TECHNICAL DESIGN AND SIMULATION OF A SCANNER BASED ON PIEZOELECTRIC ACTUATOR

A Thesis

by

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Submitted to the
Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical and Electronics Engineering

Özyeğin University
June 2024

TECHNICAL DESIGN AND SIMULATION OF A SCANNER BASED ON PIEZOELECTRIC ACTUATOR

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Eşime ve Aileme ...

ABSTRACT

Microelectromechanical systems (MEMS), offers compact and tailored solutions for a wide variety of applications such as laser beam guidance, tomography, microfluidic control, laser-based displays, LIDAR. These advantages of MEMS technology are important for the efficiency of the designed systems. This thesis aims to develop a scanner with high scanning frequency and scanning angle moved by a PZT-4 thin film. Our thesis focuses on optimizing the designed system using finite element modeling. With this modeling, the movements resulting from the electrical input applied to the PZT-based actuator are evaluated. Additionally, with finite element modeling, the stress distribution on the system and its natural mode oscillations are examined. In out-of-phase motion, the system was operated with 100V at a mechanical resonance frequency of 91 kHz. In-phase movement is at 208 Hz levels. This movement adds depth to the scan. Under these operating conditions, a scanning angle of 12.5 degrees is achieved. The width of the mirror is made is 0.66 mm. Mechanical deformations occur as a result of the system operating at high frequency. The theoretical calculation shows that 70 % of the existing mirror surface can be used efficiently. According to theoretical calculations, the power consumption of the system is around 1.5 mW. The designed system is intended to be used in applications where speed is needed, such as laser projectors and medical applications.

ÖZETÇE

Mikroelektromekanik sistemler (MEMS), lazer ışını rehberliği, tomografi, mikroakışkan kontrol, lazer tabanlı ekranlar, LIDAR gibi çok çeşitli uygulamalar için kompakt ve özel çözümler sunar. MEMS teknolojisinin bu artıları, tasarlanan sistemlerin verimliliği için önem arz etmektedir. Bu tez, bir PZT-4 ince film ile hareket ettirilen yüksek tarama frekansına ve tarama açısına sahip tarayıcı geliştirmeyi amaçlamaktadır. Tezimiz, sonlu eleman modelleme kullanarak tasarlanan sistemi optimize etmeye odaklanmaktadır. Bu modelleme ile PZT tabanlı aktüatöre uygulanan elektrik girişi ile ortaya çıkan hareketler değerlendirilir. Ayrıca sonlu eleman modelleme ile, sistemin üzerindeki stres dağılımı ve doğal moddaki salınımları incelenir. Faz dışı harekette sistem, 91 kHz mekanik rezonans frekansında 100V ile çalıştırılmıştır. Faz içi hareket ise 208 Hz seviyelerindedir. Bu hareket, taramaya derinlik katmaktadır. Bu çalışma şartlarında 12.5 derecelik bir tarama açısı sağlanmıştır. Aynanın genişliği 0.66 mm'dir. Sistemin yüksek frekansta çalışması sonucu mekanik olarak deformasyonlar ortaya çıkmaktadır. Yapılan teorik hesaplama, mevcut ayna yüzeyinin 70 %'nin verimli bir şekilde kullanılabileceğini göstermektedir. Teorik hesaplamalara göre sistemin harcadığı güç tüketimi 1.5 mW seviyelerindedir. Tasarlanan sistemin lazer projektörler, medikal uygulamalar gibi hıza ihtiyaç duyulan uygulamalarda kullanılması hedeflenmektedir.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my thesis advisor, Asst. Prof. Gokturk Poyrazoglu. I would like to thank Prof. Hakan Urey and everyone who provided their support during my graduate study journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The term 'piezoelectric' is of Greek origin, with 'piezo' meaning 'to press' and refers to electricity generated by the effect of pressure. The Curie brothers conducted studies on whether a physical factor such as pressure would reveal an electric charge on the surface of the crystal. This phenomenon, discovered by the Curie brothers in the 1880s, rapidly evolved into a burgeoning field of research towards the end of the 19th century [1]. And while this field was developing it was acknowledged that electrical charges were generated in a manner correlated with a mechanical force [2]. The aforementioned acceptance encompasses the revelation that the applied pressure occurs, charges emerge on opposing surfaces of the crystal, and the magnitude of the produced electric charge related to the surface area of the crystal. (Due to the asymmetric arrangement of positive and negative charges, a permanent dipole occurs in the crystal structure.) After this acceptance shortly, the phenomenon of inverse piezoelectricity is a comparative geometric strain when a voltage is applied, was observed. With the discovery of these two phenomena, subsequent experiments continued to prove that the deformation occurring in piezoelectric crystals was reversible. Since that time, one of the best and most widely used piezoelectric materials has been quartz. During the years of World War II, piezoelectric ceramics were discovered. These ceramics were found to have a much better piezoelectric effect than quartz when high voltage was applied. Since this discovery, it became extensively utilized in transducers and sensors. In the 1950s, it was found that a solid solution could form between PbTiO3 and PbZrO3, and that this solid solution exhibited significantly enhanced piezoelectric properties. Currently, these solid solutions are referred to as PZT and are widely employed. The excellent and adjustable piezoelectric properties, high Curie temperature, and low sintering temperature have established the dominance of PZT in the application market. The high Curie temperature indicates that the crystal structure of the material will not easily deteriorate. Many currently existing piezoelectric materials and their applications are expected to continue continuous development and become environmentally friendly in the future. In order for these expectations to be realized, a thorough understanding of piezoelectric principles, particularly those of the widely available PZT ceramics, is crucial.

As the importance of PZT ceramics became widespread, they began to be used in igniters, alarms and transducers. With the increase in publications on piezoelectrics, the piezoelectric effect has found a wide place in sensor and actuator applications. In this context, it has been very useful in accurately collecting dynamically changing data in measurements involving mechanical variables such as pressure, acceleration, etc. The extensive use of PZTs as piezoelectric materials in MEMS actuators and scanners is an important opportunity for the development of systems based on the piezoelectric principle. Based on this opportunity, a scanner was designed by designing a PZT thin film-based actuator, which has become widespread in recent years for platforms such as LIDAR, laser projector, medical applications, etc., where working speed and scanning angle are very important. The design, which is based on the principle of movement of PZT thin film with an electric field, aims to enable the system to scan angularly at a high scanning speed and to be included in applications such as LIDAR. The designed system is aimed to be compact and to respond to requests quickly and with a wide range. It met these needs with a scanning frequency of approximately 91kHz and a scanning angle of ± 12.5 degrees. Additionally, theoretical calculations showed that the power consumption was at a very good level of 1.3mW. When the figure of merit analysis is made, it is in a very good position compared to its competitors.

1.1 Motivation and The Scope of Thesis

The piezoelectric effect, discovered for the first time in history by the Curie brothers, combines electricity and mechanics. The opposite of this effect is also true. Piezoelectric materials have specific crystal orientations and deform along their orientation when exposed to an electrical signal. Today, PZT is the most widely used piezoelectric due to its low production cost and high performance. Piezoelectric devices are among the indispensable parts of our daily lives. They are in very high demand in the global market. Therefore, piezoelectric-based actuators provide very important contributions. These actuators stand out among other actuators working with different principles due to their high sensitivity, compact and flexible structure and low power consumption, and they stand out in optical and micro electromechanical systems. Although piezoelectric-based activation has various advantages in MEMS-based scanners compared to other types of scanners that work according to different principles, it was not widely used in the past due to the insufficient development of production techniques. With the development of production techniques, piezoelectric materials could be deposited in thin film form and attracted attention. Piezoelectric-based MEMS actuators were first realized with materials such as ZnO, etc., which also have piezoelectric properties. Although these materials are more convenient to produce and deposit, PZTs have become a favorite of MEMS scanners because PZTs exhibit better piezoelectric performance when they have the same size thickness.

Compact size and high operating frequency are crucial considerations for these systems. To address these needs, a system with a significantly miniaturized mechanical structure was designed. This design enables achieving high operating frequencies due to the reduced system mass. Furthermore, the design aims to enhance system efficiency by achieving a wide scanning angle, thereby simultaneously fulfilling both critical requirements. The study was tested in a simulation environment. Afterwards, the aim is to produce and test the design.

1.2 Thesis Outline

As a result of the motivation in our thesis, an extensive literature was included in Chapter 2 in order to better understand the subject. Chapter 3 , briefly describes its applications. In Chapter 4, the piezoelectric-based actuator for scanning design is briefly mentioned and the results are given. In the last chapter, the results are discussed and evaluated for future studies.

CHAPTER II

LITERATURE REVIEW

The desire to increase efficiency and reduce the size of designed systems was an important factor in MEMS technology coming to the fore in scanning technologies. Systems such as LIDAR, which work based on the scanning principle, are systems in which MEMS technology predominates and were first used in the 1960s [3]. With the emergence of the idea of using lasers in similar years, MEMS-based scanners found a place in a wide range of fields such as barcode reading and imaging in the medical field, in addition to LIDAR etc. systems. With the development of such systems, the goal has been to develop browsers with high performance. As seen in Figure (1), there are many platforms with MEMS-based structures. MEMS structures placed in complex systems are important for the efficient operation of the systems and play a critical role.

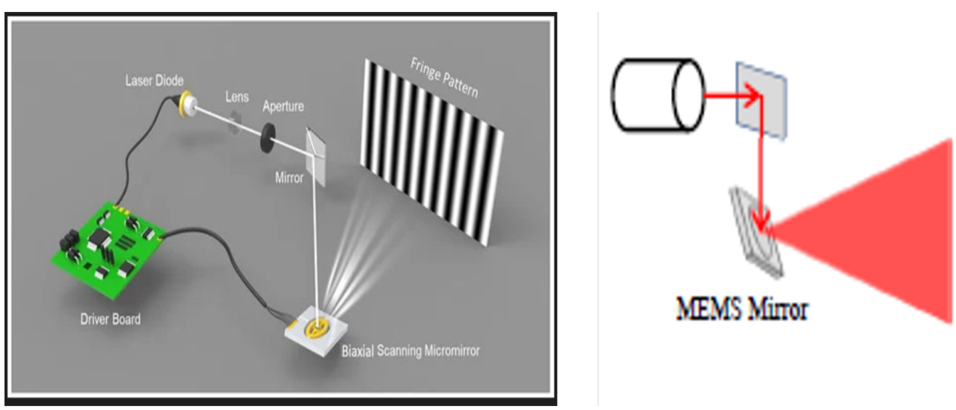

Figure 1: Examples of MEMS Mirror [4][5]

Many of the systems such as laser scanners, LIDAR, and communication systems are systems that use micro mirrors that move angularly by directing the light to create images, etc., as seen in the figure above. MEMS technology is a field that combines electrical and mechanical factors on a microscale. Piezoelectric materials can be miniaturised using MEMS technology, offering the potential to produce high-function, low-cost devices. MEMS mirrors have critical features such as being small and directing light in an empty space. With the mentioned features, MEMS mirror-based scanners have outstanding features compared to other scanner types when comparing scanning speed, compact structure and production costs [5]. Appropriate power consumption and the design of a system with a fast scanning frequency are among the difficulties encountered in actuator design. In recent years, different operating types for MEMS scanners and methods of driving these scanners have been seriously studied. Each researched study has its own advantages and disadvantages. As mentioned before, there are many factors that affect the performance of actuator-based MEMS mirrors. Based on these factors, a definition called FoM is used to understand to what extent MEMS mirrors are suitable for their application areas (Figure of Merit). Depending on the type of application area, this definition includes definitions such as optical scanning angle, power consumption, actuator temperature, width of the scanning mirror and operating frequency. In our thesis study, as shown in Equation (1) the figure of merit is the product of the distance of the scanning mirror to the rotation point, the scanning angle and the resonance frequency.

$$FoM = \theta * d * f \tag{1}$$

In addition to the factors in the definition of Figure of elevation, the mirror surface used can remain flat against dynamic movements. This factor is also very important in order to gain maximum benefit from the light used while scanning. θ, one of the FoM parameters we used, expresses the optical scanning angle in radians, but we calculated it in degrees in our thesis study. The part shown as d represents the distance to the rotation point of the mirror and is expressed in mm. f is defined as kHz and is the resonance frequency of the MEMS mirror.

Both fast and slow axis scanning are very important for MEMS scanners. The scanning speed of the slow axis determines the scanned frame rate. The resolution of the scan is related to the frequency of the fast axis. The variation of these two frame rates and resolution is very important for scanners [5]. High resonant frequency is very important for fast scanning, high resolution and more robust performance and is defined as follows:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

Above Eq. (2) defines a spring frequency. We can compare the movement of the MEMS mirror to a spring. Therefore, m in the above equation represents the mass of the MEMS mirror and k represents the spring constant of the MEMS mirror. In ideal conditions, the MEMS mirror should operate exactly at the resonance frequency, with a constant angular sweep and a constant phase delay. Changes in environmental conditions or resulting stresses may cause deviations in the resonance frequency of the MEMS mirror.

Scanner size is very important in systems such as LIDAR, where the MEMS scanners we talked about are used extensively. The importance of size and weight becomes even more important in systems such as robotic mobile platforms. The weight of Hokuya UST-10LX, which attracts great attention in such applications, is 130 g [6].

Scanners have different working principles. Each working principle has its own advantages and disadvantages. Although the piezoelectric-based operating principle offers various advantages over other operating principles in MEMS scanners, it has not been used frequently compared to other operating principles due to insufficient production techniques. With the development of manufacturing methods, piezoelectric materials have become common for MEMS scanners. The first breakthroughs in producing piezoelectric-based MEMS scanners were made with materials such as ZnO and AlN. Although they are easier to form into thin films than PZT, PZT produces much more force at the same thickness [7]. Because of this feature, PZTs have become very popular for MEMS scanners.

PZT-based scanners produced with thin film technique are more efficient by consuming lower power than other operating principles. Additionally, they have smaller dimensions [8]. Piezoelectric-based actuators induce current by changing their polarization upon application of voltage. This current is proportional to the deflection speed. By monitoring the change in this current, the speed of the actuator is revealed and the total deviation can be calculated. This way they can also be used as angle sensors for scanners [9]. In addition to its advantages, deviations of a certain size in PZT-based scanners emerge as a significant problem since wide angle is needed in applications requiring high resolution.

In addition to the above mentioned, the power consumption of piezoelectric-based scanner systems depends on the factors included in Eq. (3) mentioned by Ledermann in his publication [10]. Power consumption depends on the actuation frequency, capacitance of the piezoelectric material, loss factor and actuation voltage.

$$P = \omega.C.tan\sigma.V^2 \tag{3}$$

Here ω represents actuation frequency, C represents capacitance, $\tan\sigma$ represents loss factor and V represents actuation voltage. When tension is applied to piezoelectric materials, the charges inside are reoriented and a potential occurs on the surface. The ability to store the charge on the surface determines the capacitance of the material. Loss factor describes the amount of energy dissipated as heat within the material when it is under mechanical or electrical stimulation. This value is an important factor in terms of performance.

Resonance MEMS scanners are promising structures with their piezoelectric-based working principle, wide angle and simpler structures. In recent years, significant research has been done for the development of this type of browsers. In cases where the frequency at which the produced PZT-based scanners operate is high, the limited movement of damping and structure poses a challenge for piezoelectric-based structures.

In 2005, Smit and his colleagues succeeded in developing one of the scanners powered by piezoelectric film. This scanner contained a 1.3mm mirror and required a voltage of 6V. With this structure, a scanning angle of ±10 degrees could be achieved by operating at a frequency of 17.4 kHz [11]. This structure, which is shown in Figure (2) and has various features, has also become a milestone for piezoelectric-based scanners.

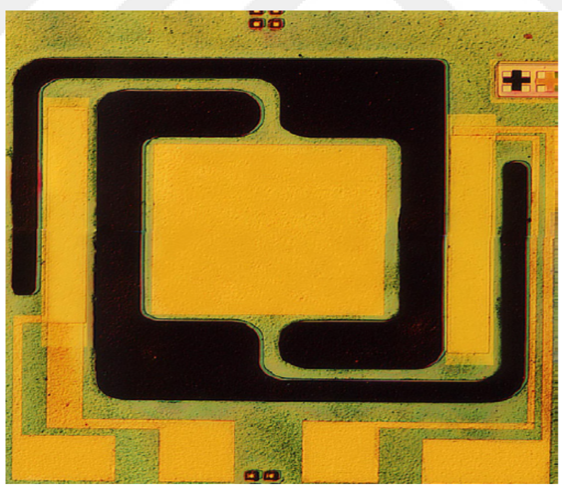

Figure 2: Microscope photo of the Smith's scanner [11].

CHAPTER III

PIEZOELECTRICITY

Piezoelectricity is a phenomenon where materials with these properties produce electric current when exposed to mechanical stress such as pressure or vibration, and vice versa. Due to the internal structure of piezoelectric materials, they have an atomic order that naturally creates polarization. When exposed to stress, their polarization changes and separation of charges occurs. This separation causes a potential difference and electric current.

3.1 Classification of Dielectric Materials

The dimensions of dielectric materials change physically by applying an external electric field to these materials. What causes this is the interchange of positive and negative charges within dielectric materials. When an electric field is applied to these materials, the positive charges in the material move in the same direction to the electric field, and the negative charges move in the opposite direction as the electric field. Deformation occurs due to this movement. Physically, the change in size can be large or small depending on the material.

Dielectric materials deform when exposed to an electric field due to their structure, regardless of the direction of the applied field. In dielectric materials with a non-symmetrical crystal structure, the ions in the material move unsymmetrical due to the electric field, which causes deformation. Such materials are called piezoelectric materials.Dielectric materials, grouped according to their properties, can be classified as in Figure (3).

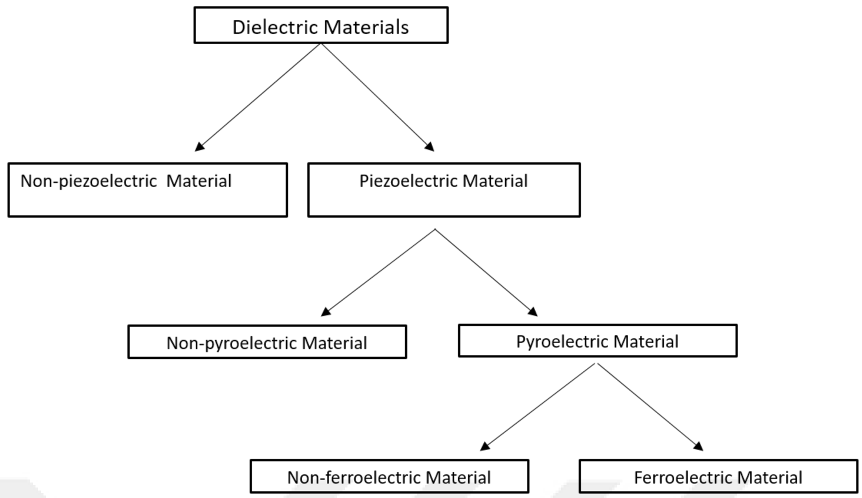

Figure 3: Categorization of Dielectric Materials

3.2 Important Dielectric Parameters

Dielectric parameters are parameters that define the properties of materials that interact with an electric field. Good dielectric parameters are important for the development of device designs.

3.2.1 Electric Polarization P

Electric polarization describes the separation of the centers of charge within a material. Shows the reaction of the material to the electric field. In a polar dielectric material, there are many atoms or molecules with electric dipole moments. Dipole moment is a phenomenon that occurs due to the distance between the charges within the atom or molecule. The total net moment of dielectric materials is equal to the vector sum of all dipole moments. The electric polarization P can be expressed as the total moment per unit volume.

In polar dielectrics, electric dipoles individually orient randomly, resulting in a net polarization of zero. However, upon the application of an external electric field, the dipoles align themselves in the direction of the electric field. "The polarization increases with an increasing electric field and attains saturation when all the dipole moments are oriented in the direction of the field "[12]. The saturation of the electric polarization is very important as it directly affects the stress intensity of piezoelectric ceramics [13].

Spontaneous polarization is the polarization that arises from the nature of the material, without the need for applying an electric field to the material. Changes due to thermal effects may cause changes in the polarization of materials. Ferroelectrics have spontaneous polarization. They have polarization even if no external electric field is applied.

3.2.2 Dielectric Displacement or Flux Density D, Dielectric Constant ε_r, and Electric Susceptibilty χ

The displacement of electric charges with the applied electric field is called dielectric displacement. The applied electric field causes a change in polarization. This definition has an important place in the design of electronic devices. The electric current occurring in the material due to the electric field or displacement of dielectrics is expressed as in Eq. (4).

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \tag{4}$$

ε_0 represents the permittivity of free space. Permittivity of free space describes the interaction of electric charges with each other and how the electric field propagates in space. Additionally, Equation (4) can also be expressed as in Equation (5).

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 \varepsilon_r \vec{E} \tag{5}$$

ε_r is the dielectric constant, and its unit is C/m^2. Dielectric constant expresses the degree to which the applied electric field can polarize the material. The high dielectric constant means that the material can be polarized easily.

Polarization is the rearrangement of charges in the material by the electric field. In piezoelectric actuator and sensor systems, the strength of the piezoelectric effect is directly proportional to the polarization. By accurately controlling polarization, dipole directions can be adjusted and sensitive systems can be developed [14]. Polarization is directly related to the externally applied electric field, as stated in Eq. (6).

$$\vec{P} = \varepsilon_0 \chi \vec{E} \tag{6}$$

where χ is the electric susceptibility. Electric susceptibility is basically the material's response to an electric field. It explains how much polarization the applied field causes in the material.

3.3 Piezoelectric Effect

Non-symmetrical dielectric materials are called piezoelectric materials. Deformation occurs due to the non-symmetrical displacement of anions and cations in the material with the electric field. Due to this deformation, a strain is generated. This strain occurring in piezoelectric materials either expands or compresses the material depending on the direction of the electric field. This is called indirect piezoelectric effect.

When external stress is applied to piezoelectric materials, electric dipoles within the material create an electric field by creating positive and negative charges. This is called the direct piezoelectric effect.

The poling voltage across a poled piezoelectric material is shown in Figure 4(a). When an external tensile voltage is applied towards the endpoints of the material, it develops a voltage across its face with the same polarity as the polarity voltage like shown in Figure 4(b). However, as shown in Figure 4(c) when compressive stress is applied to the material, voltage is produced in the opposite direction to the polar voltage. The poling voltage across a poled piezoelectric material is shown in Figure

4(a). When an external tensile voltage is applied towards the endpoints of the material, it develops a voltage across its face with the same polarity as the polarity voltage like shown in Figure 4(b). However, as shown in Figure 4(c) when compressive stress is applied to the material, voltage is produced in the opposite direction to the polar voltage. As shown in Figure 5(d), when a DC field is applied in the same direction as the polarization direction, tensile stress is induced in the material. When a DC field is applied in the opposite direction, compressive stress is induced in the material like shown in Figure 5(e).

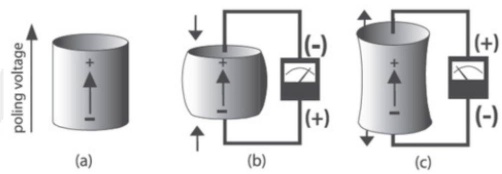

Figure 4: Direct Piezoelectric Effect [15].

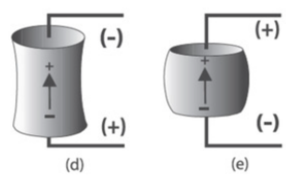

Figure 5: Reverse Piezoelectric Effect [15].

The direct and inverse piezoelectric effect has many applications because it involves the conversion of mechanical energy to electrical energy or vice versa, one of which includes sensors and actuators [12].

3.4 Ferroelectric Materials

Ferroelectric materials exhibit piezoelectric properties. Ferroelectrics exhibit spontaneous polarization and have polarization reversibility that can be reversed by an externally applied electric field.

3.4.1 Ferroelectric Domains and Hysteresis

A ferroelectric domain is a microscopic region within a material where there is a short-range strong interaction caused by internal electric fields. In ferroelectrics, each domain has a specific direction of polarization. When no external electric field is applied, the net polarization is zero because all the fields are randomly oriented. Upon the application of an external electric field, the domains rotate towards the direction of the applied electric field and grow. As a result, the material is directed to a single area. Ferroelectric fields play an active role in converting mechanical energy into electrical energy and vice versa. In actuator applications, the positioning of domains is of great importance in precise positioning systems [16]. The positions of ferroelectric fields determine the polarization of materials. Therefore, their behavior when exposed to an electric field is very important.

A ferroelectric domain is a microscopic region within a material where there is a short-range strong interaction caused by internal electric fields. Every field in ferroelectrics has a distinct polarization direction. When no external electric field is applied, the net polarization is zero because all the fields are randomly oriented. Upon the application of an external electric field, the domains rotate towards the direction of the applied electric field and grow. As a result, the material is directed to a single area. Ferroelectric domains play an important role in the conversion of mechanical energy into electrical energy and vice versa. In actuator applications, the positioning of domains is of great importance in precise positioning systems. Polarization is determined by the placement of the ferroelectric domains. Therefore, their behavior when exposed to an electric field is very important. The change of polarization with the applied electric field is shown in Figure (6).

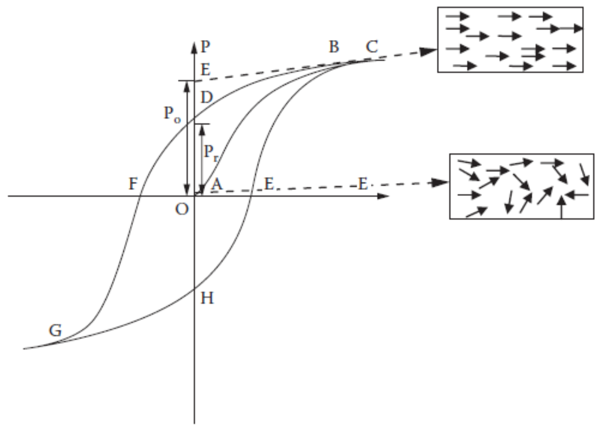

Figure 6: P and E curve [12].

When the externally applied electric field is zero, all of the fields are randomly oriented and the polarization is zero (point O). As the applied field increases, the domains align with the field direction, and initially, the polarization increases linearly. The portion of the curve represented by the OA segment is shown in the diagram. As the area is further increased, the number of directed domains increases and the curve ceases to be linear. And finally, when all the domains are oriented, the polarization reaches its maximum level (point B). Polarization at this level is called P0 (OE). If the applied electric field is gradually reduced, the polarization decreases but the curve does not recover in the same way. Polarization decreases quite slowly. The change in polarization is not as rapid as in the electric field. This change is shown by the BD part. When the electric field is reduced to zero, a finite amount of polarization remains, called P_r (OD). In order to eliminate the remaining polarization, an electric field must be applied in the opposite direction to the initially applied electric field. This is referred to as the coercive electric field (E_c). The polarization becomes zero at point F. If the applied field is increased further, the domains are oriented in the direction of the electric field and the polarization increases in the opposite direction. Polarization reaches the saturation value (P_S) in the opposite direction at point G. When the applied electric field is reduced to zero, the curve follows the GH path and is now in the form of polarization (P_R) at point H. When the field is increased in the positive direction, the remaining polarization disappears at point $+E_C$. Further increase in the applied field follows the E_CB path and closes the loop, known as the hysteresis curve.

3.5 Piezoelectric Characteristics and Coefficients

Piezoelectric materials convert mechanical energy into electrical energy and electrical energy into mechanical energy. In the direct piezoelectric effect, the input is mechanical energy and the output is electrical energy. The mechanical input is stress (X) or strain (x). Voltage (V), electric field (E) or surface density (D or P) is the electrical output. In the indirect piezoelectric effect, the input is mechanical energy and the output is mechanical energy. The surface charge density is in the form of electrical input, voltage or electric field. There are many coefficients that describe the properties of piezoelectric materials.

Piezoelectric parameters are important for sensor and actuator designs due to the relationship between mechanically generated voltages and electrical outputs and the reverse mechanism, electrical inputs and mechanical voltage outputs. The importance of these coefficients for applications is shared in detail in Ref [17].

In the direct action, the mechanical strain is mentioned in Eq. (7) and the electrically induced output is mentioned in Eq. (8).

$$D = ex \tag{7}$$

$$E = hx \tag{8}$$

In Eq. (9) and Eq. (10), mechanical voltage and electrical output are included.

$$D = dX \tag{9}$$

$$E = gX \tag{10}$$

The coefficients that directly concern the piezoelectric effect are the coefficients e, h, d and g. The working principle of piezoelectric materials is based on their relationship with mechanically acting stress and electric field. Coefficients are also used very well when explaining the relationship between stress and electric field. The coefficient d is related to the change between the applied mechanical stress and the electric field. The coefficient e is related to the relationship between the applied mechanical stress and electrical polarization. The coefficient h defines the relationship between applied electric field and mechanical strain. The coefficient g is related to the relationship between applied mechanical strain and electric current. The parameters that are related to each other in the piezoelectric effect are shown in detail in Figure (7). A summarized view of these coefficients is given in Table 1.

The parameter observed in the piezoelectric effect is not an absolute value, but rather a change in the parameter. In the direct piezoelectric effect, a change in strain ∂x (or stress (∂X) leads to a change in polarization (∂D) or a change in electric field ∂E).

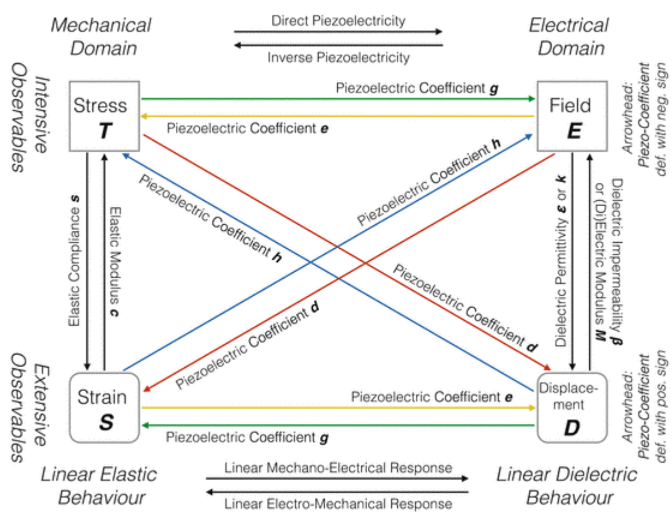

Figure 7: Relationships of piezoelectric coefficients [18].

Table 1: Piezoelectric Coefficients—Definitions and Units

Piezoelectric Coefficient	Definition	Unit
d	$\frac{polarization}{stress}$	C/N
g	$\frac{electricfield}{stress}$	V.m/N
e	$\frac{polarization}{strain}$	C/m^2
h	$\frac{electricfield}{strain}$	V/m

The following expressions can be written for the direct and indirect piezoelectric effect. The first equation below can be called the sensor equation and the second equation can be called the actuator equation.

Equation (11) and Equation (12) can be written for direct and indirect piezoelectric effect. Equation (11) is called the sensor equation, and Equation (12) is called the actuator equation. While the sensor equation defines the electric field resulting from the application of stress on the system, the actuator equation defines the stress resulting from the electric field applied to the system.

Under a constant stress;

$$D = dX + \varepsilon^X E \tag{11}$$

Here, ε^X denotes the permittivity under constant stress. The dielectric permittivity is a characteristic that expresses the degree of polarization experienced by a material more simply, it gauges how easily molecules in a substance can align themselves in the presence of an electric field. Permittivity is related to the ratio of the electric displacement in a material to the electric field that causes it. High permittivity leads to larger displacements of piezoelectric actuators with low power consumption as it enables a more efficient energy conversion. The relationship with the applied electric field is studied in detail in Ref [19].

The piezoelectric charge constant (d) expresses how much electric charge per unit is generated for each unit of applied mechanical stress on the material. Or it denotes the induced strain per unit of applied electric field. In short, it tells you how well it converts mechanical stress into electrical charge. The value of the coefficient d represents larger displacements or forces for actuator applications [20].

Under a constant electric field;

$$x = s^E X + dE \tag{12}$$

In this case, s^E elastic compliance constant. The most important parameter that characterize piezoelectric materials are the elastic compliance. This is related to stress. Elastic compliance defines the material's resistance to deformation when stress is applied to it. In actuator applications, the elastic compatibility of materials must be high. When a small electrical potential is applied, high deformation occurs [16].

The following expressions can be written for the direct and indirect piezoelectric effect. The first equation below can also be called the sensor equation and the second equation can also be called the actuator equation. These equations describe how piezoelectric materials convert mechanical stress into electric field or, conversely, the strain caused by the applied electric field.

In piezoelectric materials, Young's modulus and Poisson's ratio affect mechanical and electrical behavior. Young's modulus measures the material's resistance to deformation when it is under tension or pressure. The change of Young's modulus causes a change in the resonance frequency of the material. In Ref [21], the effect of changing Young's Modulus on the shift in the resonance frequency is discussed [21]. Poisson ratio expresses the ratio of transverse stress to longitudinal stress when a stress is applied.

3.6 Strain versus Electric Field in Piezoelectric Materials

Piezoelectric materials work by creating tension on the material with an electric field. This is known as the inverse piezoelectric effect. Although the strain shows a linear relationship when the electric field is first applied, it saturates later. When the electric field is gradually reduced, the strain does not decrease in the same way. The change in strain lags behind the electric field. This is due to piezoelectric materials that produce hysteresis loops when an electric field is applied. When positive and negative voltages are applied to these materials, the resulting curve creates a butterfly shape. This resulting shape is discussed in Figure (8).

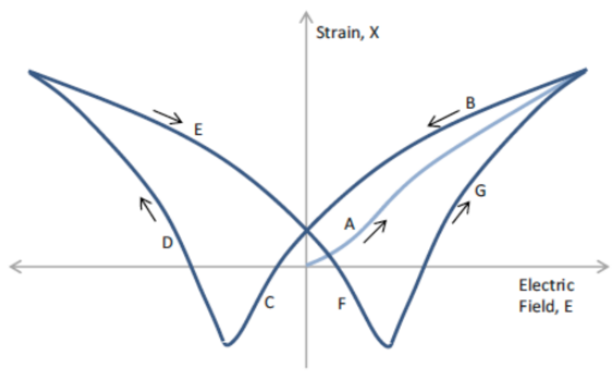

Figure 8: A strain vs. Electric Field curve for a typical piezo material [22].

The increase in strain in a piezoelectric material caused by an externally applied electric field is generally linearly proportional to the increase in the electric field (Path A). The highest level of strain relies on the saturation of polarization. As the electric field begins to decrease, the strain diminishes at a slower rate compared to the electric field (Path B). However, as the electric field begins to shrink, the strain decreases faster than the electric field (C path). The piezoelectric material reaches a point with the polarization completely reversing and the polarity in the material changes. In this way the strain increases again as the voltage becomes negative (Path D). When the electric field reverses again and becomes positive, the strain again decreases more slowly than the electric field (Path E). As the electric field becomes smaller and smaller, the strain decreases more rapidly (F Path). At a certain point, a point is reached where the polarization of the piezoelectric material suddenly changes, causing the material to expand in physical dimensions until it reaches its limits (Path G).

3.7 Piezoelectric Coupling Coefficient k

This factor is an indicator of the material's ability to convert electrical energy into mechanical energy or mechanical energy into electrical energy. This ratio is dimensionless. When designing piezoelectric devices, the k value is very important for good design and optimization. The calculation of this factor is given in Eq. (13). The importance of this factor in actuator design is discussed in reference [23].

This ratio is expressed as follows,

$$k^2 = \frac{Piezoelectric\, energy\, density\, stored\, in\, the\, material^2}{Electrical\, energy\, density\, x\, Mechanical\, energy\, density} \tag{13}$$

3.8 Dynamic Behaviour of a Piezoelectric Material

Piezoelectric materials possess the capability to produce a deformation that can be managed by applying an electric field, and conversely. A piezoelectric material can be thought of as a spring that has the ability to remain in balance through an electric field. When exposed to an AC electric field, the material undergoes changes in length. In other words, it vibrates. To comprehend the properties of such a material, an equivalent electrical circuit, encompassing both electrical and mechanical constituents, is established. This equivalent circuit is shown in Figure (9). The ability of piezoelectrics to produce and respond to vibrations is very important in sensor and actuator applications. It is very important to use this ability correctly. In Ref [24], the dynamic behavior of piezoelectric sensors is discussed in detail.

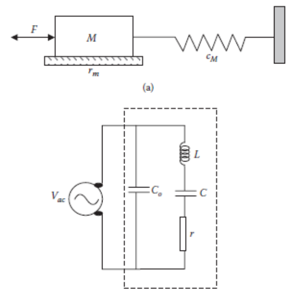

Figure 9: Equivelent Circuit [12].

Vibrating piezoelectric material can be depicted through either a mechanical system or an equivalent electrical circuit. In the mechanical system, F is the vibration applied to the system with mass M. r_m was the resistance due to friction. c_M is the mechanical spring constant. Vibration applied to the piezoelectric material behaves similar to alternating voltage. The piezoelectric material is characterized like a capacitor of the form C=$C_0 = \frac{\varepsilon A}{d}$, where epsilon represents the permittivity, A is the area of the material, and d is the material thickness. Inductance (L) corresponds to the mass (M) of the piezoelectric material, while compliance is equivalent to capacitance (C). Internal mechanical losses are also denoted by r. C_0 is the capacitance of the piezoelectric material. The behavior of piezoelectric materials within the system is modeled both electrically and mechanically. Impedance is important in electrical behavior. As shown in Figure (10), the point where the impedance is at its minimum is called the resonance frequency, and the point where it is at its maximum is called the antiresonance frequency.

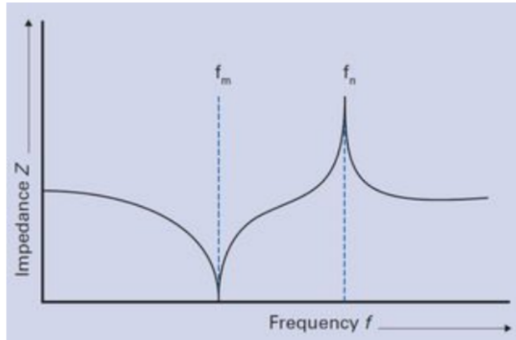

Figure 10: Resonance and anti-resonance frequencies in piezoelectric impedance frequency response [25].

In vibration-dependent systems, impedance depends on frequency. When the frequency reaches the resonance frequency, the system reaches maximum vibration. Assuming that there are no mechanical losses, the antiresonance frequency and the resonance frequency of the equivalent circuit are equal to each other.

3.9 Piezoelectric Materials

Piezoelectric materials are a type of dielectric material with non-centrosymmetric crystal structures. In this study, we chose the commonly used primary material, PZT, which will be further discussed in subsequent sections that will cover its properties and production.

3.9.1 Lead Zirconate Titanate (PZT)

PZT materials, which means Lead Zirconate Titanate, are widely used materials for transducer and actuator applications. Its explicit formula is PbZr(Ti)O_3 and the lead and titanium ratios in the formula may vary. PZT materials consist of lead (Pb), zirconium (Zr) and titanium (Ti) materials. There are lead ions at the corners of the unit cell of PZT, oxygen ions at the surface centers, and zirconium and titanium ions at the center of the volume. The location of zirconium and titanium ions is some distance from the center of the unit cell. For this reason, a permanent electric dipole occurs in PZT. In order for a material to exhibit piezoelectric properties, it must have a dipole moment.

PZTs have very important properties such as mechanical and piezoelectric properties. They can be prepared in the form of fine powder and can be produced in any desired physical shape. The coupling coefficient, k, is a crucial factor in understanding the characteristics of piezoelectric materials. It indicates the efficiency of converting mechanical energy into electrical energy. In this regard, PZTs have very high coefficients of conversion. The unit cell representation that provides the properties of PZTs is given in Fig. (11). Thin film PZTs are widely used. More detailed information about their structures and applications is given in Ref [26].

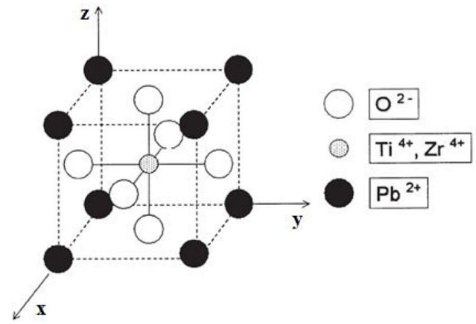

Figure 11: Unit cell of PZT [27].

The unit cell comprises Lead at cube corners, oxygen at face centres, and Zr or Ti atom at the body centre.

3.9.2 Fabrication of PZT Thin Films

PZT thin films have many applications such as actuators, sensors, etc. They are prepared using techniques such as the following.

- Vacuum Sputter Deposition Technique
- Spin Coating Technique
- Chemical Vapour Deposition

3.9.2.1 RF Sputtering Deposition Technique

In deposition of thin PZT films, RF (Radio Frequency) sputtering is a common method and offers a high probability of film deposition success. Once the deposition process begins, the ions bombard and increase the temperature of the substrate, which increases the coating density to high levels. By applying high potential through electrodes, the inert gas is ionized. At a certain potential point, ions move towards the target under the influence of the electric field and hit the surface, breaking the atoms. Thin film coating is performed with this method.

In the RF sputtering process, it is very important that parameters such as power, pressure, temperature can be precisely controlled, the process is repeatable and the process is consistent. This control is critical for the production of thin films with the desired quality and properties. This degree of controllability of the process allows reliable and repeatable results to be obtained in industrial applications and electronic devices. Figure (12) shows the schematic of the RF Sputter. Reference [28], gave a detailed explanation on the repeatability of the process, stating the importance of parameter controls.

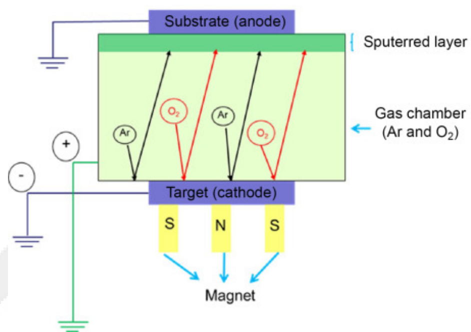

Figure 12: RF Sputering Technique [29].

3.9.2.2 Spin Coating Technique

This basic and simple method is one of the most basic methods for growing films on a substrate. The process begins with diluting the material to be coated. The created solution is evenly distributed on the substrate. The substrate then begins to be spun at high speeds. The deposited film thickness depends on the rotation speed, the surface tension of the coating surface and the viscosity of the solution used. The solvent is gradually removed from the environment at high temperatures. The film growth process results in a relatively flat surface. This technique is used to deposit materials such as PZT. Fig. (13) shows the working principle of the method.

The advantages of this method include simplicity, low cost and suitability for a wide range of materials. Additionally, being solution-based allows for easy application of various materials. However, it may have some limitations in controllability and coating quality. Therefore, it can be combined with more complex growth techniques that have specific requirements for particular applications.

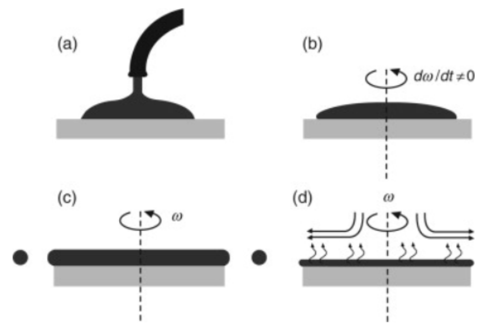

Figure 13: Spin Coating Technique [30].

3.9.2.3 Chemical Vapour Deposition Technique

In this technique, a chemical reaction begins in a vacuum chamber. Chemicals released at high temperature after the chemical reaction are deposited on the substrate. Under vacuum conditions, it allows materials to react and become gases at high temperatures. It then forms a film with these gases. This resulting film may have a certain thickness and properties. The working principle is mentioned in Figure (14).

It can be very effective, especially in terms of producing thin films and controlling properties. Under atmospheric pressure, it causes some undesirable reactions and control of this situation is important. In addition, this technique requires high vacuum. The advantages and applications of thin film coatings made by CVD are discussed in detail in [31]

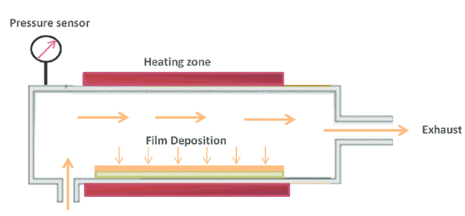

Figure 14: CVD Working Principle [32].

CHAPTER IV

ENGINEERING APPLICATIONS OF PIEZOELECTRIC MATERIALS

Piezoelectric materials are natural transducers that use the direct and indirect piezoelectric effect. In other words, they convert mechanical energy into electricity or electrical energy into mechanical energy. Based on this effect, they are used in many applications in engineering and medicine. Fig. (15) shows the interconversion of inputs and outputs in sensor and actuator applications.

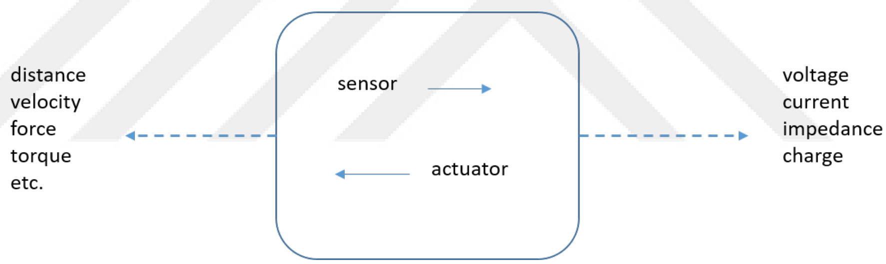

Figure 15: Typical conversion principles Piezoelectric Sensors and Actuators.

4.1 Piezoelectric Actuators

Actuators convert electrical energy to mechanical energy. Piezoelectric-based actuators undergo a dimensional change when subjected to an electric field. Because of this feature, they benefit from the tension and strain produced within themselves by the reverse piezoelectric effect. These properties are used for precision applications.

Piezoelectrics exhibit dielectric properties, causing polarization in the structure due to relative displacements of positive and negative ions when subjected to pressure. In addition, when they exhibit ferroelectric properties, they result in spontaneous electric dipoles represented by P. PZT ceramics, which have undergone many processes, are used for actuator applications. Figure 16(a) shows the polling directions of the domains. The alignment resulting from the application of high voltage across the sample is shown in Figure 16(b). The remaining electrical polarization after polarization is shown in Figure 16(c). As shown in Fgure 16(d), presentation of piezoelectric actuator.

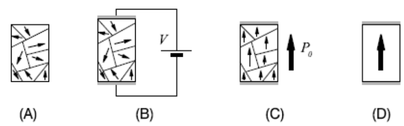

Figure 16: A bulk piece of piezoelectric material [33].

As soon as a voltage V is applied between the two electrodes, the length of the actuator increases. There is a certain relationship between increasing length and tension. The relationship between them is practically in the form of a hysteresis curve. This curve depicts the displacement caused by the applied electric field. Studies on modeling the hysteresis curve are mentioned in Ref [34].

The actuators not only expand in length but also shrink in lateral directions. Therefore, the deformation occurring in the component takes place in three dimensions. Depending on the shape of the material, lateral changes can be ignored or taken into account. Piezoelectric materials are used in actuator applications by making selections in the longitudinal direction, that is, in the same direction as the polarization direction, and in the transverse direction, that is, perpendicular to the polarization direction. Voltage is applied in the direction of permanent polarization in transverse and longitudinal modes. A third mode is available. It is the shear mode. This mode allows the rotation of both sides of the material without changing its length in other directions. The representation of the modes is given in Figure (17).

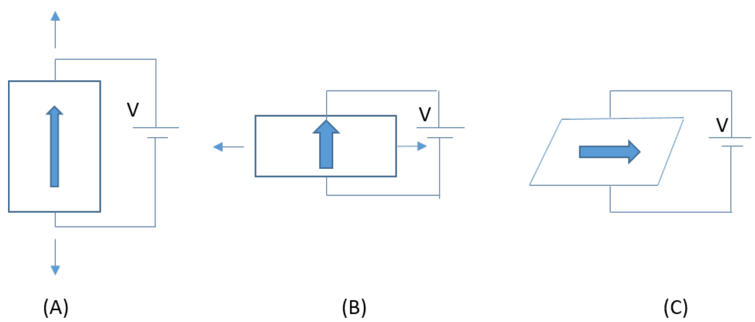

Figure 17: Modes of piezoelectric actuator

(A) longitudinal mode , (B) transverse mode, and (C) shear

When we look at piezoelectric actuators electrically, they behave capacitively. The equivalent circuit includes capacitive effect, mechanical losses and inductive effect. These components are shown in Fig (18). V represents the voltage between the electrodes and i represents the current.

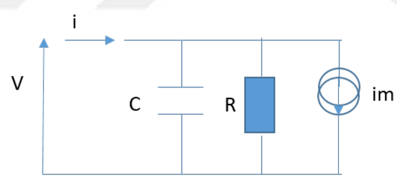

Figure 18: Equivalent circuit of piezoelectric actuators

4.1.1 Advanced piezoelectric actuators

One of the disadvantages of piezoelectric actuators is that they require high voltage to operate. Many ways have been developed to reduce the voltage required for displacement :

- Multilayer (or stack) actuator,
- Bender

4.1.1.1 Multilayer Actuators

Stack actuators consist of each plate stacked on top of each other, connected in parallel with each other in alternative polarity direction and electrical perspective. Therefore, when voltage is applied to the electrodes, the plates elongate, resulting in a larger displacement. Multilayer actuators are used in many applications because they work to precisely convert applied electrical energy into motion and vice versa. Its applications and designs in the industry are mentioned in detail in Ref [35].

Stack actuators have both advantages and disadvantages. The primary advantage is the higher voltage-strain ratio compared to a bulk actuator of the same size. It is multiplied by the number of layers. In addition, the longer of two actuators with the same layer thickness undergoes greater deformation under the same voltage.

Besides its advantages, it also has disadvantages. The decrease in voltage increases the need for current. This means that the current increases to achieve the same displacement. The current required is related to the number of layers. Each of the layers acts like a capacitor. Increasing the current may cause thermal stress and deformation of the electrodes. Its working mechanism and stacked form are shown in Figure (19).

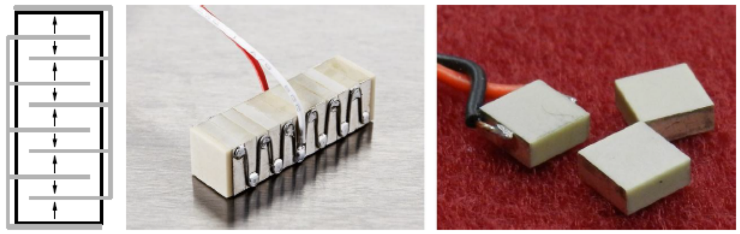

Figure 19: Stack Piezoelectric Actuator : (A) Working mechanism, (B) thick and (C) thin plates [33]

4.1.1.2 Bender

Piezoelectric benders are divided into two categories: bimorphs and unimorphs. Piezoelectric bimorphs consist of two thin piezoelectric strips connected to each other. Bimorphic structures can be used in serial and parallel connected structures. One end of the bimorph structure is fixed, and the other end is free. In the series connection, the two strips are polarized in opposite directions and connected to each other. Electrodes are fixed to the external surface and voltage is applied. In this connection type, each strip has a tendency in the same direction. However, since they are polarized in the opposite direction, the upper side expands and the lower side narrows with the transverse piezoelectric membrane (d_{31} coefficient). This movement causes the bimorph structure to bend downwards.

In parallel bonding, the strips are connected to each other so that they are polarized in the same direction. The common face is grounded and the outer two electrodes are exposed to positive voltage. With this application, the upper strip widens while the lower strips narrow. In this way, the bimorph structure becomes bent. With the use of MEMS systems, bimorph structures are used in many areas. An example mechanism is shown in Figure (20).

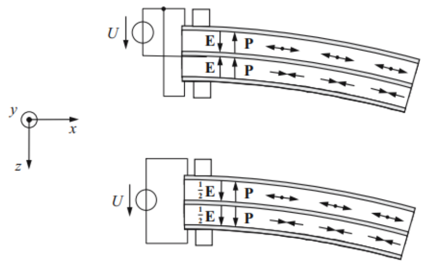

Figure 20: Bimorf piezoelectric bender mechanism [36].

Unimorph actuators consist of a single ribbon. As in bimorphs, in unimorphs the material is compressed from one end and released from the other end. It starts working by bending the strip when a voltage is applied. Unimorphic actuators are made by depositing a thin piezoelectric film onto a non-piezoelectric substrate. The system is compressed at the end point and then voltage is applied to the film surface. The film is stretched with the applied voltage. The layer beneath the film responds to the stress that occurs when voltage is applied. As a result of this reaction, it begins to bend uniformly.

Unimorph actuators can be used in two modes. d_{33} and d_{31} modes. In d_{33} mode, the piezoelectric structure is polarized parallel to the plane (3 direction). With longitudinal stitching, the film again expands and bends in the 3rd direction. In d_{31} mode, it is polarized perpendicular to the plane. Due to the transverse effect, the film expands and bends in the transverse direction. (1 aspect) Micron-sized piezoelectric unimorph actuators can be produced with MEMS techniques. Films are deposited on silicon oxide etc. substrates. The most common of the deposited films are PZT and ZnO. This working principle and structure are shown in Figure (21) and Figure (22).

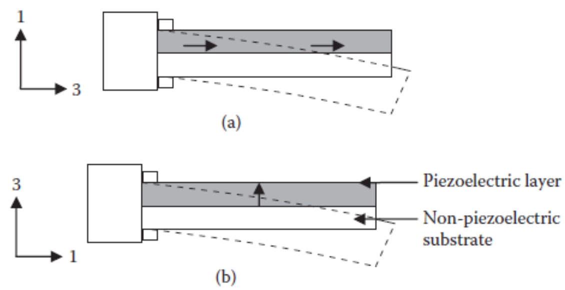

Figure 21: Piezoelectric unimorf (a) d_{33} mode and (b) d_{31} mode [36].

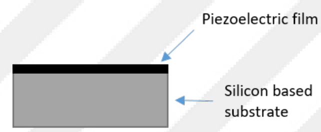

Figure 22: Diagram of piezoelectric unimorf actuator.

Piezoelectric actuators exhibit leverage to increase mechanical displacements and the resulting force. Mechanical advantage is tried to be maximized by using the geometry of the designed mechanical system. By having the designed actuator in a lever-like shape, the displacement is increased and the mechanical output is increased. This emerging advantage is used in systems such as precise positioning etc. In this way, it is aimed to increase the efficiency and performance of the system.

The leverage effect greatly affects the scanning angle of piezoelectrics. The small displacement of the piezoelectric structure raises the lever arm, resulting in larger angular rotations at the lever tip. The lever arm acts as a magnifying glass. Without the leverage effect, displacement occurs in very small amounts. When the piezoelectric material expands, the lever rotates around a point, creating angular rotation. The arm length of the designed lever and the selected piezoelectric material are factors that affect the scanning angle. Figure (23) is shown as an example where leverage effect.

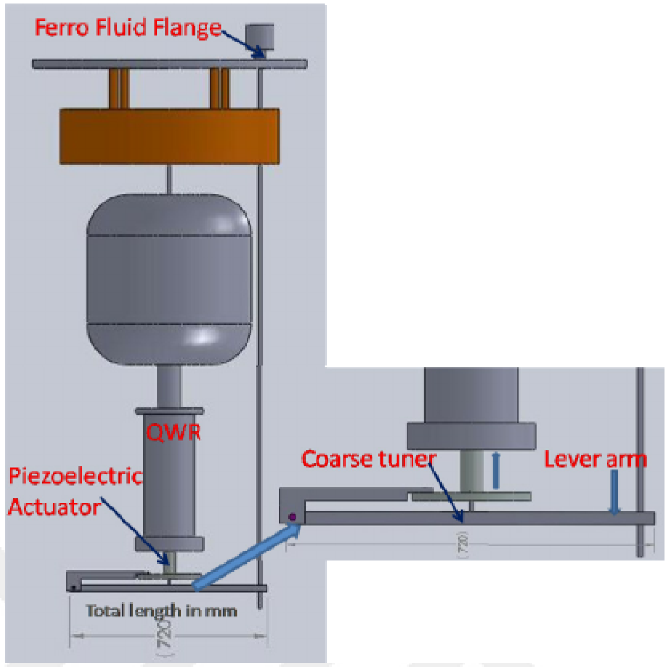

Figure 23: Piezoelectric actuator with lever arm [37].

In the system shown as an example in the figure above, the piezoelectric actuator is fixed to an arm and allowed to move up or down. It functions as an adjustment arm so that the system can operate at the desired frequency.

In piezoelectric actuators, torsion describes rotational movement around the axis. By expanding or contracting the material, torsion movement is achieved, the material bends and rotation occurs. Figure (24) shows the mirror design that works on the torsion principle. The amount of rotation affects the angle, and the angle varies depending on the material properties and applied voltage. Sustained torsional stress on the material can cause material fatigue, reducing actuator life.

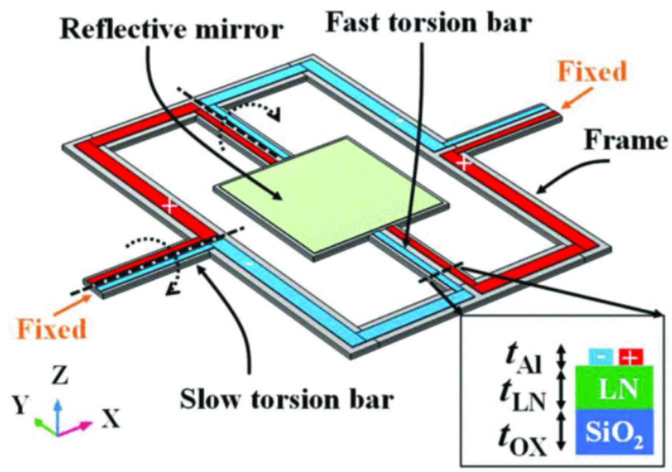

Figure 24: The schematic of the dual-axis mirror [38].

Power consumption of piezoelectric actuators is an important factor. Power consumption is important for the system to operate stably and precisely. The operating mode, electrical parameters or mechanical properties of the structure affect the power consumption of the system. In the designed system, the physical size of the structure in which the piezoelectric material will move determines the total power consumption. Choosing a material with a high piezoelectric coefficient causes larger displacements under the same voltage. This reduces power consumption. Calculation of power consumption is given in Equation (14). The formula given in Reference [10] can be used to calculate the power consumption of piezoelectric actuators.

$$P = w * C * \tan(\delta) * V_0^2 \tag{14}$$

The $\tan(\delta)$ of a piezoelectric actuator is important in terms of energy efficiency and performance. It defines the energy lost as heat during the process of converting electrical energy into mechanical energy or vice versa. A lower value tells us less energy loss. That means high efficiency. Capacitance (C) plays an important role for piezoelectric actuators and has a great impact on performance. It manages the relationship between voltage and the resulting charge. Higher capacity leads to higher displacements. Larger capacitance means being able to store larger charge. This causes greater deformation.

In the design processes of piezoelectric actuators, COMSOL Multiphysic plays an important role. Modeling is necessary to accurately understand the behavior of piezoelectric materials and provide predictions. To understand mechanical and electrical behavior, COMSOL is a suitable tool. The deformation and therefore the stress resulting from the applied electric field are modeled. With these modeling, a prediction can be made about the behavior of the designed system in a real environment.

One of the most important analyzes performed with COMSOL Multiphysics is eigenfrequency analysis. Eigenfrequency, or natural frequency, is the vibration speed that occurs when an object moves without being exposed to any pushing or damping force. Systems exposed to vibration may have more than one natural frequency, depending on how they were initially disturbed. The dynamic properties of the system are determined by it.

4.1.2 Applications

In industrial applications, averages in the micron range represent accuracy. High accuracy is essential in systems such as machine tools and measurement systems. As shown in Figure (25), when extracting surface topography for AFM, the deflection of an object is measured through laser light. This is done by scanning the sample surface with a probe. In STM, the level of current flowing from the tip to the sample is measured. The mechanism operates by detecting changes in current during the scanning process.

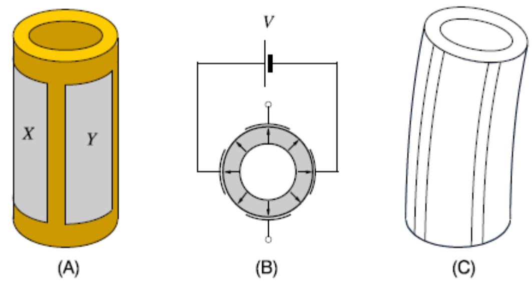

Figure 25: AFM microscope tube (A) XY scanner (B) voltage connection (C) tube deformed [33].

In addition, in haptic sensors, the sense of touch is utilized to convey information. Actuators are again used to detect this feeling. Vibrations during notifications, such as calls on smartphones, are facilitated by actuators. Vibrations are also produced using piezoelectric benders for high-sensitivity tactile needs.

Another application area is piezoelectric actuator-based scanning mirrors, which have similar structures as in Figure (26). They are used in many areas in the market such as vehicle headlights, smart lighting, projectors, augmented reality glasses and LIDAR applications.

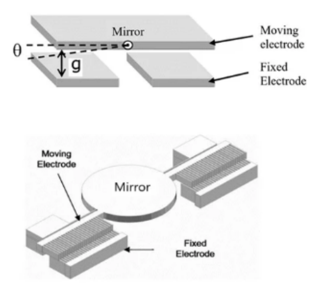

Figure 26: Structure and actuation of mirror [39].

CHAPTER V

SIMULATION RESULTS

Thin-film coated PZT-based actuators are an important actor to meet both size and power needs. But mechanical design challenges are difficult to overcome. For PZT-based actuators operating at high frequency, the level of high deformation and sweep angles is an important issue. In this section, a comparison is made between PZT-based actuators of different designs and the actuator in this thesis.

In the thesis we present, the system that works as a PZT-based unimorph bender consists of 2 frames. By applying voltage to the PZT coatings, the movement is achieved by indirect piezoelectric effect, resulting in longitudinal movement. The outer frame acts as an actuator. PZT thin film is coated on the outer frame. In addition, another PZT film attached to the outer frame moves as a whole with the outer frame to create the leverage effect. The inner frame holds the scanning mirror. The inner frame moves with the mirror to limit the deformation of the mirror. Movement of the inner frame is provided by a PZT-based unimorph bender actuator, which is also attached to the outer frame from the inside. As shown in the figure, PZT actuators are positioned on the outer frame and inner frame edges. In piezoelectric material selection, PZT-4 was chosen. Additionally, by adding a piezoresistive material on the outer frame, it is aimed to be an energy source for equipment such as sensors etc. to be used in the system to be created later.

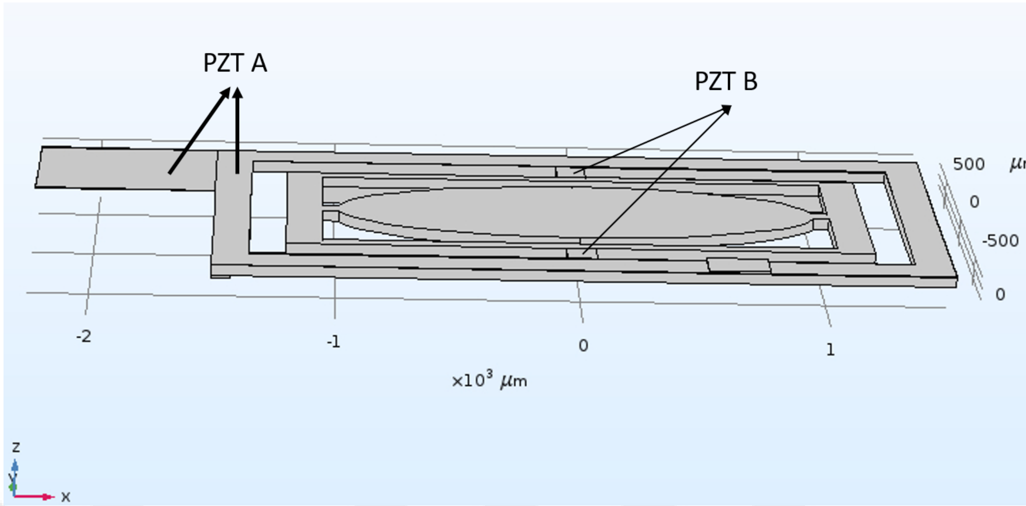

Figure 27: Cross section view of PZT Actuator

By operating the system out of phase, larger scanning angles were obtained with the aim of keeping the system away from extra stress. In addition, support beams have been placed in certain areas on the bottom of the device while the system is operating, aiming to make it more resistant to bending and twisting. Figure (27) and Figure (28) show the top and bottom views of the designed system, and Figure (29) shows the relevant points of the measurements made on the system.

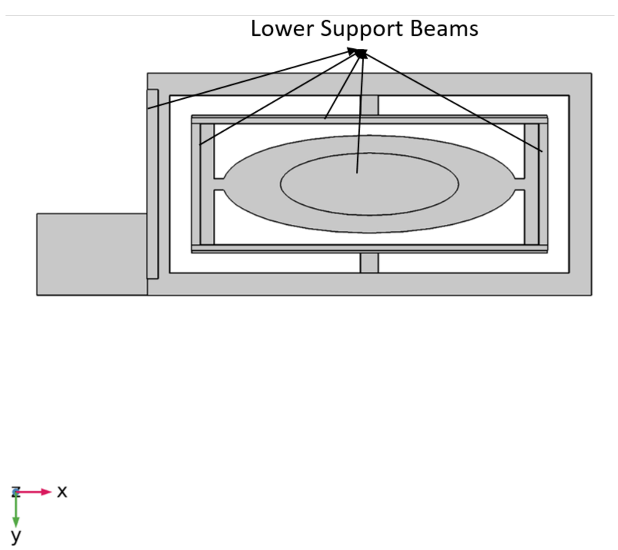

Figure 28: Cross section view of PZT Actuator

The designed device has mold dimensions of 3 mm x 1.5 mm. The entire structure is 3.75 mm long and 1.5 mm wide. The thickness of the substrate is 50 μm. The thickness of the beams in the lower support section is also 75 um. The total thickness of the device is 135 μm. The inner frame has dimensions of 2.4 mm x 0.93 mm. The inner frame is fixed by attaching it to the outer frame. The actuator that provides movement to the inner frame is also coated on the substrate. The thickness of the PZT coated on the outer frame is 10 μm. The actuator that provides movement to the inner frame has dimensions of 0.12 mm x 0.135 mm. Its thickness started from 3 um and increased up to 15 um. A 0.9 mm x 0.66 mm ellipse mirror is used for the designed device. Piezoresist material, which is considered as an energy source for equipment such as sensors, has dimensions of 0.25 mm x 0.15 mm. Its thickness is 10 μm. The mentioned geometric measurements and the parametric properties of the materials used for the designed system are given in Table 2.

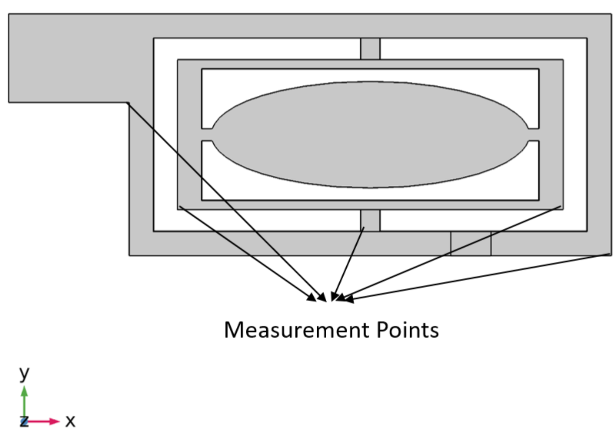

Figure 29: Top view of PZT Actuator

Table 2: Material Parameters for Modelling

Parameter	PZT-4	Si
Relative Permittivity	762.5	11.7
Density (kg/mm^3)	7500	2329
Young's Modulus (Pa)	7.8	170 x 10^9
Poisson's Ratio	0.31	0.28

Modal analysis was performed through the COMSOL Multiphysics program to reveal the eigenmodes of the system. This analysis was performed by changing the thickness of the PZT film connecting the inner frame to the outer frame so that the total thickness remained the same. Since the total mass did not change, no significant differences in frequencies emerged while the eigenmodes emerged. In mode 1 at 208.61 Hz, the movement of the outer and inner frame is in phase, as shown in Figure 30 That is, the entire structure bends in the same direction at the same time. In the 5th mode, 91088 Hz, the movements of the outer and inner frame are out of phase. That is, different aspects of the structure bend in different directions. The movement mechanism that occurs in the operating modes of the system is shown in Figure (30).

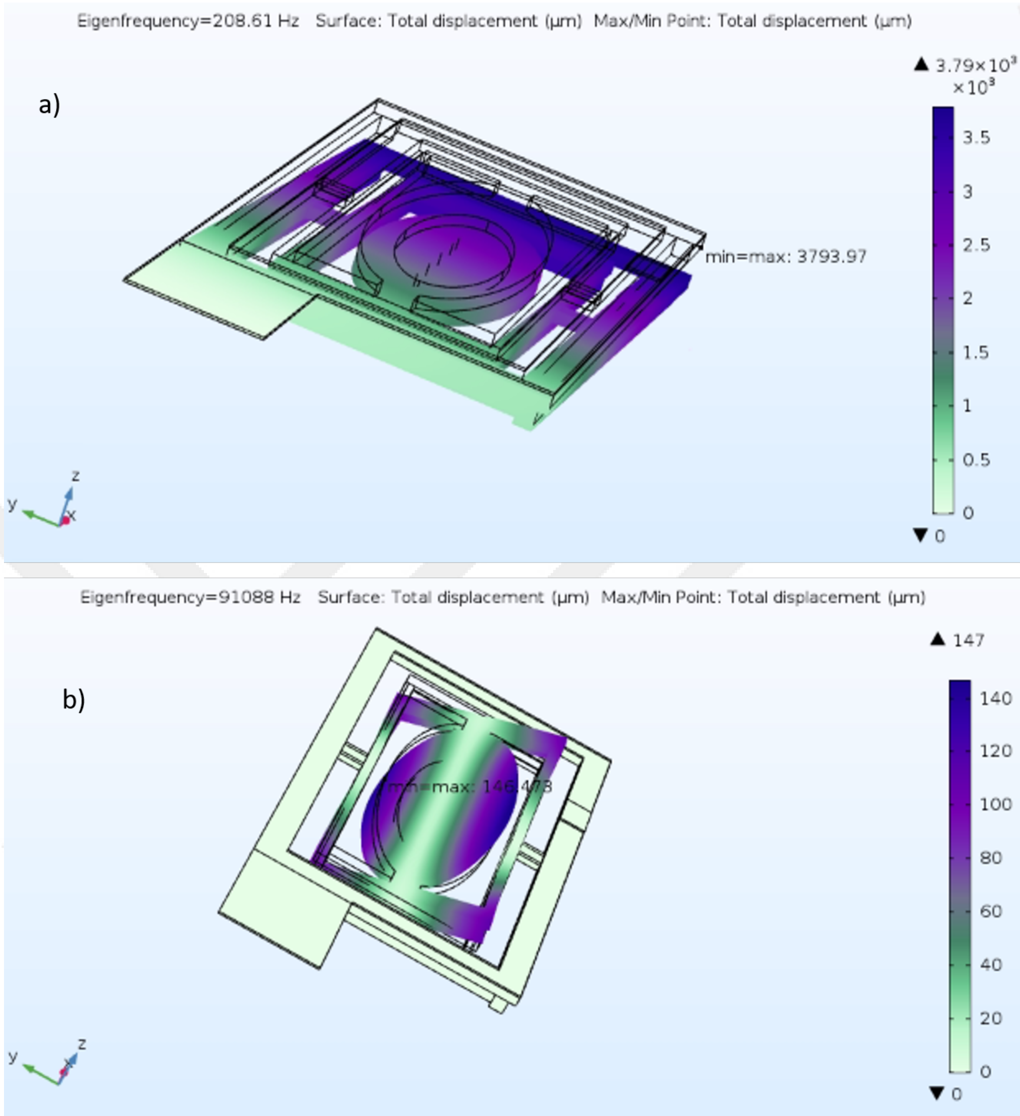

Figure 30: Shapes of eigenmodes of PZT actuator.

a) Torsion with inner and outer frame movements in phase at 208.61 Hz and b) torsion in which the inner and outer frame movements are out of phase at a frequency of 91088 Hz.

In the designed device, the PZT thin film layer applied to the outer frame adds depth to the movement by allowing the frame to be scanned slowly. Keeping the thickness of this layer constant, the thickness of other PZT layers responsible for the movement of the inner frame was tested from 3μm to 15μm. While performing these experiments, it was observed that the voltage applied to the PZT layers changed over time and stress and displacement changes were observed on the system. In this application, the system was not driven in resonant mode and its reactions in static state were examined. According to the results, the maximum voltage was determined based on the resistance of the materials used in the system according to the applied voltage. The voltage level varies depending on the thickness of the PZT layer. The voltage carrying capacity of PZT-4 is $\sim$1kV/mm. Therefore, in order to prevent structural degradation of piezoelectric materials, we aimed to drive the system at 100V levels, based on the PZT actuator responsible for the movement of the inner frame. The movement of the activated system is shown in Figure (31).

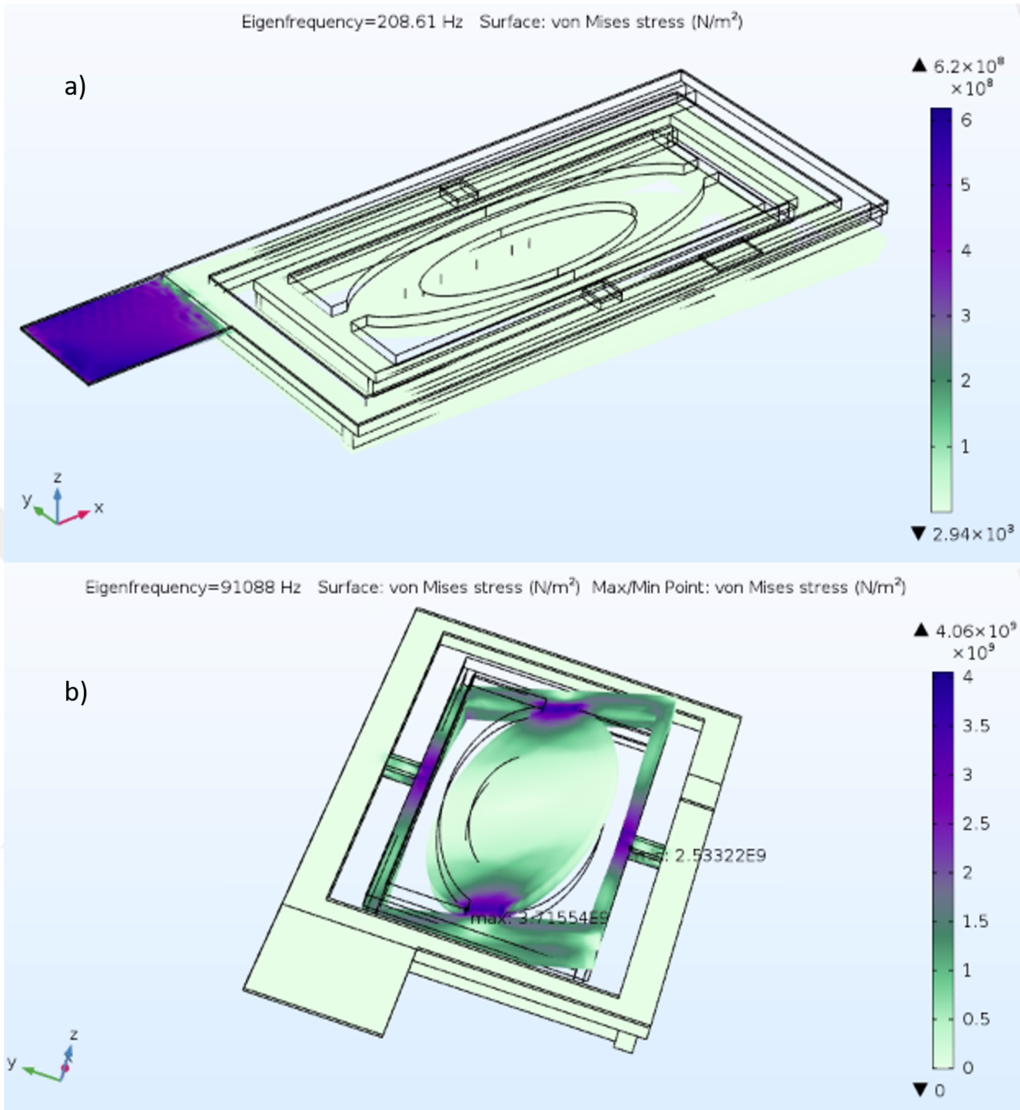

Figure 31: Stress Distrubution of Actuator.

Figure (31) shows the stress distribution of the system. The figures on the right and left show the stress during fast and slow scans. The figure on the left shows the movement for the phase in which the system moves completely together. The system was given motion by using the leverage effect. In case of slow scanning, the system oscillates at 208 Hz and scans approximately 51 degrees. While performing this scan, it is observed that MPa levels of stress occur on the system. The figure on the right shows the moment when the fast scan was performed. This scanning is done at 91 kHz levels. The resulting scan angle is approximately 12.5 degrees. The stress that occurs during scanning is at GPa levels. Silicone and piezoelectric materials are capable of handling the stress that occurs during both scans.

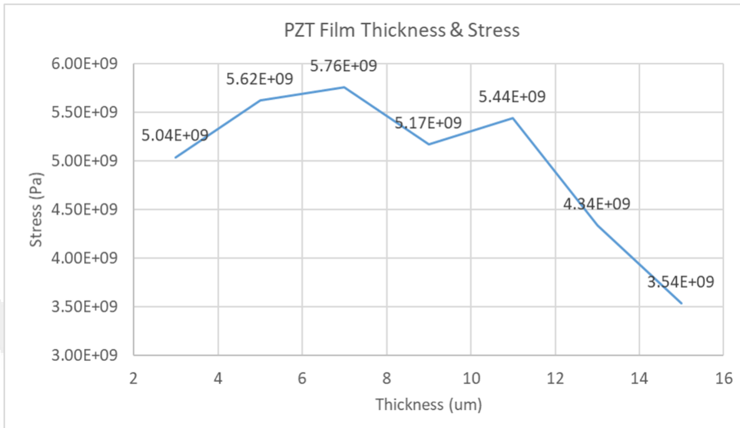

Figure 32: Stress variation according to the thickness of the PZT responsible for the movement of the inner frame.

Examining Figure 32, stress changes are observed based on the thickness of the PZTs responsible for moving the inner frame. Increasing the thickness has a positive impact on stress management, but it negatively affects the scanning angle. Therefore, it is essential to use the thickness and scanning angle with maximum efficiency. As our designed system operates at high frequencies, it is subjected to intense stress with every torsion movement. The system experiences deformation after each movement, which causes fatigue. To promote system health, a larger thickness was chosen over the screening aspect. During this analysis, the system's Figure of Merit (FoM) was also considered. The frequency change versus the thickness of the piezoelectric material responsible for the movement of the entire system is shown in Figure (33).

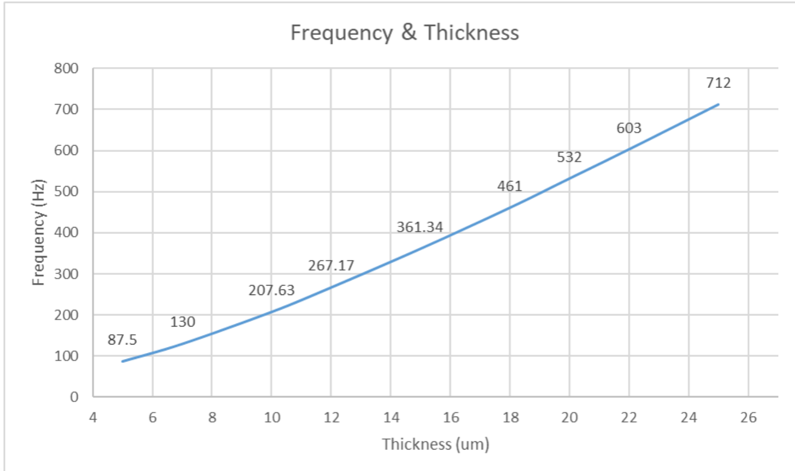

Figure 33: Illustration of the frequency at which the system operates versus the thickness of the PZT that moves the entire system.

The change in the thickness of the PZT that moves the entire system affects the operating frequency of the system. In this structure, the entire system is bent and bent. More movement of the system is achieved by using the leverage effect. The thickness of the PZT responsible for this movement is responsible for both the operating frequency and the displacement caused by the leverage effect. This movement operates as high displacement with low operating frequency. Again, when choosing the thickness, the most optimum thickness was chosen by taking the FoM values into consideration. As a result of this selection, the thickness of the PZT, which is responsible for the movement of the entire system, was chosen as 10 microns. As a result, the system scans approximately 51 degrees with an operating speed of 207 Hz. When the system operates at these values, the stress on the system is at MPa levels. These values are within the range of values that both PZT and silicon can easily handle. The displacement and stress levels resulting from the movement of the system are shown in Figure (34). Similarly, in Figure (35), the values of the stress and displacement levels of the system at the resonance frequency are shown.

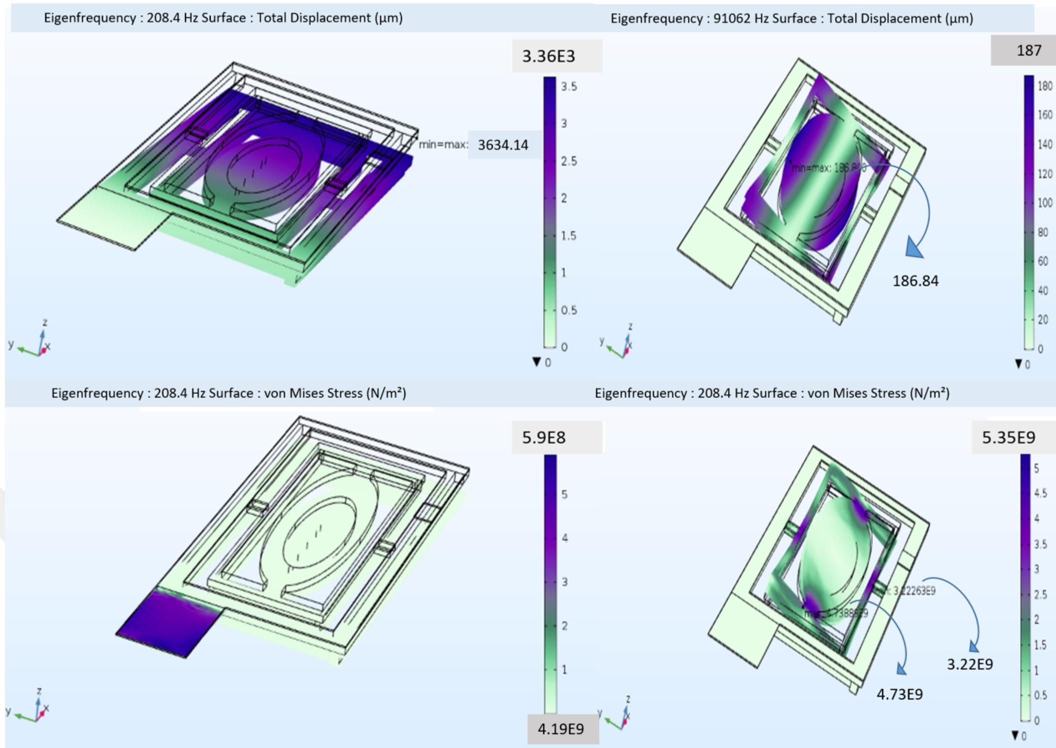

Figure 34: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 13 μm.

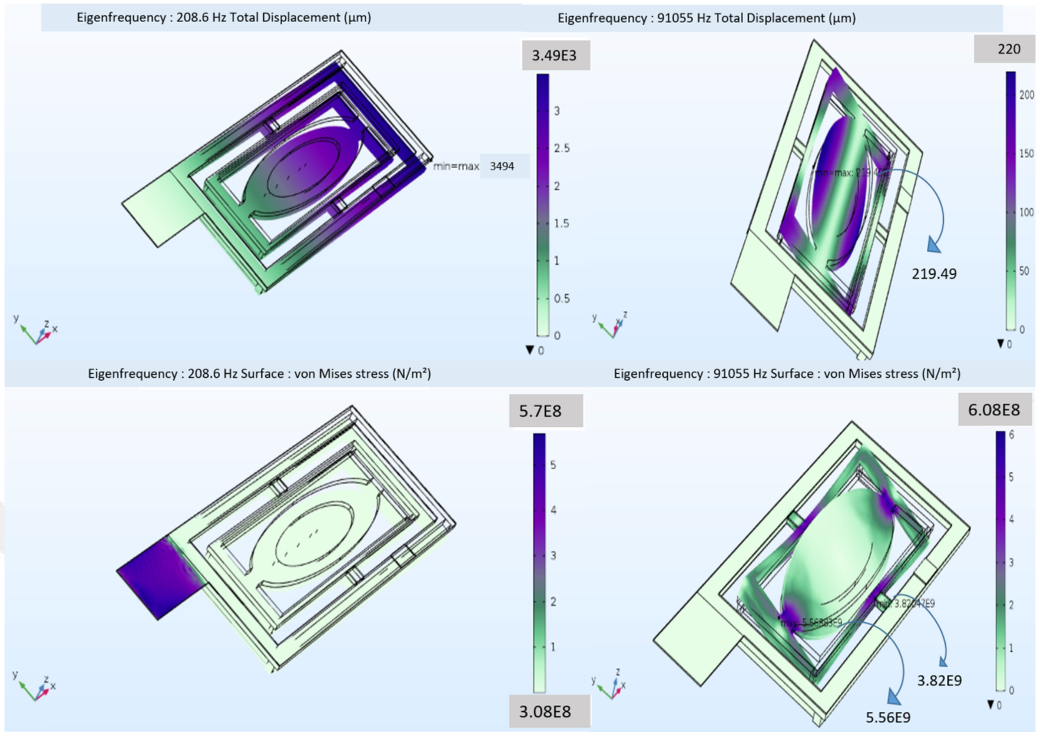

Figure 35: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 11 μm.

The thickness of the PZT, responsible for the movement of the inner frame, does not significantly affect the operating frequency of the system, as expected. The system is designed as a spring, meaning that any significant increase in mass is required to affect the operating frequency. Increasing the torsion by decreasing the thickness results in an increased scanning angle. It has been observed that higher torsion levels lead to increased stress on the joint areas. Similarly, in Figures 36-39, the stress and displacement results resulting from the change in the thickness of the piezoelectric material used are shown.

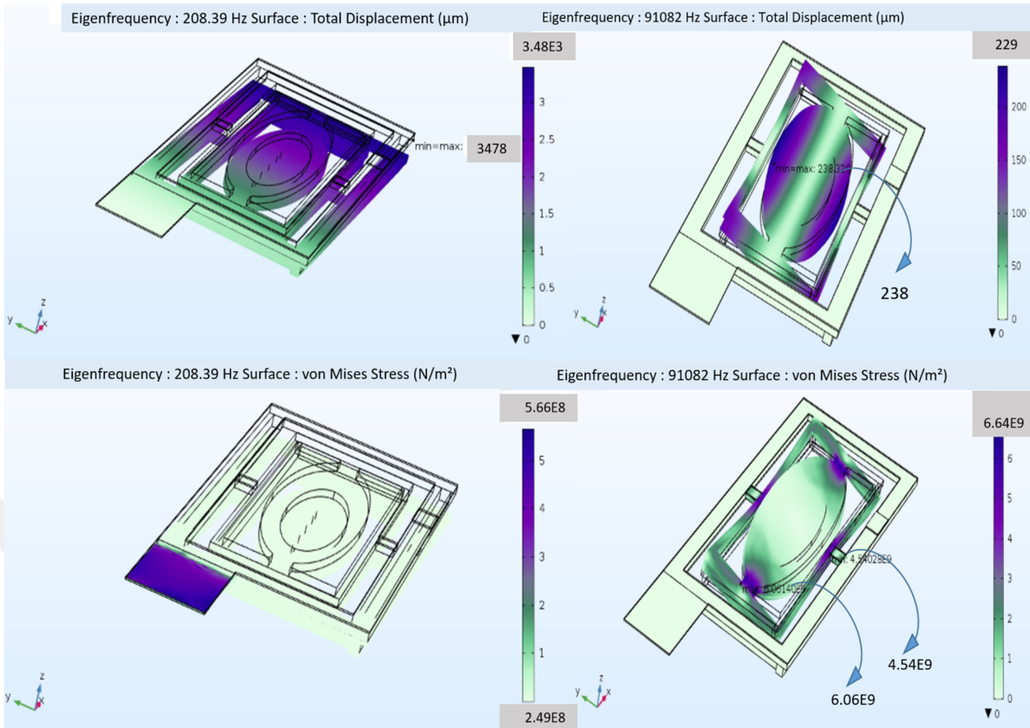

Figure 36: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 9 μm.

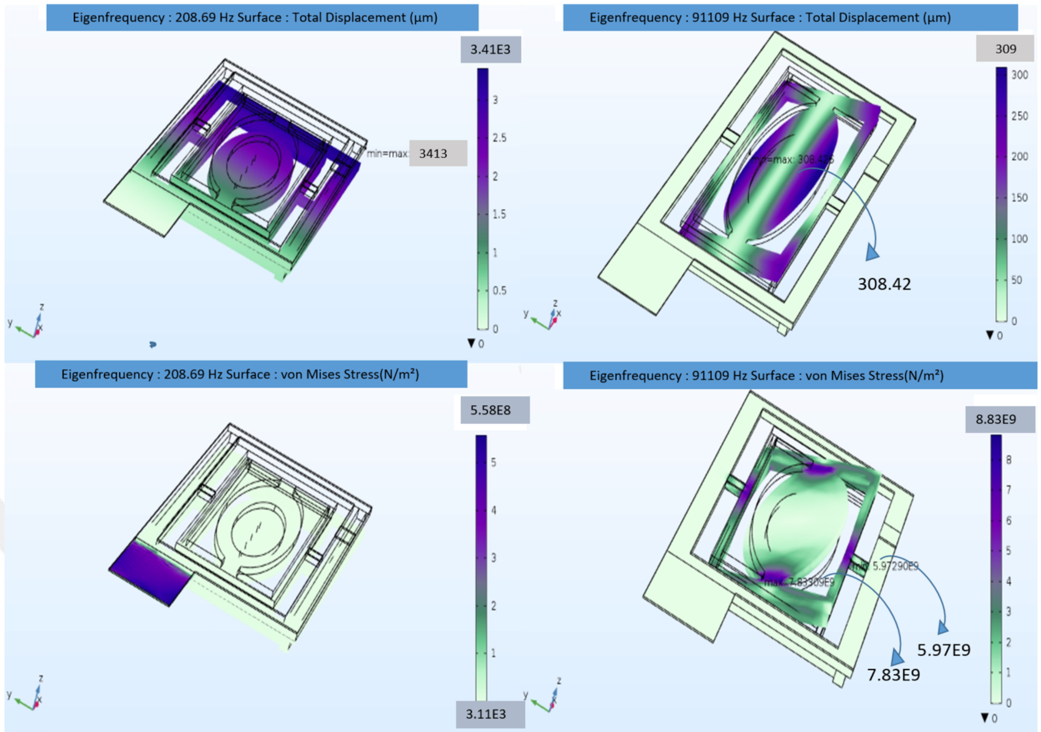

Figure 37: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 7 μm.

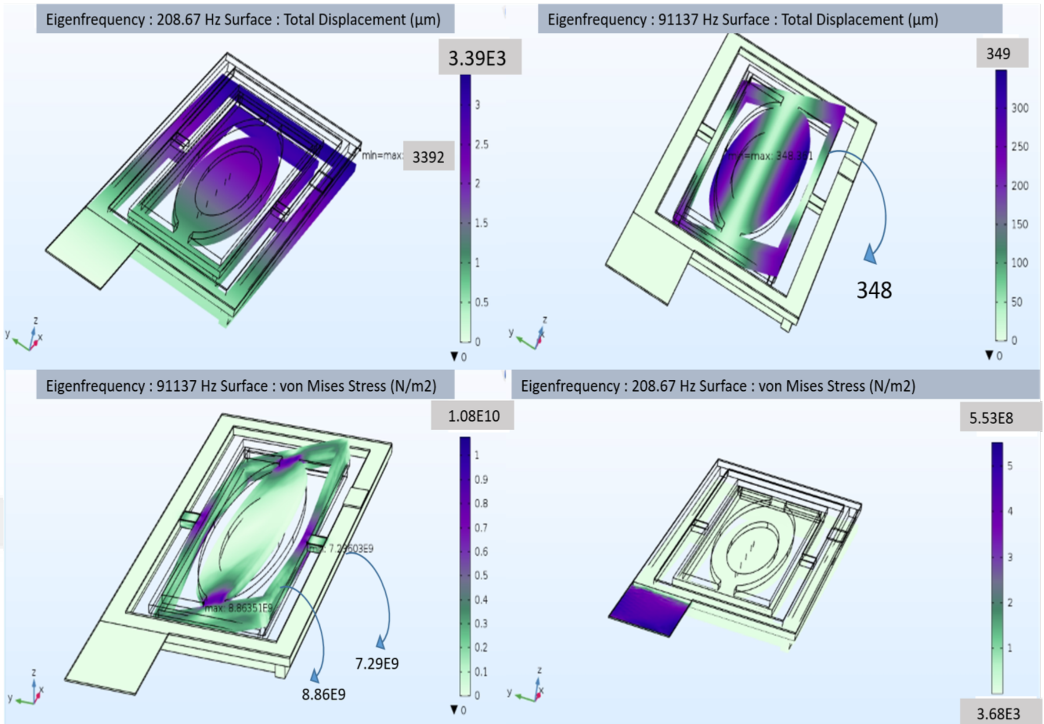

Figure 38: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 5 μm.

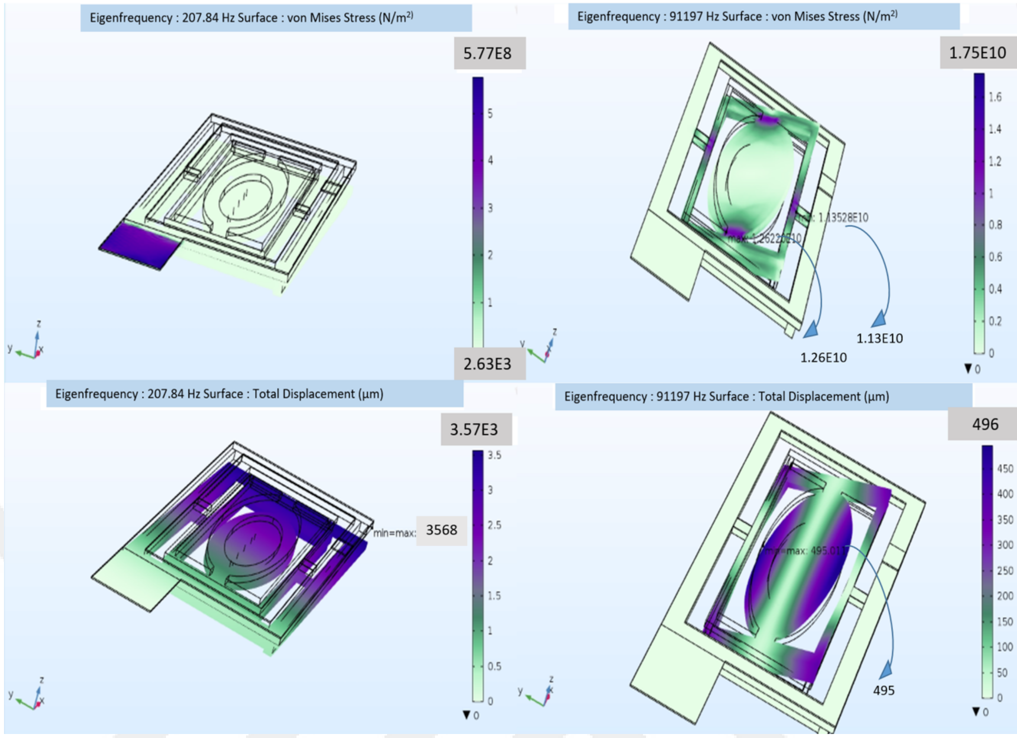

Figure 39: Stress and displacement distributions in the system when the thickness of the PZT responsible for the movement of the inner frame is 3 μm.

Similarly, results with the same logic are observed in Figures 38 and 39. The reason for this is that changing the thickness of the PZT used causes differences in the piezoelectric character. As the thickness decreases, the PZT used has a smaller volume. For this reason, as the thickness of the material decreases, the energy that the material can store increases. Therefore, it causes more tension. In addition, as the thickness becomes thinner, the mechanical resistance of the material decreases, causing k^2 to increase and therefore more torsion with a higher amplitude difference. According to this result, the change in the rotation angle due to the change in the thickness of the piezoelectric material is discussed in Figure (40).

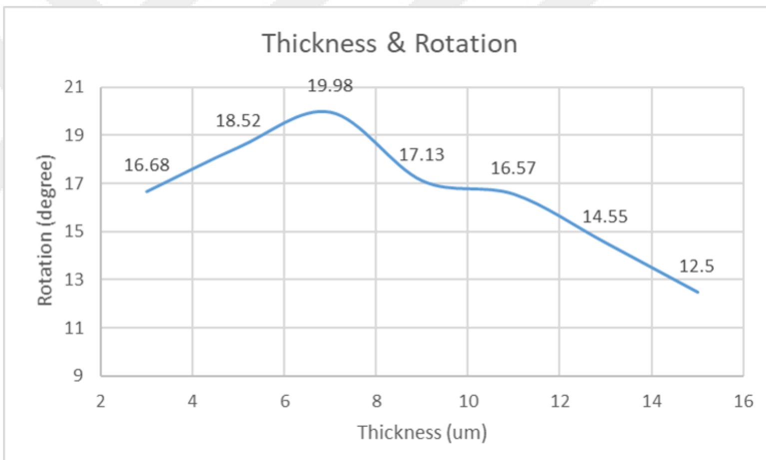

Figure 40: Scanning angle graph versus the change in the thickness of the PZT responsible for the movement of the inner frame.

The most important parameters for the scanning system we designed are the tension during movement and the resulting scanning angle. To keep the stress levels on the system low, scanning was waived. The stress levels occurring on the surface of PZT and silicon are within the materials' limits. Maintaining low levels of deformation is crucial for the health of the system. Additionally, when producing PZT thin films, thickening the structure can aid in the production process due to the difficulty in producing high-quality thin films.

Eq. (15) allows us to predict a theoretical approximate value before the simulation result. When comparing the simulation results of our designed system with the formula results, we found that they were approximately equal. The formula takes into account the displacement of the PZT used to bend the system, the distance of the rotation axis to the other ends, and the damping ratio, which characterises the damping of piezoelectric materials. We used a damping ratio of 0.01 in this formula, which is expressed as follows:

$$\theta_z = \frac{3z}{4l_x dampingz} \tag{15}$$

z in the formula is the displacement value of the relevant piezoelectric material for the system to scan. l is the distance of the rotation axis to x. When the relevant values were substituted, the calculation made as a formula found approximately 14.4 degrees. The simulation result was calculated as 12.5 degrees. The formula and the simulation result almost match each other.

For scanning systems, dynamic deformation is very important for scanners produced with MEMS architecture. The upper limit for deformation is around %50. In the system we designed, a lower beam addition was made to reduce the tension on the mirror. However, the acceptable level may be approximately %25. According to the deformation analysis we conducted on COMSOL Multiphysics, %70 of the mirror's surface area can be used efficiently. We can design different beam structures to reduce the deformation of the mechanical structure. Since the efficiency that can be obtained when scanning at point E reaches 0.35 levels, we can benefit from approximately %70 of the available surface area. In Figure (41), the points where mechanical deformation analysis is made are discussed.

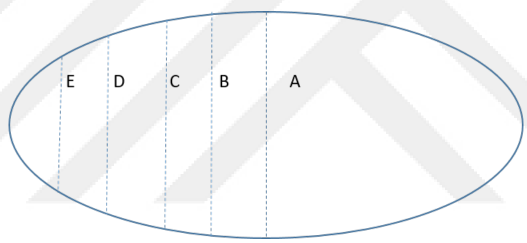

Figure 41: COMSOL analysis of dynamic deformation of mirror at 12.5 mechanical rotation angle.

At 100V, the scanning angle is 12.5 degrees and the width of the mirror in the scanning direction is D = 0.66 mm and f= 91088 Hz, θ_{OPT} x D x f , we obtain the figure of merit result as 751 deg x mm x kHz. When compared to similar studies, the designed system is in a good position. In Figure (42), the figure of merit comparison of piezoelectric film actuated scanners in the literature is given. Compared to the scanners in the literature, the system we designed gives a good result in terms of figure of merit performance compared to its counterparts, according to the results we obtained in the simulation environment.

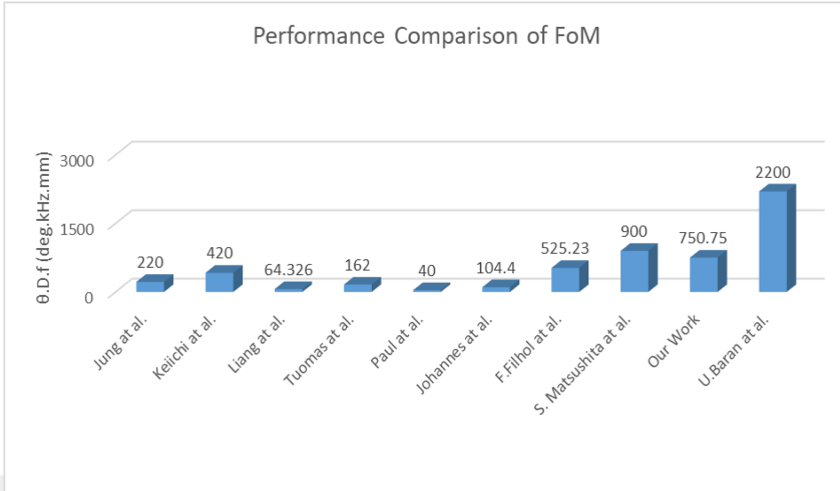

Figure 42: Performance comparison of piezoelectric film actuated scanners based on literature. [40, 41, 42, 43, 44, 45, 46, 47, 8].

There is a capacitive effect in systems with piezoelectric materials. Each of the parameters in the equation is very important in power consumption. Therefore, the power consumed by the system is calculated as in Equation (16).

$$P = \omega.C.tan\sigma.V^2 \tag{16}$$

Here ω represents actuation frequency, C represents capacitance, tanσ represents loss factor and V represents actuation voltage. When the values are substituted in this formula, the theoretical power consumed by the PZT thin film, which is the active component in the designed device, is calculated as 1.5mW.

With the piezoresistive materials we placed on the system we designed, it is aimed to produce voltage with the stress that occurs during the movement of the system. It is aimed to produce more voltage with the materials placed at points where stress is intense. This generated voltage is intended to be used to power the sensor to verify the angular measurement. Figure (43) shows the voltage produced by piezoresistive materials placed at points where stress is intense.

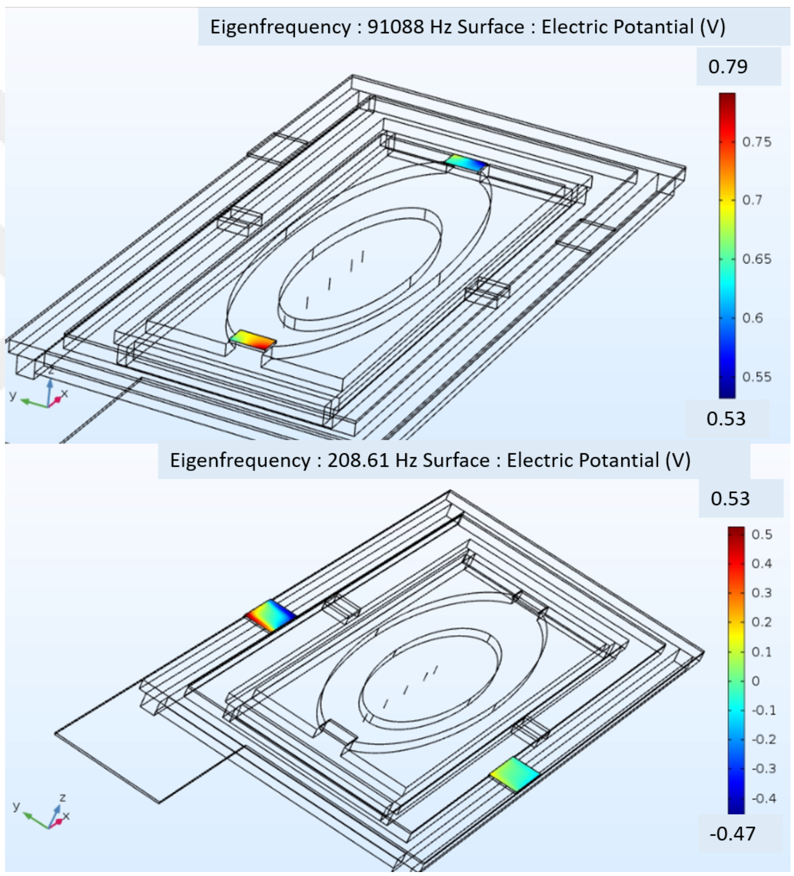

Figure 43: The distribution of voltage that occurs following the stress placed on the piezoresistive material.

The image of the angular scan made by the MEMS mirror, which is a part of the system we designed, is shown above. Visualization of the ±12.5 degree scan is provided. A conical shaped scanning area emerges with the scanning angle at which the entire system moves together. Figure (44) shows the positioning of the designed scanner.

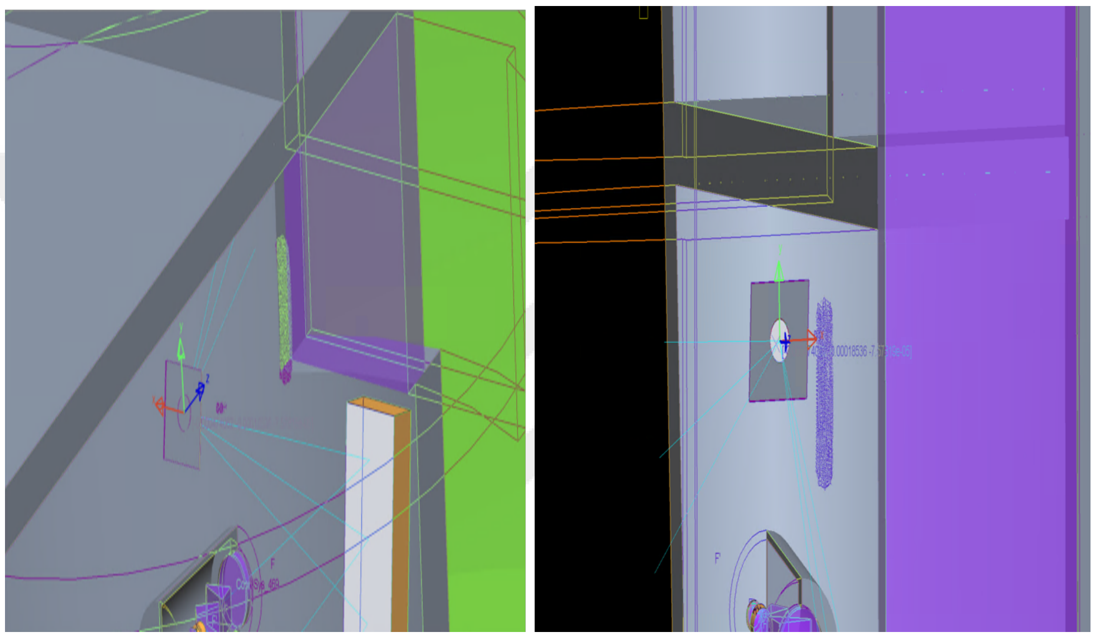

Figure 44: In the LightTools program, the representative angle that the mirror we designed scans when the sample is placed on the LIDAR.

In Figure (45), the angular scanning made by the designed mirror at the frequency it operates is represented. After the beam coming out of the laser went out of the designed mechanism, it hit the object and returned to the system. The incoming rays were dropped on the detector thanks to the lens used and data was collected. In real systems, similar mechanisms are used to interpret the rays falling on the detector and process them.

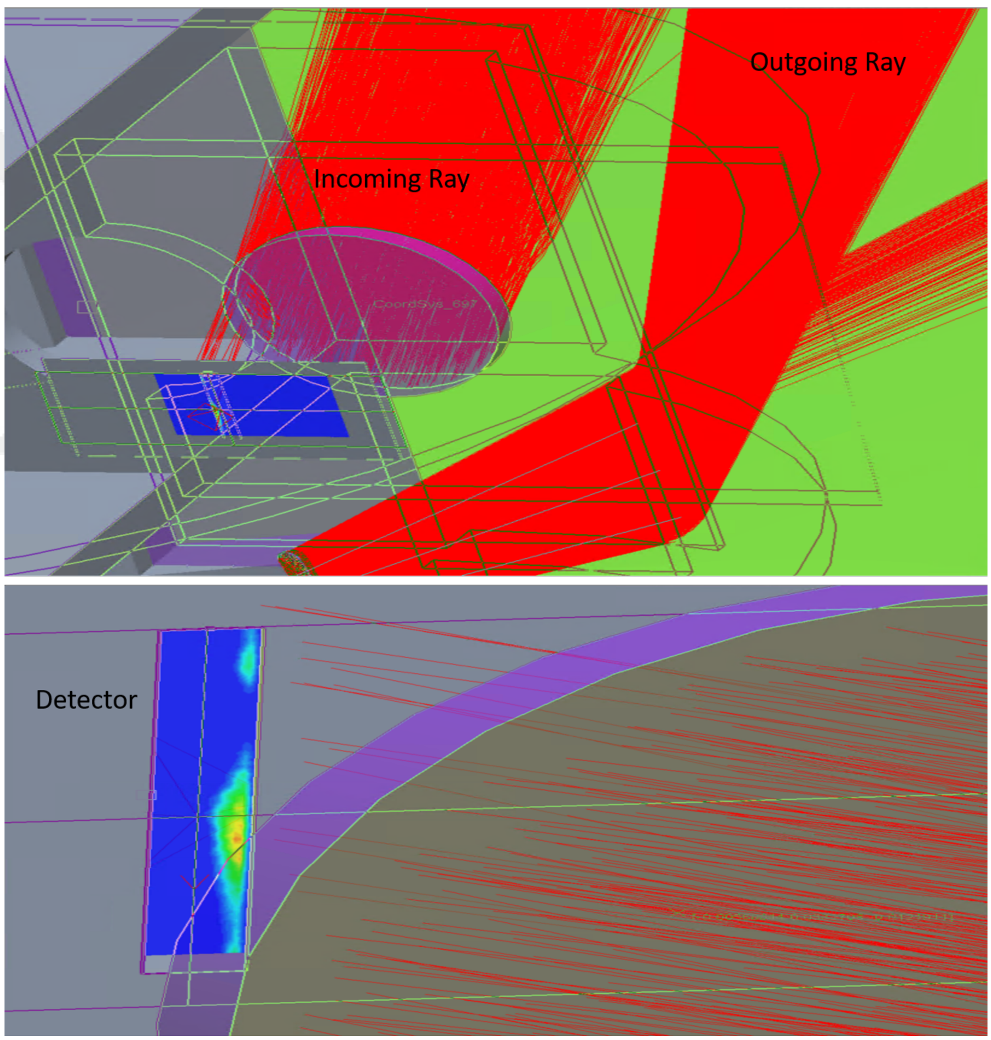

Figure 45: In the LightTools, the detail representative of rays and detector.

CHAPTER VI

CONCLUSION

This thesis reports the design and simulation results of a piezoelectric-based actuator scanning in one dimension. The design aims to enable scanning at high frequencies and wide angles. The targeted structure will be mechanically interconnected and activated by PZT thin film. The effect on the system is discussed by changing the thickness of the PZT thin film. Accordingly, it is aimed to proceed with a PZT thin film of 15 µm thickness. The system oscillates at 208.61 Hz with in-phase motion, adding depth to the scan. The main dimension of the designed structure is 0.66 mm in the scan axis and the scan angle is 12.5 degrees according to the simulation results. These values are reached at 91 kHz. According to the literature, the scanner performance is at a good level. In addition to the performance of the system, it theoretically consumes 1.5mW of energy. Support beams were added to reduce the deformation of the system. The designed system meets the frequency and scanning requirements and will be validated by producing the system. In addition, the reduction of mechanical deformations on the system will be studied.

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