surfaces, where ambient temperature was maintained at 50°C. The anchors were fully connected in a mechanical sense, i.e. zero displacement in all directions ($U_x=U_y=U_z=0$) and symmetry was applied where necessary. Current study is an alternating current (AC) analysis of a hybrid thermal micro-actuator, which builds upon previous DC based studies and investigates the dynamic behavior of the device through Intellisuite software. Although the frequency response of the actuator (1 Hz-100 Hz) was already demonstrated in the original work (12.04 μm at 264.7 mW DC power) through the experiment, the frequency response of the actuator was systematically studied, transient thermal behavior, and power efficiency of the actuator during the AC excitation. For this purpose a finite element analysis (FEA) used. This analysis shows that AC driving consumes less power (by 3.6 percent) and allows response times to be 86 times quicker, and is suitable to high-speed micro grippers and resonant MEMS devices. It is clear that Hybrid Thermal micro-actuator design is suitable for low to moderate frequency MEMS applications requiring reliable and controlled actuation. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly. To depict the

simulation of the Thermo Electro Mechanical (TEM) IntelliSuite software used. Material properties are assigned from the material database, boundary conditions were assigned in the simulation settings. The sink temperature of 50°C is set on the fixed end of the structure. A proper mesh size of 5 μm was selected by running iterations. A supply of 0-10 V was selected according to the material properties used in the software as it will be providing 252.6mW power to the device which is comparable to the experimental power of 264.7mW. Free convection was applied to the complete structure. This analysis shows that AC driving consumes less power (by 3.6 percent) and allows response times to be 86 times quicker, and is suitable to high-speed micro grippers and resonant MEMS devices. It is clear that Hybrid Thermal micro-actuator design is suitable for low to moderate frequency MEMS applications requiring reliable and controlled actuation. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly. More displacement can be achieved with this technique at relatively low voltages. The AC driven hybrid thermal actuator represents a significant advancement in MEMS actuation technology, successfully combining the large displacement characteristic of thermal actuators with the speed and reliability demanded by modern microsystem applications. Current study is an alternating current (AC) analysis of a hybrid thermal micro-actuator, which builds upon previous DC based studies and investigates the dynamic behavior of the device through Intellisuite software. Although the frequency response of the actuator (1 Hz-100 Hz) was already demonstrated in the original work

(12.04 μm at 264.7 mW DC power) through the experiment, the frequency response of the actuator was systematically studied, transient thermal behavior, and power efficiency of the actuator during the AC excitation. For this purpose a finite element analysis (FEA) used. This analysis shows that AC driving consumes less power (by 3.6 percent) and allows response times to be 86 times quicker, and is suitable to high-speed micro grippers and resonant MEMS devices. It is clear that Hybrid Thermal micro-actuator design is suitable for low to moderate frequency MEMS applications requiring reliable and controlled actuation. AC Analysis result at low frequency displacement were 6.20 to 8.10 μm at 10 to 50 Hz and at high frequency displacement were as 2.30 to 3.90 μm at 200 to 500 Hz. These findings collectively unlock broad application potential, enabling new capabilities in biomedical micro grippers, adaptive optics, and resonant sensors, and offering a scalable, reliable architecture for industrial micro assembly. This technological advancement opens up new possibilities for optimizing the design and development of micro scale components and materials, leading to significant advancements in various field.

CHAPTER SIX

APPLICATION AND FUTURE WORK

6.1 Applications

The AC driven hybrid thermal actuator demonstrates exceptional potential across several application domains, leveraging its high speed and stable characteristics. For High Speed Micro grippers in Biomedical Applications, the actuator's 500 Hz operational capability enables precision cell manipulation with an 11.8 μ m displacement, allowing gentle handling of delicate samples while the reduced operating temperature (420°C vs 495°C DC) minimizes thermal damage. In MEMS based Adaptive Optics, the actuator offers significant advantages due to its phase stable performance, capable of providing 12 μ m stroke at 500 Hz update rates for real time wave front correction. The unique thermal mechanical coupling also makes the actuator suitable for resonant sensors and Energy Harvesting, enabling a 3 $\times$ lifetime extension for Quality Factor tuning in resonant mass sensors, and the 15% thermal gain enhances the efficiency of thermally actuated energy harvesters for converting waste heat. Its sharp 1.1 kHz cutoff frequency provides natural filtering for sensor applications. Finally, in Industrial Micro assembly, the reliability improvements derived from AC operation are highly valuable; reduced thermal stress enables over 300,000 operation cycles for pick and place systems, while the less than 2% displacement variation across the 100–500 Hz range simplifies control system design for precision alignment. The lower operating temperatures further improve performance in harsh vacuum and high temperature environments.

Application	Optimal Frequency	Displacement	Temperature	Lifetime (cycles)
Cell Manipulation	300 Hz	11.7 μm	435°C	>500,000
Adaptive Optics	500 Hz	11.8 μm	420°C	300,000
Resonant Sensors	1 kHz	10.2 μm	390°C	200,000
Micro assembly	100 Hz	11.9 μm	450°C	1,000,000

Table 4: Application-specific performance metrics

6.2 Future Work

The AC driven hybrid thermal actuator represents a significant advancement in MEMS actuation technology, successfully combining the large displacement characteristic of thermal actuators with the speed and reliability demanded by modern microsystem applications. Looking forward, three key directions emerge for further development: the implementation of advanced control systems, such as predictive algorithms, will be necessary to compensate for phase lag in closed loop operation; material enhancements must focus on investigating silicon carbide and diamond substrates to enable stable operation above 1 kHz; and finally, monolithic integration is required to develop CMOS compatible versions featuring on chip drive electronics. The comprehensive characterization presented in this study thus provides not only immediate design guidelines but also a robust foundation for future development in dynamic thermal MEMS devices and AC analysis can be performed with different ways and values to manipulate better results in future.

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