SIMULATION OF SPIRAL-SHAPED MEMS HUMAN ENERGY HARVESTER USING PIEZOELECTRIC TRANSDUCTION

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The undersigned, appointed by the Associate Vice Chancellor of the Office of Research and Graduate Studies, have examined the thesis entitled

SIMULATION OF SPIRAL-SHAPED MEMS HUMAN ENERGY HARVESTER USING PIEZOELECTRIC TRANSDUCTION

presented by **Tanya Srivastava**,

a candidate for the degree of **Master of Science**,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Dr. Khaza Anuarul Hoque

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Dr. Yaw Adu-Gyamfi

Dedicated to my lovely family-

Mom, Dad and Pulkit

without your support and love

it would not have been possible

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Abstract

Energy harvesters are one of the focus areas in the field of research. The complex smart devices and miniaturized electronic design limit the use of traditional wired power source. The need for an efficient human energy harvester for such devices is growing exponentially every year due to an increase in the demand of energy sources and power requirement for the electronics. In the recent years, the trend of research is leading us to come up with a better solution of replacing the use of non-renewable energy with the renewable sources. Human energy harvesting technique has evolved as an efficient substitute to these. But there are few challenges in designing such energy harvesters. Firstly, obtaining higher efficiency. Moreover, since the efficiency is lower it is difficult to obtain enough energy considered to size. The goal is to model and simulate small scale energy harvester which harvests the ambient energy efficiently. There are several advantages of human energy harvester which make it beneficial, cost-effective and has grabbed the attention of researchers since past several years.

In this thesis report, a human energy harvester has been designed in a 2-loop spiral design and simulated to obtain an efficient design using piezoelectric materials.

Keywords: Energy harvester, spiral-shaped, bimorph, Lithium Niobate, Aluminum Nitride, PZT, piezoelectric, low-frequency design

CHAPTER 1

INTRODUCTION

A. MOTIVATION:

Since the era of "electronics revolution", the rise in digital economy has affected the industry leading to furious innovation and therefore an exponential increase in research investment. This trend in digital economy is reflected in the development of many electronic devices such a smartphone, security systems, and eco-friendly vehicles.

According to the Electric and Electronic Manufacturing Market Briefing 2017 as mentioned in (Sindhu, 2017), the global market for devices is expected to attain the growth as high as $3 trillion by 2020 with Asia-Pacific being the largest market and with China as the leader in the industry (Sindhu, 2017)[1].

The existing cutting-edge technology continues to advance to emerging, seemingly ever-growing, where the trend of the robust and complex electronics has shifted to smart electronics and to deep learning embedded and electronic systems as the next milestone. Artificial intelligence augmented reality, automotive, smart surfaces, wearables and robust and powerful developer boards are the new changes we expect to see in the near future. On account of advances in energy efficiency and low power requirement, eliminating the need for AC current to access the embedded systems and IoT devices making it suitable for remote access. The wireless technology is becoming more prevalent, opening the door to new possibilities in the areas like, but not limited to, artificial intelligence, visual augmentation, sensor systems etc. The advances in the energy harvester have pushed the boundaries of the internet of things, embedded devices and other smart devices where the energy harvesting technologies are combined by energy efficient power storage, low power platforms and smart devices which can utilize this seamlessly.

With the advent of these emerging technologies, the traditional power sources are replaced by energy harvesters allowing the devices to operate in a standalone manner, affecting the maintenance cost and time significantly and increasing the life of these devices.

Solar Energy can be used as an indefinite power source, but the drawback is these cells are bulky and have low energy conversion efficiency. However, Alta Devices has developed a single -junction solar cell which has a 28.9% energy conversion rating. This solar cell is based on GaAs which makes it lightweight, flexible and small making it compatible to use in small devices as well. (Atwell, 2018)[2].

Thermoelectric generators based on technology used for integrated circuits. Researchers from Waseda have designed a small thermoelectric generator which generates 12μWcm^{-2} utilizing 5°C temperature difference. The limitation with this design is that the mechanical strength of the device degrades over the lifetime (Atwell, 2018)[2].

B. LITERATURE REVIEW

Wireless power sources have the advantage over the wired source as they allow not only portability but also reduces the maintenance cost. There is a wide range of solutions to overcome this complicate and a huge challenge, one of the several efficient and eco-friendly method is harvesting energy from humans. To meet the power requirement of the complex systems and maintain the constraint of size makes it challenging for the battery technology. Due to the same limitation, the growth of battery technology has become relatively stagnant over the past decade while on the contrary to that the performance of systems has grown steadily with time (Steven R Anton, 2007)[3] Several methods have been investigated for obtaining the energy from the sources for intense electromagnetic induction as mentioned in (Glynne-Jones P, 2003)[4], electrostatic generator as mentioned in (P.D. Mitcheson∗, 2004)[5], piezoelectric materials, dielectric elastomers in (Kornbluh R D, 2002)[6]. In (Roundy, 2005)[7] a qualitative comparison of three methods of energy harvesting was performed. Based on the comparison (Roundy, 2005)[7] states electrostatic generators are easier to integrate into microelectronic and mechanical systems, but it requires a voltage source to operate. Electromagnetic generators on the other end do not require any additional source for voltage. The voltage output, however, is relatively low. The experiment in (Roundy, 2005)[7] showed that piezoelectric converters can generate more power per unit volume relative to electrostatic converters.

Piezoelectric materials can be configured and changed through modification in electrode pattern, piezoelectric material, change in the stress and poling direction and shape of the harvester, increasing the layers in the harvester and tuning the device frequency. There are various research conducted on improving the performance of these harvesters. In (Lee C S, 2005)[8] investigated a PVDF film-based energy harvester with PEDOT electrodes. The advantage of this material is that it provides resistance to damage and cracks caused in electrodes. First, the comparison was conducted between PVDF film with PEDOT/PSS electrodes to film coated with inorganic electrodes. The Pt electrode developed crack when subjected to 33KHz frequency. Whereas indium tin oxide (ITO) withstand the crack up to 213Hz. However, the PVDF with PEDOT/PSS electrode withstands 1MHz without any damage.

In (Churchill D L, 2003)[9], the author has investigated the PZT micro-fibers composite structure which offered more flexibility to the structure. (Baker J, 2005)[11] investigated 3 different piezoelectric materials. The result shows the -31 mode has a lower coupling coefficient (k) in comparison to -33 mode. The same result was presented in (Roundy S, 2003)[12] concluding the system is more likely to be driven at the resonance, operating in -31 modes with a lower resonance frequency and thus resulting in more power. In (Yang J, 2005)[13], the author has analytically shown for a piezoelectric plate operating in -33 mode. The output of the piezoelectric plate depends on the dielectric constant and the coupling coefficient (k). (Cho J, 2005)[14] continued the work of (Richards C D, 2004)[15] in a piezoelectric power harvester by analytically optimizing the coupling coefficient.

Another method to improve the performance of energy harvester is by designing the harvester with multiple piezoelectric materials. The traditional design of the harvester consists unimorph design with serval types of piezoelectric material generally piezoceramic in bending mode. The unimorph cantilever beam structure is described by Johnson et al in (Johnson T J, 2006)[17]. In (Sodano H A, 2004)[18] the author has developed a mathematical model to predict energy harvested by a cantilever beam with bimorph structure. The author in (F, 2005)[19] analyzed a bimorph harvester with two piezoelectric material on sides of non-piezoelectric material to form a beam. (Jiang S, 2005)[20] modeled a bimorph type cantilever structure which has a proof of mass attached to the tip. In this paper, the experiment shows that the thickness of bimorph's elastic layer and proof mass at the end of the cantilever is indirectly proportional to the resonant frequency of energy harvester. In (W, 2006)[21], Anderson and Sexton (2006)[21] concluded a similar relation. They concluded this result by optimizing the physical and geometrical parameter- proof mass, length, and width.

In (Platt S R, 2005)[22] 145 PZT wafers were layered together and solid monolithic PZT cylinder. The advantage of this system is matching resistance frequency is in KΩ range for proposed design whereas in GΩ for monolithic PZT cylinder design. Similarly, in (Bayrashev A)[22], the author has discussed about an energy harvester in which a piezoelectric patch is used. The patch is fabricated between two magnetostrictive materials. Several pieces of research have been conducted to improve the cantilever design by attaching patch at the beam. In (F, 2005)[19] the author has investigated analytical comparison between rectangular shaped and triangular shaped energy harvester. For the same dimension, the triangular shaped beam produces more power in comparison to the rectangular shaped cantilever beam. Whereas (Roundy, 2005) suggested that strain is more evenly distributed. For the same volume of PZT material, a trapezoidal shaped cantilever structure generates twice as much as the energy generated in compared to rectangular shaped cantilever beam structure.

In (Danak A D, 2003)[24], the author researched optimizing the design of curved unimorph PZT energy harvester. The dome height is directly proportional to the output charge. Similarly, an increase in thickness of PZT and substrate results in an increase in higher output charge. The thickness of substrate affects the output charge more than the thickness of the PZT layer, increase in substrate stiffness results in the generation of more charge.

Human energy harvester is used to utilize human energy in many ways with various human activities. (Gonz´alez J L, 2002)[25] ‘s work focused on harvesting energy from finger movement while typing keyboard and results shows it can generate up to 19W. In (Renaud M, 2005)[26], the author investigated on harvesting power obtained from movement of wrist and arm motion while walking. Similarly, in (Platt S R, 2005)[22], they have developed an in-vivo piezoelectric harvester and sensor used in total knee replacement units which are self-powered. In (Mateu L, 2003)[27], the author has experimented the energy harvester with two piezoelectric films inserted into a shoe. Several combinations of material are compared. Comparison has been performed between heterogeneous bimorph, homogeneous bimorph, and homogeneous unimorph were compared in -31 and -33 modes. (Duggirala R, 2006)[28] proposed a new type of piezoelectric energy harvester that involves radioactive thin films, which utilizes radioactive materials to excite a piezoelectric cantilever beam.

However, in (Hai-ren WANG H.-p. H.-s.-t., 2013)[29] a spiral-shaped piezoelectric energy harvester has been proposed. The piezoelectric spring-mass system proposed that the harvester can be operated as a low-frequency power harvester. The resonant frequency of harvester can be adjusted by diameter, the thickness of the layer, length, concentrated mass, and stiffness of spring formed by the piezoelectric wire. The piezoelectric ceramic was used in designing the spring wires.

CHAPTER 2

ENERGY HARVESTERS

A. INTRODUCTION

A renewed interest in using smart electronics is moving to scavenge the ambient energy has aroused with a reduction in the power requirement for today's electronic systems. Harvesting energy from surrounding renewable sources leads to overcoming the limitation of power system with wires. Energy harvesting is the process of using the energy derived from ambient sources from a system's environment and converted and/ or stored as usable electric power. There are several types of ambient energy sources e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy, light[3]-[4] (photovoltaic source), vibration or pressure, temperature differentials (thermoelectric generator), radio energy, biomechanical energy and biochemical energy such as energy extracted from blood sugar (Siang, Lim, & Leong, April 2018). [3]-[4] The energy scavenged can be used to power wireless autonomous devices like wireless sensor networks, wireless low-power electronic devices [3] [2], eliminating the requirement and limitation of wired-source and need for replacement of batteries [4]. In (Siang, Lim, & Leong, April 2018) et al. states that general energy harvesting system includes an energy producing circuit, energy storage module, a power regulator circuit, and protection module if required [4].

Energy harvesting systems can be broadly segmented into Energy source, energy scavenger and the external electrical circuit as shown below in Figure 1: Block diagram of energy harvesting.

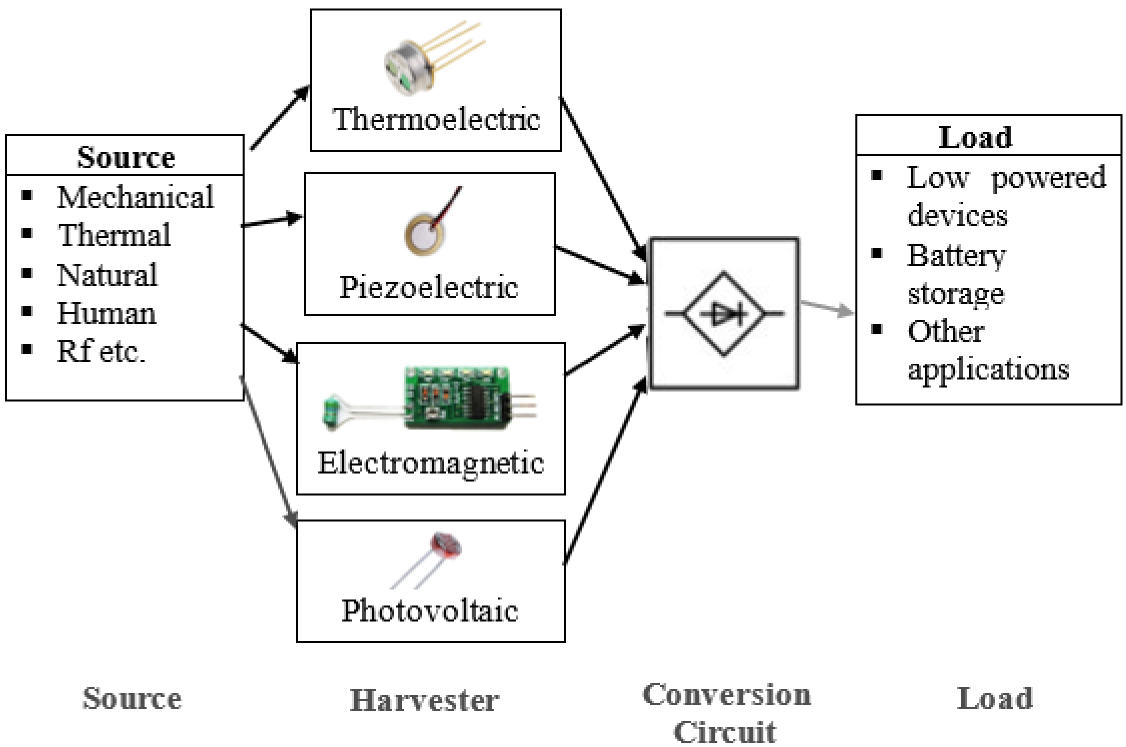


Figure 1: Block diagram of energy harvesting

B. NEED FOR ENERGY HARVESTER

A very important question that is yet to be answered is- the need for such energy harvester? For the past several decades, the electronic devices are powered by batteries or through the wire power source. However, batteries do have the limitation of lifespan and hence, must be replaced at a specific time according to their usage and time. To overcome limited operating life of battery supplied power, we need to either recharge the power storage or provide direct power supply, which is not so practical remedy to the problem.

As the concentration of research these days is focused on obtaining a more optimized design considering the power efficiency, size, cost-efficiency and portability, energy harvester is proven to be more reliable and efficient alternative to traditional sources. One of the important reasons is that although the energy scavenged by these systems is low compared to other methods, but most of the energy harvesting devices are self-sustaining, hence prove to a viable source of power. The progress in obtaining an affordable supplement to wired systems has extended the arms of technology as well as branched into several new spheres of technology and its applications.

C. TYPES OF ENERGY HARVESTER

In this section, we will be discussing several types of energy harvesting mechanism. A comparison between major types are studied and its advantages and disadvantages have been listed. Current advances in research and technologies focus on overcoming the issues with an eco-friendly solution. There are various ambient resources which can be used to obtain the energy which is renewable energy sources and environment-friendly as well. As mentioned in (Siang, Lim, & Leong, April 2018)[3], the taxonomy of potential energy harvester can be classified into either an ambient energy source or external energy source. As been already discussed in chapter 1, ambient energy harvesting is the process of using the energy derived from ambient sources from a system’s environment. The figure below illustrates the taxonomy of potential energy harvesters.

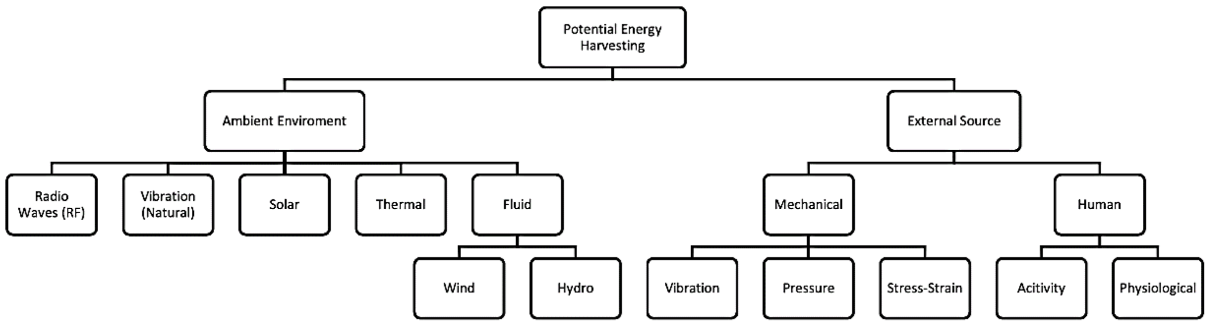


Figure 2: Taxonomy of potential energy harvesting

The energy harvesting mechanism is broadly classified into the ambient environment source and external source. As the name suggests one uses the energy from system's surrounding another from the external source. The further classification of each category is listed in Figure 1.

Amongst several sources mentioned above wind, solar, geothermal, hydropower, coal, oil, and gas are the conventional energy source which are been used over for decades. Few of these are used as energy sources since long back while the usage of few others has matured over the recent decades. But these traditional energy sources have few advantages and disadvantages over each other. There is another very important energy source- vibration energy, which is the major focus these days, is discussed in this report. Broad comparison between few of these has been listed in Table1. below.

Table 1. Environmental and operational factors for diverse energy energy-producing technologies

Characteristics	Wind	Solar	Geothermal	Coal/Oil/Gas	Vibration	Human Energy
Clean	✓	✓	✓	x	✓	✓
Deployment availability	✓	✓	x	✓	✓	✓
Minimal maintenance cost	x	✓	x	x	x	✓
Adverse climate impact	x	x	x	x	x	x
Maturity of Technology	✓	✓	✓	✓	✓	In progress

Since we are focusing mainly on micro-nano energy harvesting systems, a distinct set of energy harvesting mechanism takes place at the micro level of the system.

Bringing the size of the system into consideration, few amongst these mechanisms mentioned in the previous section are not suitable for devices operating at smaller scale, in the range of micrometers and nanometers, due to the difference in physics governing at macro and micro level and its scaling effects.

The major of them to be discussed here are:

- Electromagnetic Energy Harvester
- Piezoelectric Energy Harvester
- Electrostatic Energy Harvester
- Magnetostrictive Energy Harvester
- Ferroelectric Energy Harvester
- Hybrid Energy Harvester

1. ELECTROMAGNETIC ENERGY HARVESTER

This section discusses the basics of electromagnetic energy harvester. It describes the fundamental principles of electromagnetism and give an understanding of voltage linkage to the product of the flux linkage gradient and velocity. The flux linkage gradient depends significantly on magnets that are been used to produce the field. It also depends on the arrangement of magnets, and the number of turns and area of the coil.

Electromagnetic damping is proportional to the square of dimension. As shown in the previous research works, the decrease in Electromagnetic damping with scaling cannot be compensated by increasing coil turns.

A. Introduction: [2]

Since the early 1930s, electromagnetism has been one of the most commonly used methods for generation of electricity. Faraday's fundamental law was another breakthrough in the field of electromagnetics. Electromagnetic generators have the capability of harvesting energy in the range from µW-W which can be implemented using both rotational and linear devices. A later section of this chapter focuses on an introduction to the fundamental principles of electromagnetic induction and discussing further about scaling effects which significantly affects the behavior while miniaturizing of designs.

B. Basic Principle: [2]

Faraday's Law of electromagnetic induction was formulated in 1831 by Micheal Faraday. First Law of electromagnetic induction states that whenever an electric conductor is placed in a varying magnetic field, a potential difference is induced between the ends of the conductor. The principles state that induced emf (ε) in a conductor is proportional to the negative of the rate of change of magnetic flux[2]:

$$\varepsilon = -\frac{\mathrm{d}\phi_B}{\mathrm{d}t} \qquad (1)$$

where ε is the voltage generated or induced emf and

ϕ is the flux linkage.

Generally, most of the generator implementations have multiple turns of the coil. In this case, emf induced in an N-turn coil is given by [2]:

$$\varepsilon = -N\frac{\mathrm{d}\phi_B}{\mathrm{d}t} \qquad (2)$$

where ϕ is the total flux linkage of the N-turn coil

In this case, ϕ can be defined as an average flux linkage per turn. The flux linkage for a multiple coil can be evaluated as the sum of linkage for the individual turns,

i.e. [2]

$$\phi = \sum_{i=1}^{N} \int B \cdot \mathrm{d}A \qquad (3)$$

where B is the magnetic flux density over the $i^{\text{-th}}$ turn.

Voltage is given by:

$$V = -NA\frac{\mathrm{d}B}{\mathrm{d}t}sin(\alpha) \qquad (4)$$

where α the angle between the coil area and flux density direction

C. Advantage and Disadvantage: [2]

- Electromagnetic energy harvesters are simple resonator construction for low-frequency conversion and higher conversion efficiency.
- It does not require an external voltage source unlike electrostatic- which requires a higher potential difference.
- Electromagnetic energy harvester, however, has a lower voltage output in comparison to piezoelectric and electrostatic energy harvester.
- The complexity of fabrication of electromagnetic harvester increases upon lowering the size.
- Another limitation of electromagnetic energy harvester is that it is vulnerable to electromagnetic wave interference.
- It experiences parasitic damping due to friction, magnetic deterioration and loss due to winding.

2. PIEZOELECTRIC ENERGY HARVESTER

Piezoelectric energy harvesting is a very common technique for designing energy harvester. These devices are formed by a specific type of materials which exhibit the property of piezoelectricity.

A. Introduction

Application of strain to the piezoelectric materials electrically polarizes the material. At the atomic level, the displacement of charged atoms within the unit cell of a crystal which results in the net dipole moment within the material. In some crystals, this leads to the formation of dipole moments as a result of which net electric polarization is formed. (Dineva, Gross, Muller, & Rangelow, 2014)

B. Basic principle

Piezoelectric materials exhibit the property to produce an electrical charge when a mechanical force is exerted on the material which results in mechanical deformation. This process is called direct piezoelectric effect. The piezoelectric material when placed in an electric field experiences strain. This mechanism is known as inverse piezoelectricity.

There are two forms to define the relation between the material polarization of material and deformation. Those are: strain-charge or stress-charge form.

The IEEE standard on piezoelectric constitutive equations.

The strain-charge form is mentioned as following:

$$S = s^E T + d\bar{E} \quad (5)$$

$$D = dT + \varepsilon^T \bar{E} \quad (6)$$

S: Mechanical strain

s^E: Elastic compliance tensor (1/stiffness) (Pa^{-1})

T: Mechanical stress vector (Nm^{-2})

$\bar{E}$: Electrical field vector (Vm^{-1})7

D: Electrical Displacement (Cm^{-2})

ε^T: Dielectric permittivity tensor (Fm^{-1})

d: Electro-mechanical coupling factor (CN^{-1})

$d\bar{E}$ in the first equation represents the piezoelectric coupling term, which provides the mechanism for energy conversion (Dineva, Gross, Muller, & Rangelow, 2014).

Property variable like *d* has 2 prefix *i,j*

d_{ij} where *i* is polarization direction and *j* is strain direction.

Two different modes: longitudinal mode(d_{33}) where polarization is developed laterally whereas the second mode is d_{31} where the polarization is perpendicular to the structure.

The equation below shows *stress-charge form*:

$$T = c_E S + e^T E \qquad (3)$$

$$D = eS + \epsilon_o \epsilon_{rs} E \qquad (4)$$

Where $c_E, e, and\ \varepsilon_{rs}$ means stiffness, coupling properties, and relative permittivity at constant strain

ε_0 is the permittivity of free space

One of the most important parameters in designing the energy harvester is the resonant frequency. The resultant output attains a peak value if the operating frequency matches the resonant frequency of the device.

C. Advantage and Disadvantage: [2]

- Piezoelectric energy harvester has simple structure compared to the structure.
- The structure might depolarize which means its polarity decreases after a certain number of switching cycle, which is also known as electric fatigue.

3. ELECTROSTATIC ENERGY HARVESTER

A. Introduction

The electrostatic conversion exploits the relative motion between the electrodes which acts as capacitor plates. Electrostatic converters are capacitive in nature are made of two plates separated by air, vacuum or any other dielectric materials. A relative movement between two plates of a capacitor separate or the area of plates is modified in response to externally applied mechanical energy.

Some of the electrodes can be electrets, which means is a charged dielectric material. The work done due to the movement of electrodes against the electrostatic force between these electrodes results in the energy which is scavenged by the harvester. The electrostatic effect takes place between the parallel plates of the capacitor on which electrical charge is stored. The energy harvesting is achieved by fixing one of the plates and moving the other by an external mechanical motion to change one of the variable capacitor parameters:

- Area of the plate
- The separation between the plates.

For a variable plate capacitor, the structure mainly depends upon- variable area, the variable gap between the plates and variable dielectric constant.

The electrostatic energy harvester can be distinguished into two based upon the relative movement between the electrodes as shown in Figure 2.

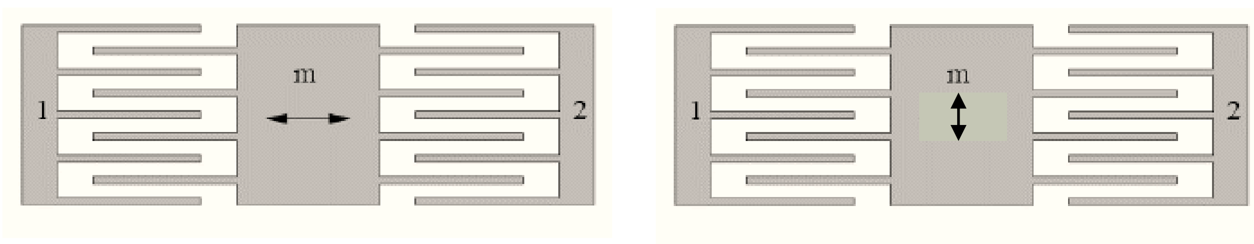


Figure 3: Different configurations of electrostatic energy harvester

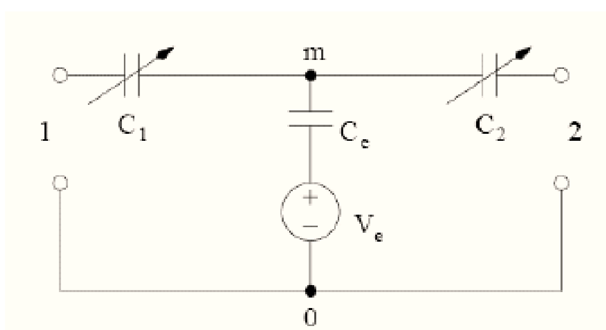


Figure 4: Electric equivalent of electrostatic energy harvester

B. Basic principle

Energy conversion is based on variable capacitor. There are two different kind of energy conversion cycle- charge-constrained and voltage-constrained conversion cycle.

In the *charge-constrained* energy conversion, the charge through the electrodes is constrained, the capacitance decreases which results in the increase in the voltage.

While on the other hand, the *voltage-constrained* conversion cycle

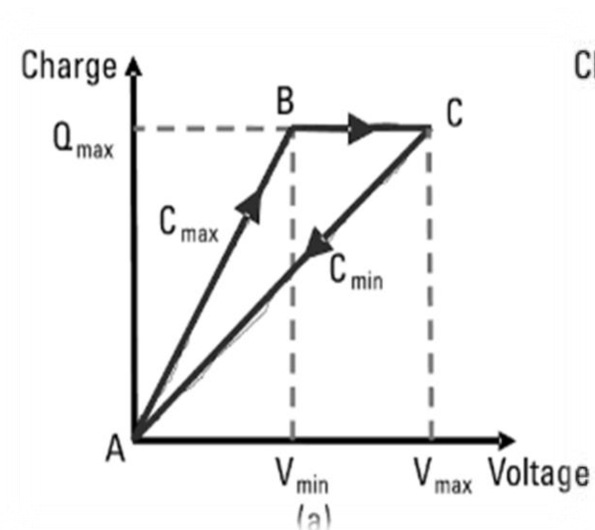


Figure 5: (a) Charge-constrained conversion cycle (b) Voltage-constrained conversion cycle (Bin Yang, 2015)

Electrostatic energy harvesters are capable of operating without smart materials. Thus, unlike piezoelectric energy harvester, their lifespan is less point of concern.

Figure 6 below shows the various mode of operations.

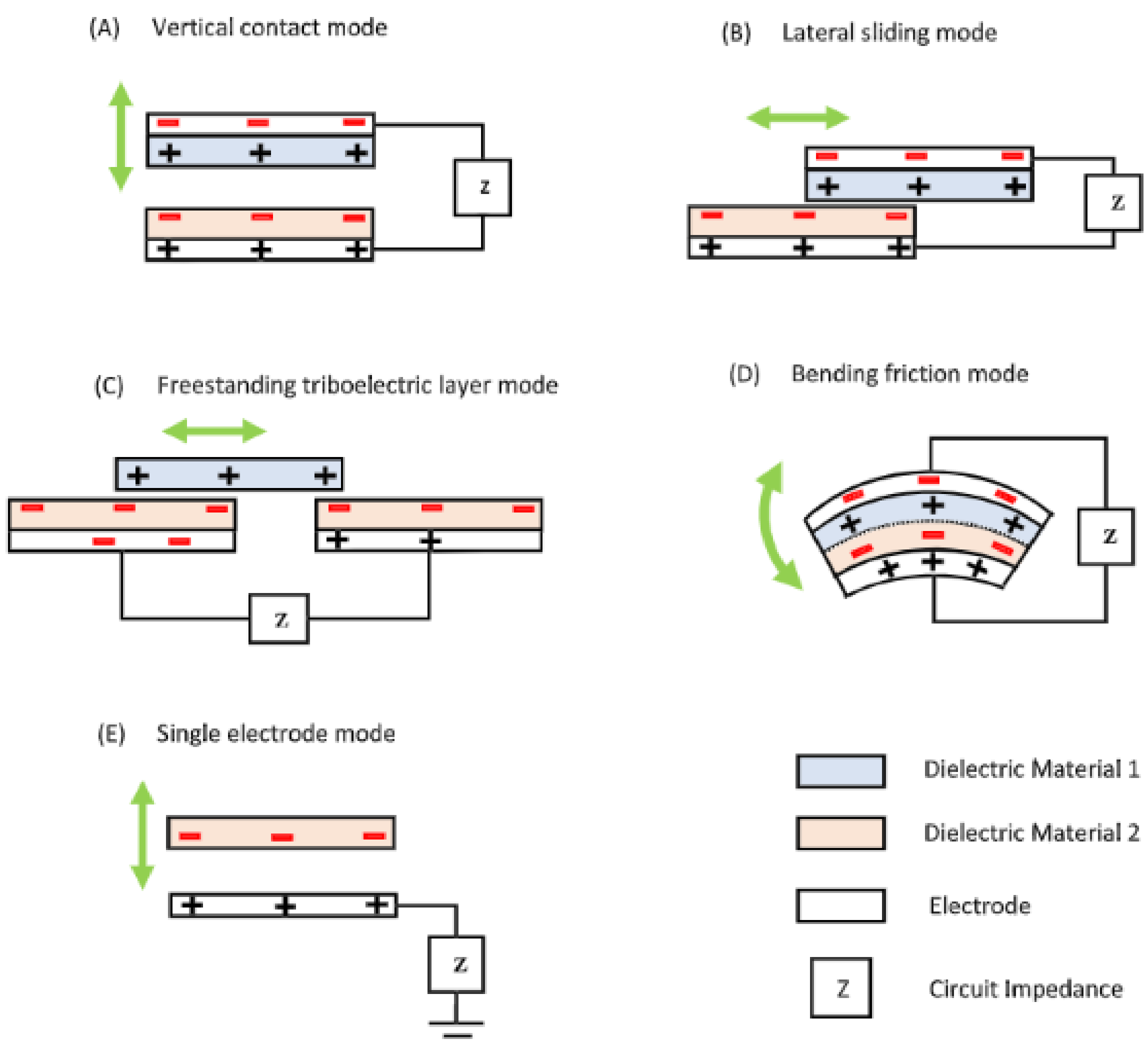


Figure 6: Modes of operation (Siang, Lim, & Leong, April 2018)

C. Advantage and Disadvantage:

- Electrostatic energy harvester does not have the issue of lifespan
- The voltage output is very high
- One of the major drawbacks is this type of harvesters are less compatible with MEMS or wireless network systems.

4. MAGNETOSTRICTIVE ENERGY HARVESTER

A. Introduction

Materials like iron-gallium alloy (Galfenol) experience strain when there is a generation of changing magnetic field.

B. Basic principle

The magnetostrictive energy harvester work based on the *Villari effect* principle. All ferroelectric materials have magnetostrictive potential. When these materials are exerted under strain, they induce a magnetic field and this changing magnetic field cause current according to faraday law.

C. Advantage and Disadvantage:

- Magnetostrictive harvester has high energy density, more flexible and long life.
- The advantage of magnetostrictive energy harvester over Piezoelectric energy harvester: former has a lower susceptibility to aging, depolarization, charge leakage and brittleness.
- Magnetostrictive energy harvester require biased magnets to function in most of the cases

5. FLEXOELECTRIC OR ELECTROSTRICTIVE ENERGY HARVESTER

Flexoelectric polymers can withstand large strains, make them smarter ideal for energy harvester in smart textiles and have a substantial ferroelectric effect on micro or nanoscale. The flexoelectric polymers sometimes outperform the piezoelectric materials in some situations. (Deng Q, 2014)

The flexoelectric field is still in the phase of research. The limited research in the field limits our familiarity about the degradation properties and current design exhibits low coefficients on the nanoscale. One of the several flexoelectric materials is barium strontium titanate ($Ba_{1-x}Sr_xTiO_3$ where ($0 \leqslant x \leqslant 0.2$)) which has high dielectric permittivity resulting in sharp – narrow dielectric peak near ferroelectric-paraelectric phase transition temperature as mentioned in (Jiang X, 2013).

6. HYBRID ENERGY HARVESTER

Hybrid type energy harvesters are the one which uses the combination of multiple energy harvesting techniques. In (Dai X, 2011), the author has presented an energy harvester utilizing multiple magnetoelectric transducers for harvesting the energy. The design contains 4 magnets arranged on the free constraint end of the cantilever beam structure. This was based on the previous work done by Huang et al in (J.K. Huang, New, high-sensitivity, hybrid magnetostrictive/electroactive magnetic field sensors, 2003) and (J.K. Huang, High efficiency vibration energy harvester, 2006) , who presented a new method utilizing magnetostrictive materials/piezoelectric laminate composite for power generation.

In (Khaligh, Zeng, Wu, & Xu, 2008), the author has presented a hybrid piezoelectric/ permanent magnet energy harvesting device (Frecker, 2000). The proposed design utilizes the advantage of both piezoelectric and electromagnetic actuation technique.

CHAPTER 3

PIEZOELECTRIC MATERIAL

A. INTRODUCTION

Piezoelectric phenomenon deals with most of the areas of classical physics such as: mechanics, elasticity and strength of materials, thermodynamics, acoustics, wave's propagation, optics, electrostatics, fluids dynamics, circuit theory, crystallography etc. [10] There is a vast list of past and current researches being done in the field, yet there are many topics to be explored in order to utilize the full potential of this technology. The objective of this chapter is to help understand the fundamental physics behind these studies and researches on piezoelectric sensors and transducers. Since piezoelectric is nowhere just confined to any single independent or specific domain, it is very important to develop a basic idea about the fundamentals before discussing the technical details.

B. PIEZOELECTRIC EFFECT: Direct and Indirect Piezoelectric

Piezoelectricity derived from '*Piezein'* which means pressure. piezoelectricity is defined as electricity caused due to the application of pressure. Pierre and Jacques Curie brothers observed that positive and negative charges appeared on several parts of the crystal surfaces when comprising the crystal in different directions, previously analyzed according to its symmetry [11].

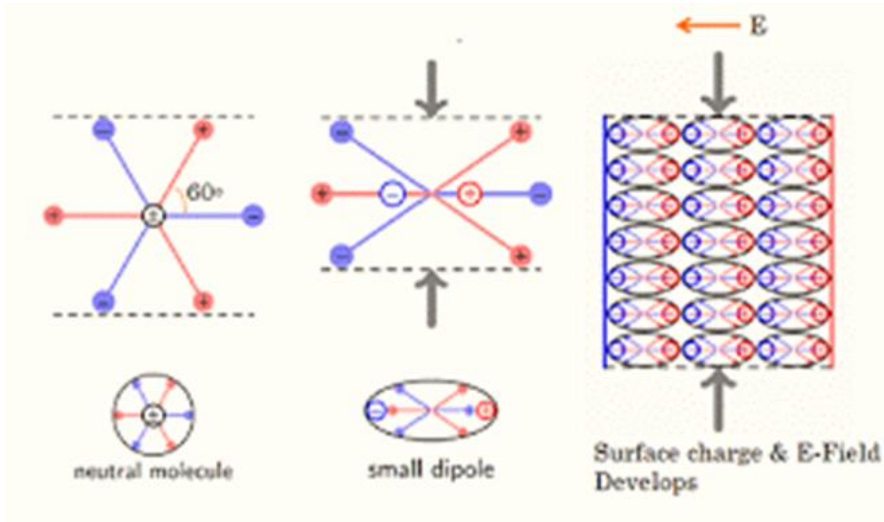


Figure 7: Piezoelectric effect

Figure 7 shows a simple molecular model explaining the basic mechanism of the piezoelectric effect. It explains the generation of electric charge on the application of the electric field. Hence, these types of materials when subjected to mechanical stress exhibit electrical property. On application of external mechanical force, the material which was initially neutral on a charge has a deformed structure which causes the separation of positive and negative gravity centers of the molecule. These gravity centers of the molecule coincide in the absence of any external force. The separation of these gravity centers results in the generation of small dipoles as shown in figure 7. The poles facing one another cancel out each other and result in small linkage charge at the surface of the material. Hence, the material gets polarized. As the result, the electric field is generated. Hence, the electric field generated in the material can be controlled by the mechanical deformation in the material. These mechanical stress-based change in polarization manifests as a potential difference across the material.

The *direct piezoelectric effect* may be defined as the change of electric polarization proportional to the strain[8].

For example, a piezoelectric material with electrodes on top and bottom surface has been taken. The material is connected to galvanometer as shown in figure 8. (Vives, 2004)

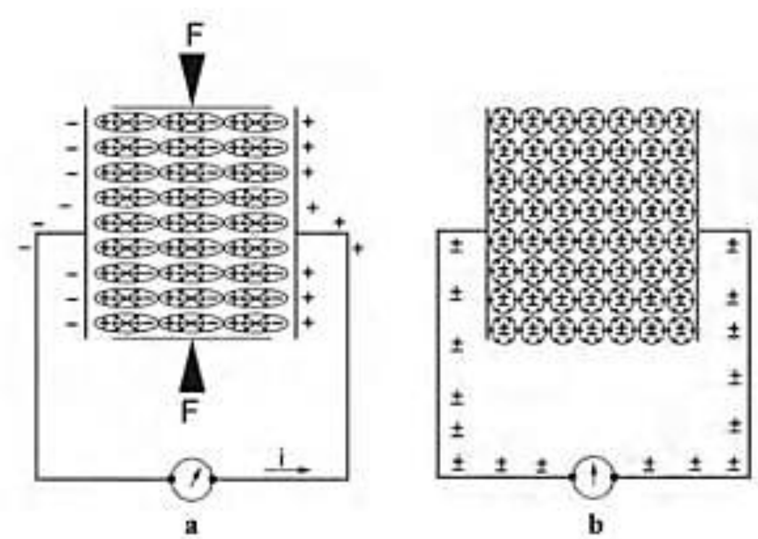


Figure 8: Piezoelectric effect with current (Vives, 2004)

When some pressure is applied to this material it develops a linked charge density on the surface which generates polarization. Polarization generates an electric field which causes the flow of free charge in the conductor. The negative charge will be attracted toward positive linkage charge and the positive charge will be attracted towards the other side and moves towards the respective ends. The flow of charge continues until the charges neutralize. On removal of the pressure the polarization disappears and current flows in the reverse direction. The magnitude of the current is sensed by a galvanometer. Hence, this mechanical energy can be converted to the electrical energy. This electrical energy depends on various factors. Hence, can be controlled or varied according to the need.

Amongst several other advantages of this method, an important feature is that this phenomenon is reversible in nature. Which means on application of electric field on such material they show a reverse operation i.e. mechanical deformation. This is referred to as the *indirect piezoelectric effect*[4]

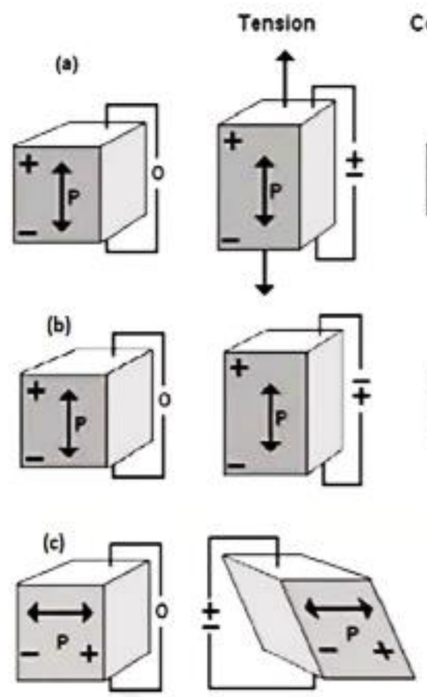


Figure 9: Representation of (a)direct piezoelectric effect (b) converse piezoelectric effect (c)shear piezoelectric effect [in longitudinal direct] (Vives, 2004)

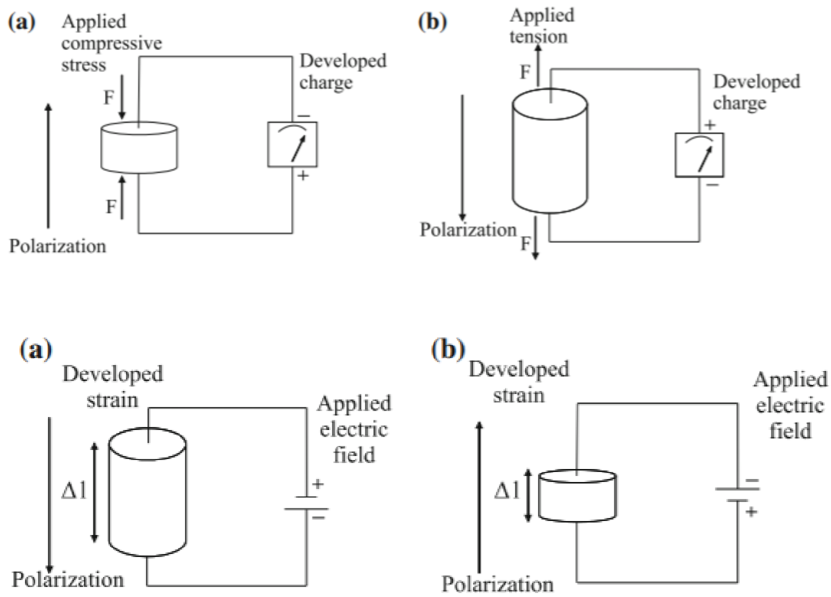


Figure 10: Inverse piezoelectric effect at the applied electric field (Vives, 2004)

C. CRYSTAL STRUCTURE

The piezoelectric effect strongly depends on the symmetry of the crystal. In[5] it is mentioned 20 natural crystal classes capable piezoelectricity with their piezoelectric constants using tensor analysis.

1. PHYSICAL PECULIARITY

Piezoelectric materials are anisotropic dielectrics in which both fields the electrical and elastic are coupled. [5]

2. ELASTIC PROPERTIES OF CRYSTALS[6]

a) *Stress Tensor*

Crystal deformation can be induced by external forces. Since the solid molecules are strongly bonded, thus any deformations will generate forces. As we know, stress is defined as the force in response to strain per unit area. There are nine stress components and is a second-rank tensor $\tau_{\alpha\beta}$, $\alpha, \beta = x, y, z$

where τ_{xx} represents a force applied in the x-direction to a unit area of the plane with normal in the *x*-direction.

τ_{xy} represents a force applied in the x-direction to a unit area of the plane with normal in the *y*-direction.

The stress components in this plane are

$$\tau_{xx} = \frac{F_{xx}}{A} \; ; \; \tau_{yx} = \frac{F_{yx}}{A} \; ; \; \tau_{zx} = \frac{F_{zx}}{A} \tag{7}$$

b) *Hooke's law: law of elasticity*

Hooke's Law of elasticity is discovered by Robert Hooke in 1660. As Hooke's Law states that the amount a spring is stretched or compressed beyond its relaxed length is proportional to the force acting on it. In other words, it states for relatively small deformations of objects; the displacement of deformation is directly proportional to the deforming force.

$$F = kx \tag{8}$$

The objects under this condition return to its original shape and size upon the removal of the external force. In an elastic material, it is implied that strain is a linear function of stress. When any object is stretched beyond the elastic limits it becomes plastic.

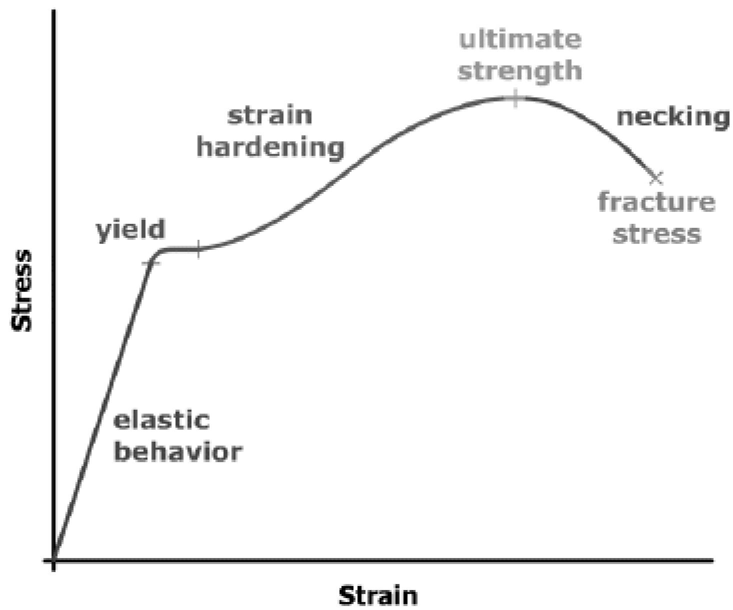


Figure 11: Hooke's Law

c) Young's modulus and Poisson's ratio

Young's modulus is a mechanical property that measures the stiffness of a material. It is the relationship between stress and strain in the linear elastic regime of the material property.

Stress where is defined as force per unit area and strain as is the relative change in shape or size of an object due to applied force.

Young's modulus is denoted by E or Y and its SI unit is Pascal.

$$E = \frac{\sigma}{\epsilon} \qquad (9)$$

where,

E: Young's modulus (Unit: Pascal)

σ : Uniaxial stress (unit: pascal)

ϵ : Strain

$$Stress\ (\sigma) = \frac{Force}{Area} \qquad (10)$$

$$Strain(\epsilon) = \frac{\Delta L}{L_0} \qquad (11)$$

In practical applications, generally, Young's modulus is in MPa or N/mm^2 or GPa.

Poisson's ratio is the negative ratio of transverse strain to axial strain.

It is denoted by ν

$$Poisson's\ ratio\ (\nu) = \frac{Transverse\ strain}{Axial\ strain} \qquad (12)$$

D. PIEZOELECTRIC MATERIALS

In the middle of eighteenth-century Carolus Linnaeus and Franz Aepinus observed that some materials exhibited certain special properties. They resulted in electric charge upon changing temperature. Further investigation in such materials was unsuccessful. However, Jacques Curie and Pierre Curie observed some unusual characteristics in certain crystals as quartz, topaz, Rochelle salt that upon applied tension or compression force it generated a voltage of opposite polarity to each other which was proportional to the load. The phenomenon was known as piezoelectric by Hankel.

Later the researchers observed that material resulted in modification of its length when exposed to the electric field. The resulted deformation was proportional to the applied field. 20 natural crystals showed the property of piezoelectricity. After several types of research, the following successful finding was obtained:

- Development of lead zirconate titanate (PZT) family as in (Jaffe B, 1954)
- Understanding the properties of perovskite crystal in the field of electromagnetic applications.
- The concept of doping and material impurities was developed. This proved to an important breakthrough toward obtaining the desired material by varying their composition and obtaining the materials with different stiffness, dielectric constant, piezoelectric coupling coefficients etc.

The piezoelectric materials were used in actuator and motor using their indirect or converse piezoelectric effect.

E. TYPES OF PIEZOELECTRIC MATERIALS

Piezoelectric materials can be broadly classified into two categories mainly: natural or man-made piezoelectric material. The natural piezoelectric materials are crystals like quartz (SiO_2), topaz, Rochelle salt organic substance like silk, bone, hair, rubber, wood. (Dineva P. , 2014)

Man-made piezoelectric materials are crystals that are quartz analogs, ceramics, polymers, and composites. The piezoelectric crystals are divided into seven groups which are associated with the elastic property.

Table 2: Piezoelectric Structure and properties

Structure	**Elastic Property**
Triclinic	Anisotropic
Orthorhombic	Orthotropic
Cubic	Isotropic

There are four more structures: tetragonal, trigonal, hexagonal and monoclinic other than the three mentioned above. Out of total 32 classes, only 20 has piezoelectric properties. Some of the common ceramics are: Barium titanate ($BaTiO_3$; Lead titanate ($PbTiO_3$); Lead zirconate titanate ($Pb[Zr_x Ti_{1-x}]O_3, 0 < x < 1$) more commonly known as PZT; Potassium niobate ($KNbO_3$) ; Lithium niobate ($LiNbO_3$); Lithium tantalate ($LiTaO_3$).

PZT has a perovskite structure. When the temperature is above the Curie temperature the material doesn’t behave as piezoelectric and its structure changes to cubic lattice structure. When the temperature falls below the Curie temperature the cubic structure changes to tetragonal lattice structure. This results in polarization creating the dipole moments. This dipole moment affects the nearby lattice and hence result in same dipole orientation in the domains. (Xu, Hansen, & Thomsen, 2012)

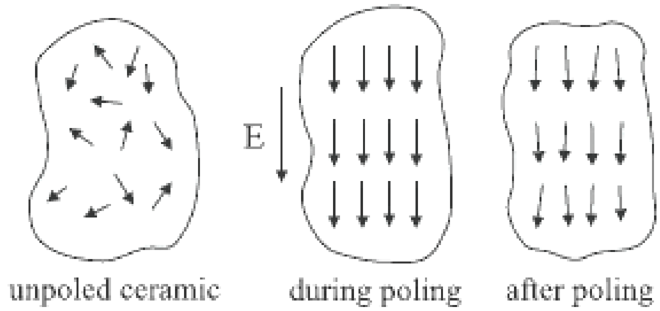


Figure 12: Poling in piezoelectric material

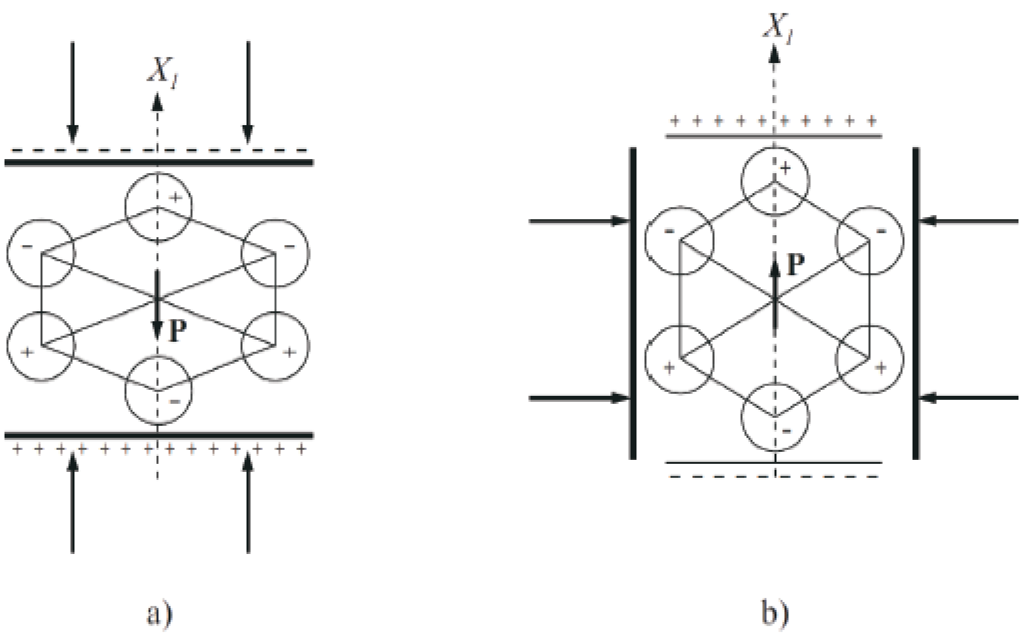


Figure 13: (a)Longitudinal piezoelectric effect (b) Transverse piezoelectric effect

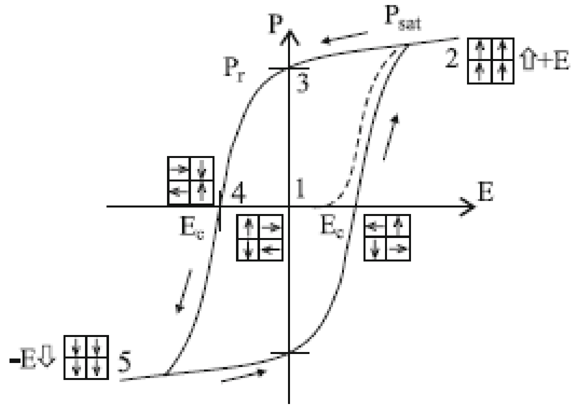


Figure 14: Hysteresis curve for piezoelectric polarization

On applying an electric field to a piezoelectric ceramic until the saturation point of polarization P_{sat} is reached. The field when reduced to zero it determines the P_r polarization reversing the field results in negative saturation of polarization and remnant polarization, and then again reversing it back will restore the positive remnant polarization. On applying an electric field which is a coercive field, there is zero net polarization.

F. CONSTITUTIVE EQUATIONS

The major contribution was done by Voigt and Duhem in the phenomenological theory of piezoelectricity. For a piezoelectric material, generally, the relationship between total internal energy *U* and mechanical and electrical work is given as:

$$dU = \sigma_{ij} ust_j + E_m dD_m. \qquad (13)$$

where E_m is Electric field vector

D_m is electrical displacement vector

Based on the thermodynamics of deformation and theory of energy density of elastic deformation, the linear constitutive equation can be derived as (Xu, Hansen, & Thomsen, 2012):

$$dD_i = \left(\frac{\partial D_i}{\partial E_k}\right)_T dE_k + \left(\frac{\partial D_i}{\partial T_{kl}}\right)_E dT_{kl}$$
$$dS_{ij} = \left(\frac{\partial S_{ij}}{\partial E_k}\right)_T dE_k + \left(\frac{\partial S_{ij}}{\partial T_{kl}}\right)_E dT_{kl}, \qquad (14)$$

Where E is the electric field

D is the electric displacement field

T is stress

S is strain

In the above equation, both *E* and *D* are first order tensor whereas *T* and *S* are the matrices.

$$D_i = \varepsilon_{ik}^T E_k + d_{ikl} T_{kl}$$
$$S_{ij} = d_{ijk} E_k + s_{ijkl}^E T_{kl}, \qquad (15)$$

Where, $\varepsilon_{ik} = \frac{\partial D_k}{\partial E_k}$ is permittivity

$d_{ikl} = \frac{\partial D_i}{\partial T_{kl}}$ is piezoelectric coefficient

$s_{ijkl} = \frac{\partial S_{ij}}{\partial T_{kl}}$ is elastic compliance

CHAPTER 4

DESIGN AND METHODOLOGY

A. INTRODUCTION

As discussed in the literature review, many kinds of research have been conducted about energy scavenging devices with each of them having a unique mechanism of harvesting human energy. These energy harvesters have unique shapes and material combination. There are several researches conducted regarding energy harvester which works on the mechanism of electromagnetic. These had simple construction on a large scale, low output impedance, and high output. But along with these advantages, the cons are low output voltage. One of the common materials is Neodymium Iron Boron.

Electrostatic is another popular method of energy harvesting. It has the advantage of generating very high voltage output, convenience for tuning the frequency and rectification of voltage. However, on the other end, there are some disadvantages like low output current is obtained, a high impedance is required, biased voltage is required. Several other energy harvesters are designed based on magnetostrictive mechanism. Metglas is one of the common materials. The advantages of this mechanism are high energy density and long-life cycle. Whereas one of the downsizing limitations is that these energy harvester gets affected by an electromagnetic field.

Another most commonly preferred energy harvesting technique is piezoelectric energy harvesting. One of the most common material for designing such energy harvester is Lead zirconate titanate. Piezoelectric mechanism offers many advantages over other techniques. Piezoelectric harvesters are suitable to small scale, offering high output voltage and high couple coefficient.

Because of several suitable features of piezoelectric suitable characteristics, piezoelectric has been used to design this energy harvester. As mentioned in (Queeni Sunder, 2014), the output of the harvester depends on various factors like design, material etc. For an energy harvesting device, the output obtained should be as greater as possible. Power output generated by a piezoelectric energy harvester is directly proportional to the mass of the energy harvester and inversely proportional to the operating frequency of the device. Which means the focus of design is to achieve low operating frequency. Various energy harvester designs and the materials have been proposed that could be used for improving the design to meet the design requirement. For example beam type energy harvester, trapezoidal, unimorph structure, bimorph structure, spiral design.

As mentioned in (Siang, Lim, & Leong, April 2018) et al. comparison of various design architecture. Cantilever design is simple to design have comparably low frequency and is suitable for micro-scaling. Linear design is simpler to design and can be used to design an energy harvester for lower frequency. However, since linear designs are mainly coil and spring technique, they are not so suitable for micromachining fabrication processes. A rotational design-based energy harvester is difficult to design. However, is suitable for microscale design. Some research has been conducted on using the spiral shape design for an energy harvester like in (Hai-ren WANG J.-s. Y.), where the author has designed a piezoelectric human energy harvester which was capable of operating at low frequency 50-200Hz. In chapter3A the author has put forward a planar spiral piezoelectric bimorph operating with the coupled flexural and extensional vibration modes based on the availability of ceramic spiral piezoelectric actuators. The spiral-shaped energy harvester performs better than beam type energy harvester.

Beam type energy harvester has a high operating frequency. We can reduce the operating frequency by increasing the size of the energy harvester. But that will not be a desirable solution for micro/nanoscale energy harvester design. As the mass of the energy harvester is responsible for maximum output power as well as device frequency to be lower. As the spiral structure has a larger mass and requires less space than the rectangular shaped design in the same dimension. Due to the same advantage, a spiral shape for the energy harvester has been chosen.

A bimorph structure is used to obtain maximum displacement and provide strength to the structure. The design used here has 2 arms which increase the mass of the energy harvester in the same space. The bimorph design generally has either a PZT layer at the top surface and bottom and shim layer sandwiched between the two layers. The main function of the shim layer is to provide mechanical strength. There are various material combinations used. The most common piezoelectric material used in such harvester design is PZT. There are two different type of piezoelectric materials: ceramic and polymer. 22 out of 32 crystallographic elements exhibit piezoelectric properties. PZT is ceramic and is chosen because of its stiffness required for obtaining spiral shape. We want to use a piezoelectric material which has less stiffness. As Young's modulus is directly proportional to the stiffness of the material. Lower is Young's modulus, less brittle the design would be. Young's modulus is a very important property when it comes for deflection of a material, it determines the rigidity of a material. A material will give maximum displacement if the Youngs modulus is less which results in greater energy generation.

B. SPIRAL STRUCTURE

In [5] the author has presented a planar spiral bimorph structure. Numerical results show that the spiral structure has relatively lower operating frequency in comparison to the beam type structure of the same size. The spiral bimorph structure presented in [5-6] has relatively low frequencies even though the dimension remains small.

Another design proposed is a spring-mass system as a low frequency energy harvester in [7] where spring is formed by winding the wire, which is piezoelectric in nature, with two helical electrodes on the surface. The design proposed in [5] is in-plane bending motion and the one proposed in [7] has out-plane torsional motion. Design mentioned in (Hai-ren WANG H.-p. H.-s.-t., 2013) is a spiral structure as shown below with gradually increasing radius as shown below in Figure 16.

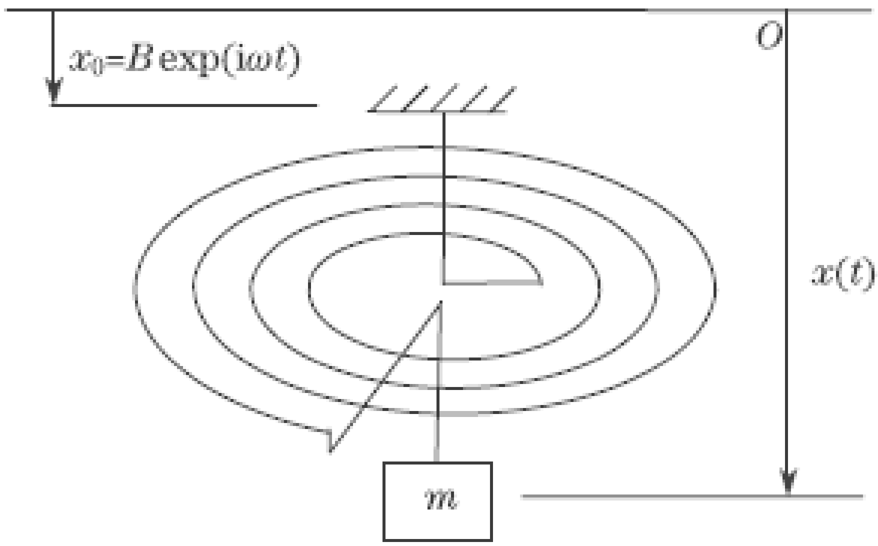


Figure 15: Spiral piezoelectric transducer with the concentrated mass as low frequency power harvester (Hai-ren WANG H.-p. H.-s.-t., 2013)

Based upon the similar concepts this energy harvester has been structured as shown below with 2 spiral loops combined into one structure.

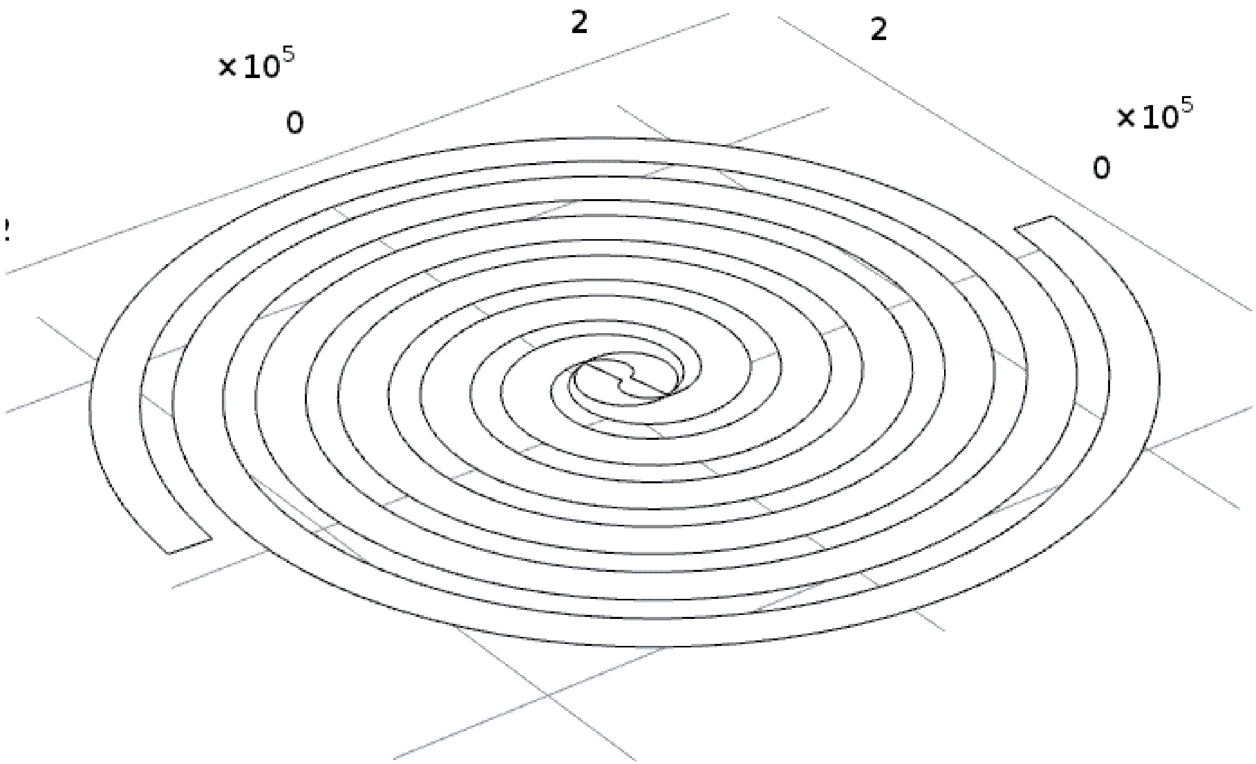


Figure 16: Spiral 2-loop structure

This structure has 2-loops winded in the spiral shape. The design operates as the lower frequency in comparison to a single-loop spiral structure shown below in figure 18.

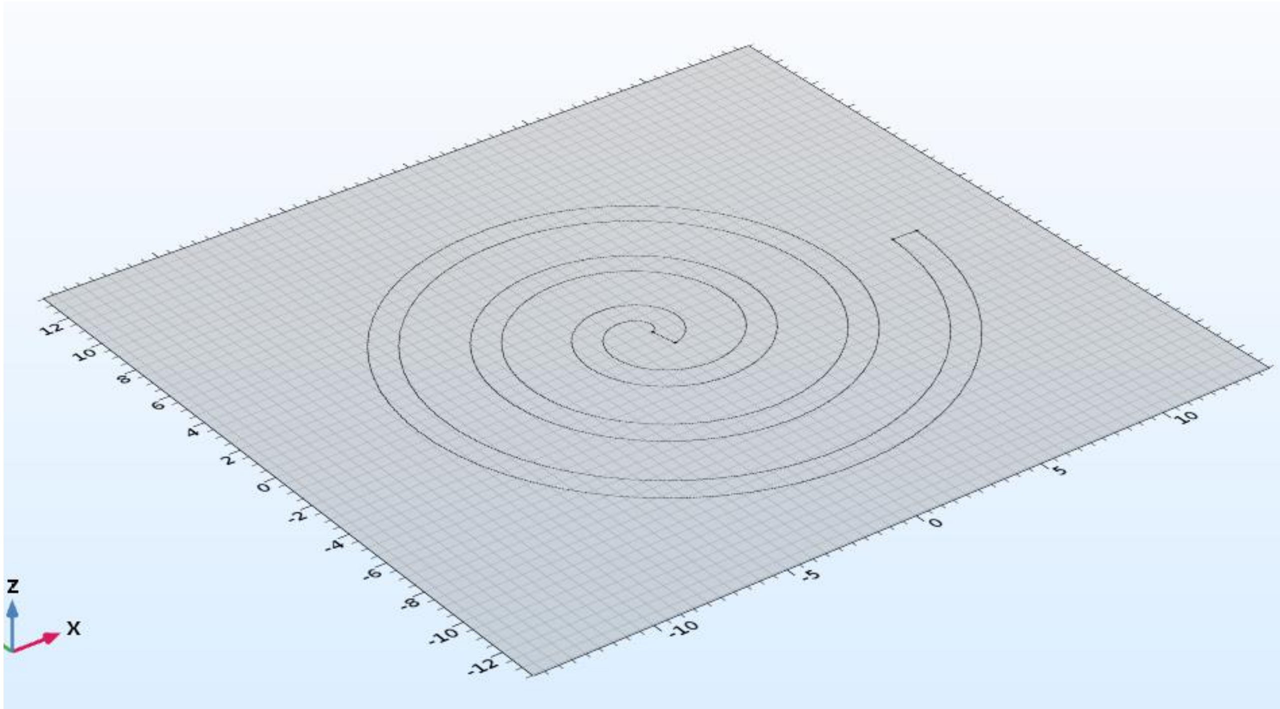


Figure 17: Single-loop spiral structure for piezoelectric energy harvester

The performance of a single-loop, however, is still better than the beam type or cantilever beam structure. This is due to the reason that the spiral-shaped structure has a longer length of the material in comparison to the traditional beam type structure, which results in increased mass. As the mass of the structure is inversely proportional to the frequency of the system.

The performance of the energy harvester depends on various factors like dimension and material property. To understand how dimension affects the performance, the energy harvester has been modeled and its dimensions are varied based upon which the behavior of the structure is analyzed.

Parametric sweep has been performed to analyze the relationship between the length of the structure and the displacement.

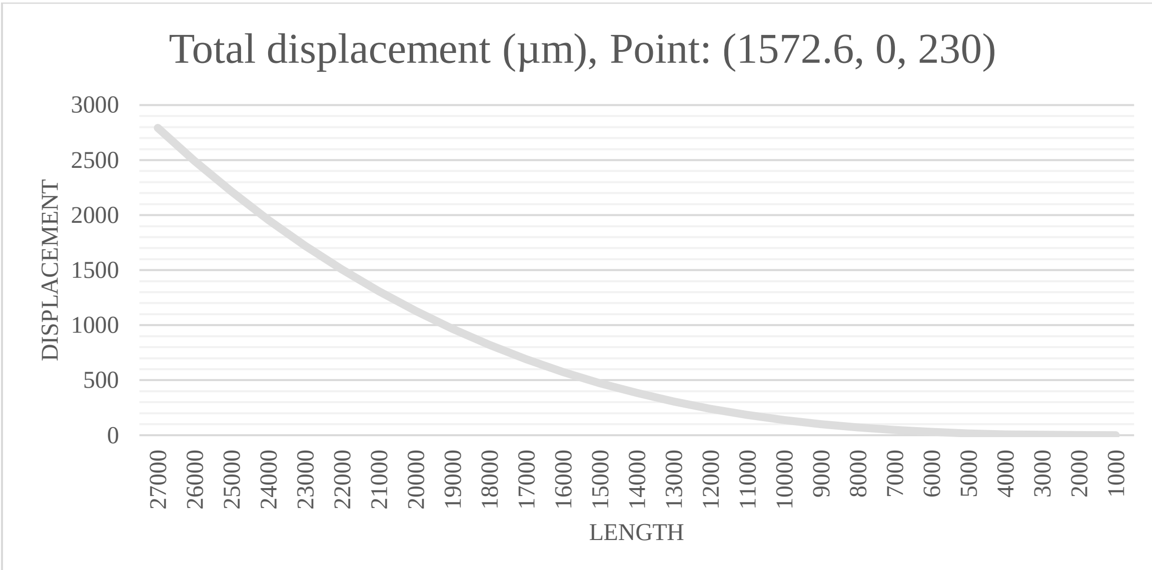


Figure 18: The Parametric sweep of length (L)

From the figure above describing the parametric sweep varying the variable length over a range of values, it was observed that the displacement of energy harvester decreases with the decrease in length. Therefore, it can be concluded that the displacement is directly proportional to the length of the device.

Similarly, the parametric sweep was performed varying the width of energy harvester. The figure below describes the relation between width and the resulting displacement. It was observed that displacement increases upon reducing the width of the energy harvester.

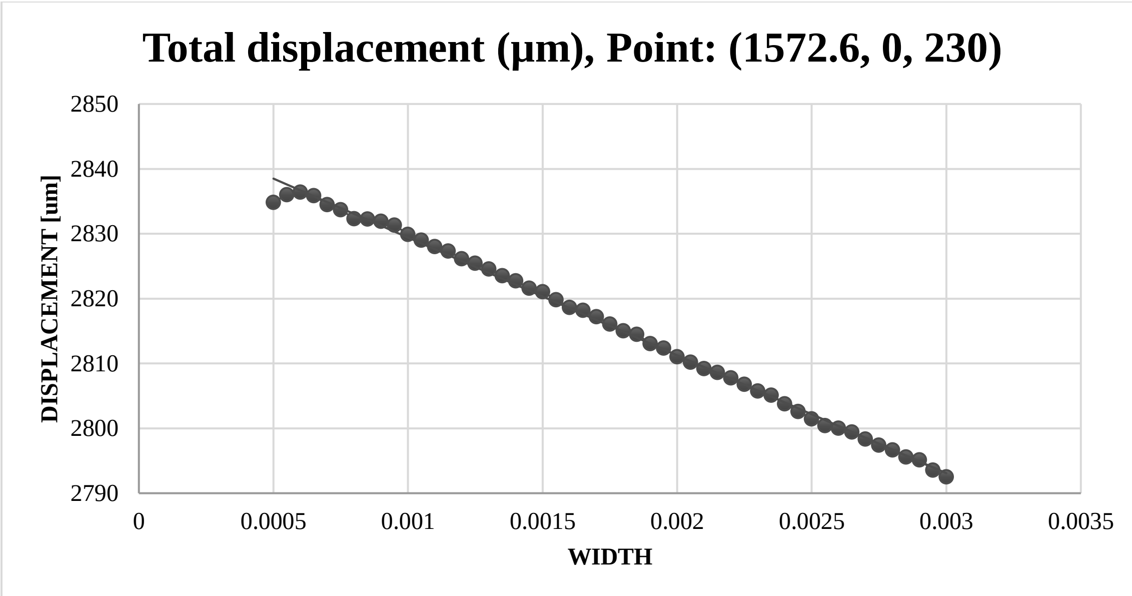


Figure 19: Parametric sweep of width (W) of the device

Also, to understand how the thickness of shim layer affect the behavior the parametric sweep was performed over the Tshim (thickness of the layer in the middle) keeping the thickness of the device constant and varying the thickness of shim layer and piezoelectric layer (both top and bottom) with the displacement.

For instance, when the thickness of entire geometry was fixed to 400µm. Tshim was varied for over a range and based on the thickness of the shim layer the thickness of the PZT layer was adjusted to keep the overall thickness same.

The variation resulted in the displacement as shown in Figure 20. It was observed that the displacement is inversely proportional to the width of the material with higher Youngs modulus value. Since the main idea behind using the shim layer is to strengthen the structure. As a result of which stiffness of the energy harvester increase with the increase in width of the shim layer at the center hence resulting in less displacement.

After parameter optimization, the spiral-shaped energy harvester was designed in COMSOL keeping the above observations in mind.

The spiral-shaped energy harvester is designed with PZT layers on top and bottom and shim layer in the center. The electrodes are at the extreme face of the structure. The structure was build using model builder in COMSOL Multiphysics software. The spiral base is formed using the parametric curve and then extruded to form several layers. The detail information about designing the structure has been mentioned in the appendix along with the material property. The figure below shows the final structure of the 2-loop spiral energy harvester.

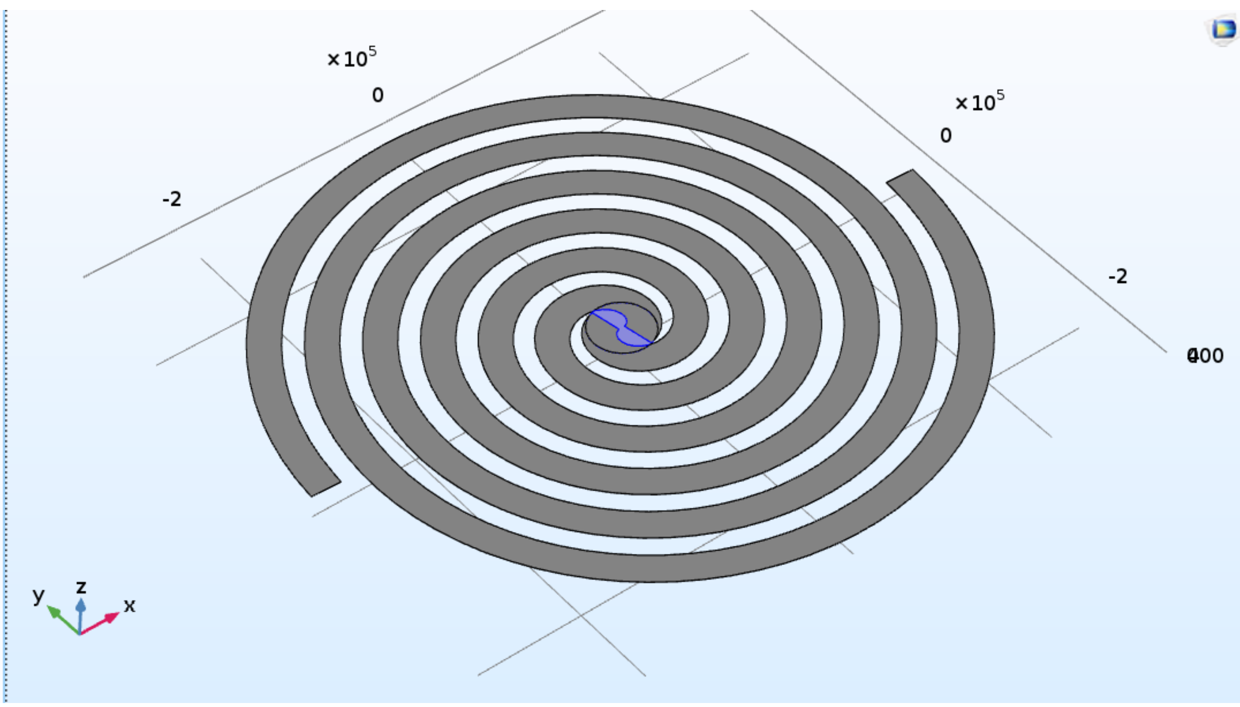


Figure 20: 2-loop spiral shaped energy harvester

After designing the geometry, the mesh was generated as shown in the figure below:

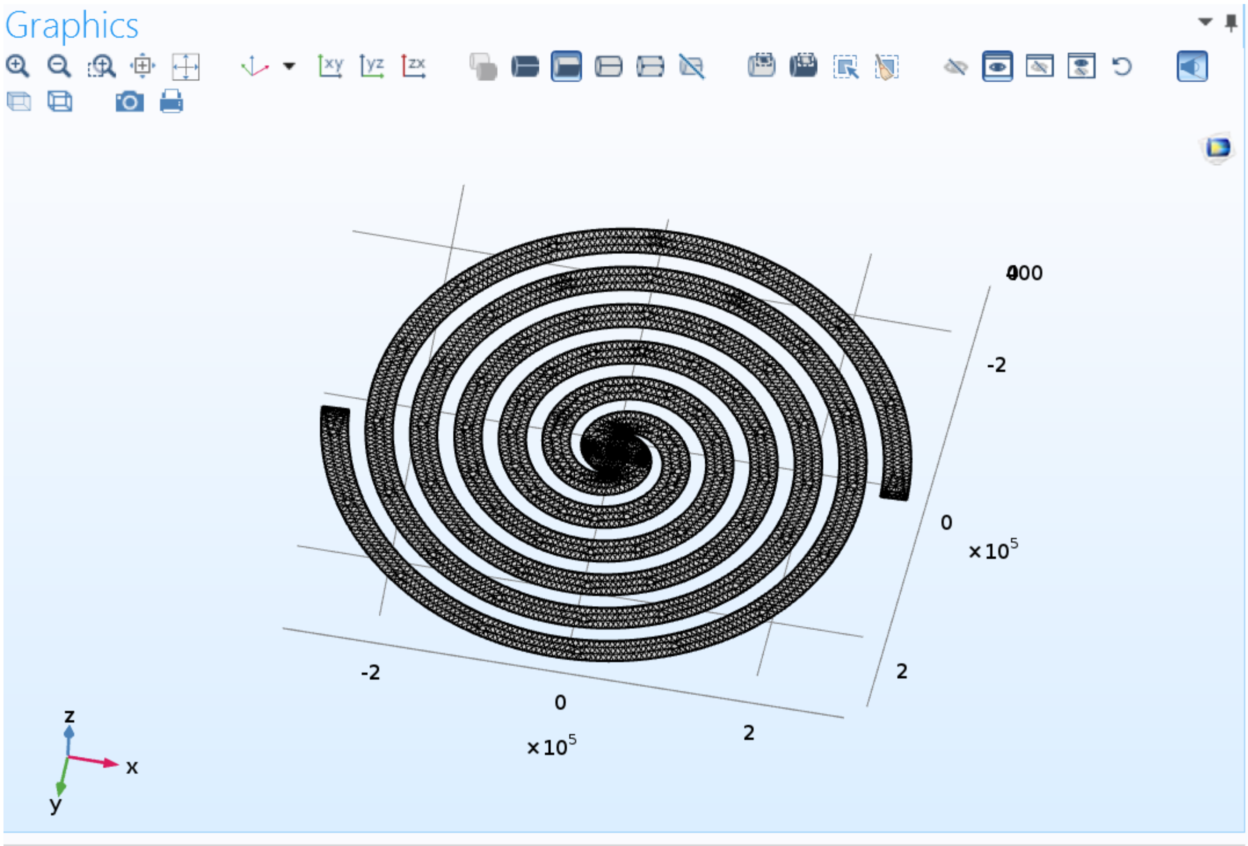


Figure 21: Mesh formation

The main idea behind mesh convergence is that more is the structure for the mesh refined better would be the accuracy of the performance analysis. There are 4 different types of mesh elements. We choose the element shape and size to find the best fit for geometry to refine the mesh. The physical significance of mesh is that increasing the number of mesh in the geometry analysis decreases the natural frequency.

For a beam of 27000*3000*400µm dimension with a 60µm thickness of the shim layer (Tshim) for meshing the geometry with normal element size, it generated the complete mesh consisting of 8106 domain elements, 4404 boundary elements, and 560 edge elements. The number of elements would, however, change with changing the mesh element size to coarser or finer on the scale.

The performance of the energy harvester with Lithium Niobate as shim layer and Aluminum Nitride is shown in the figure below. The configuration with PZT-5H- AlN-Ni was simulated with the same dimensions of energy harvester. The displacement obtained was observed to be 6.8 um approximately. This result was higher than the displacement obtained by the PZT-5H -Nickel configuration.

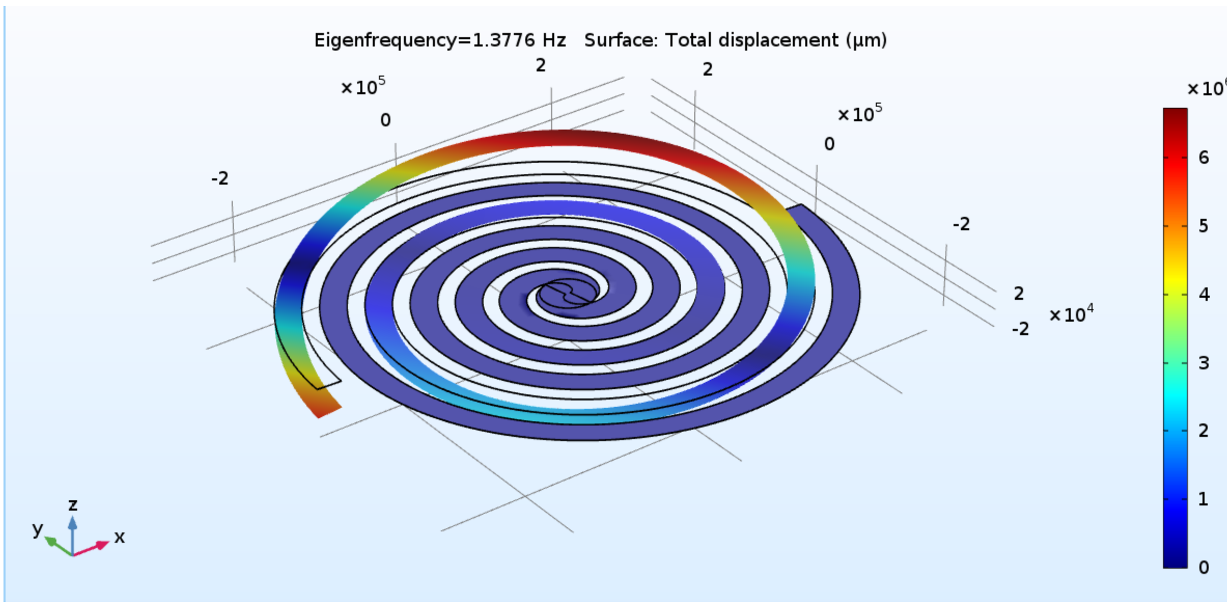


Figure 22: 2-loop energy harvester with AlN as the shim layer

From the simulation of PZT-5H-$LiNbO_3$-Ni combination structure it was observed that the maximum displacement was obtained as 7.23 um approximately, is higher than the PZT-5H-AlN-Ni material combination. However, both shows higher displacement in comparison to similar spiral structure simulated in other papers, which was obtained to be at the maximum of 6.12um in the other configuration with PZT-5H and nickel shim layer.

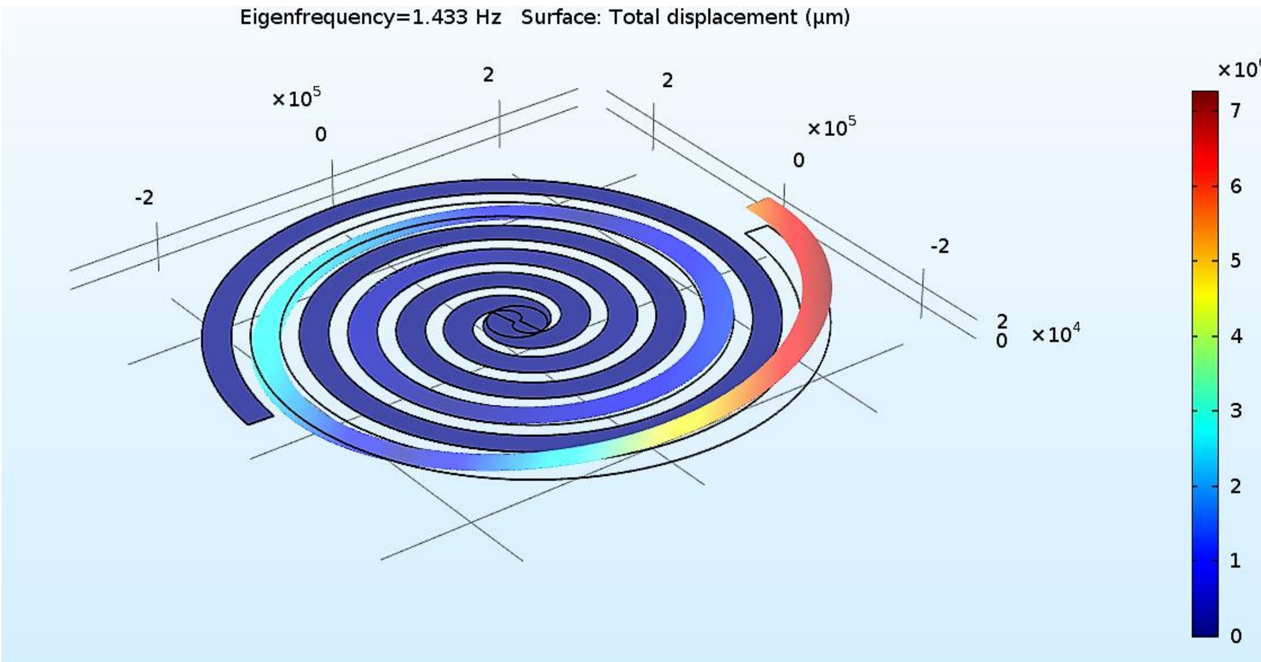
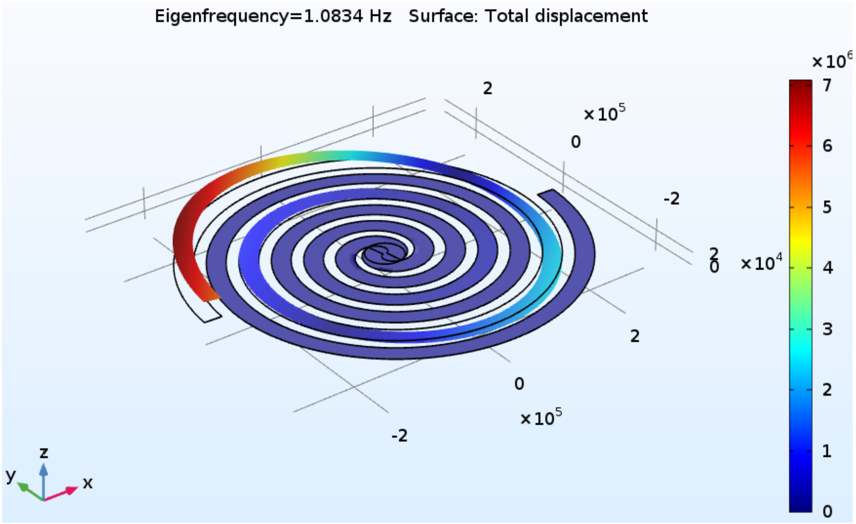
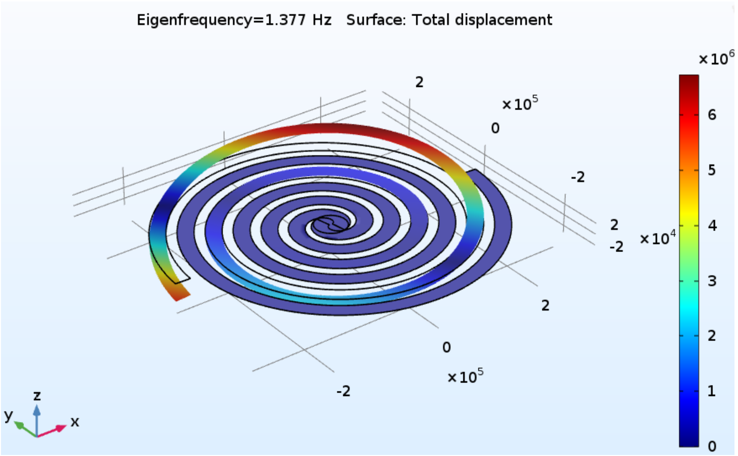
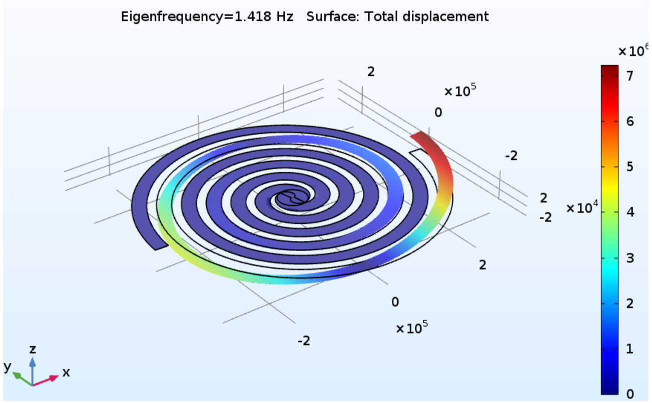


Figure 23: 2-loop energy harvester with Lithium Niobate as the shim layer

Below are the von-stress diagram and 6 eigen frequency computation for PZT-5H-AlN-Ni and PZT-5H-$LiNbO_3$-Ni in the plots below.


Eigenfrequency=1.0834 Hz Surface: Total displacement
×10^6
7
6
5
4
3
2
1
0
×10^5
×10^4
×10^5
2
0
-2
z
y
x


Eigenfrequency=1.377 Hz Surface: Total displacement
×10^6
6
5
4
3
2
1
0
×10^5
×10^4
×10^5
2
0
-2
z
y
x


Eigenfrequency=1.418 Hz Surface: Total displacement
×10^6
7
6
5
4
3
2
1
0
×10^5
×10^4
×10^5
2
0
-2
z
y
x

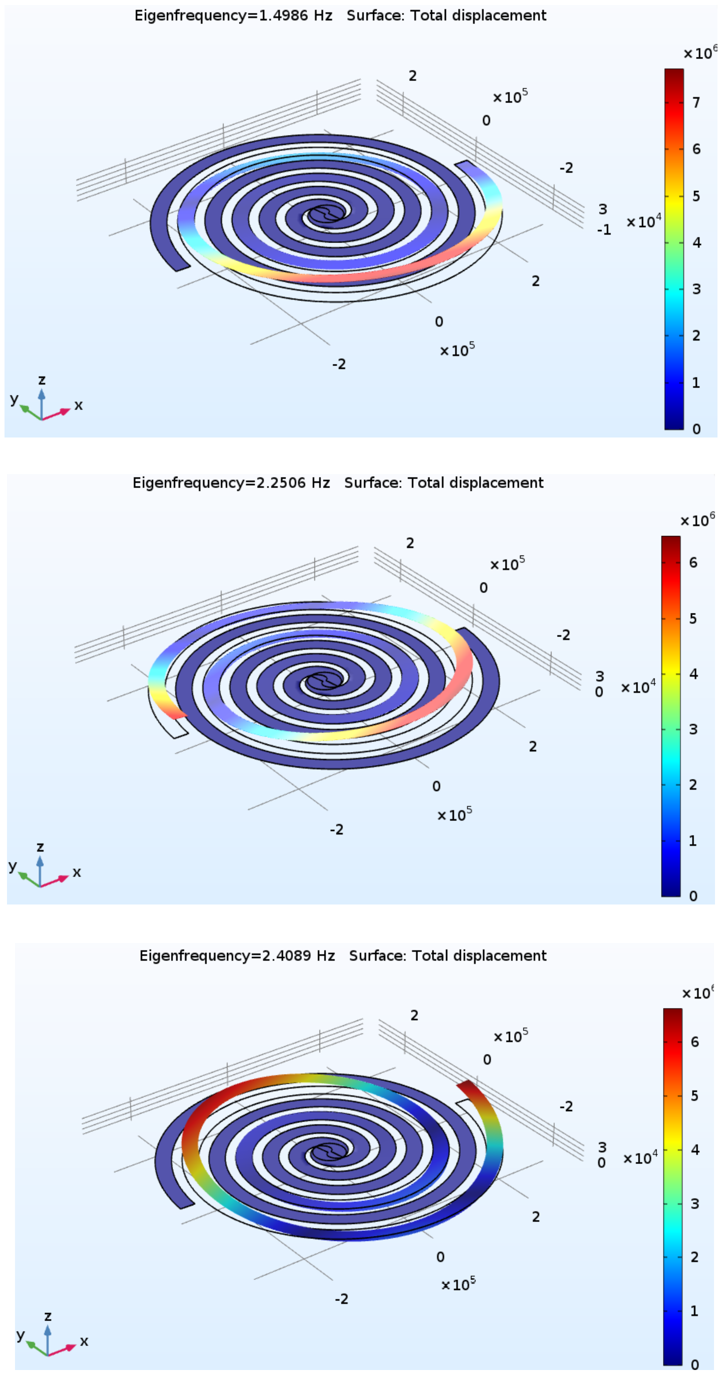
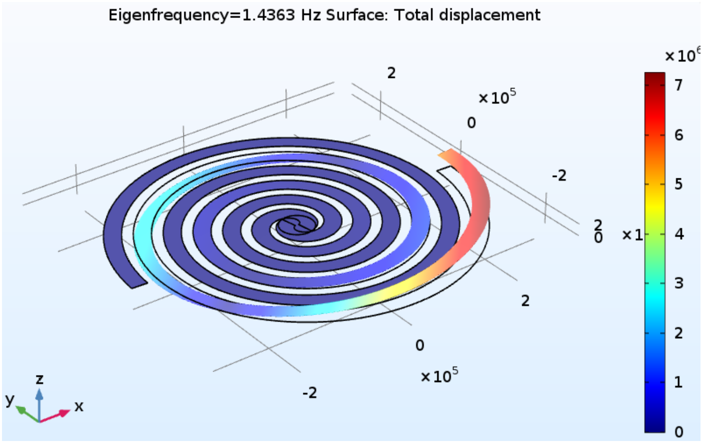
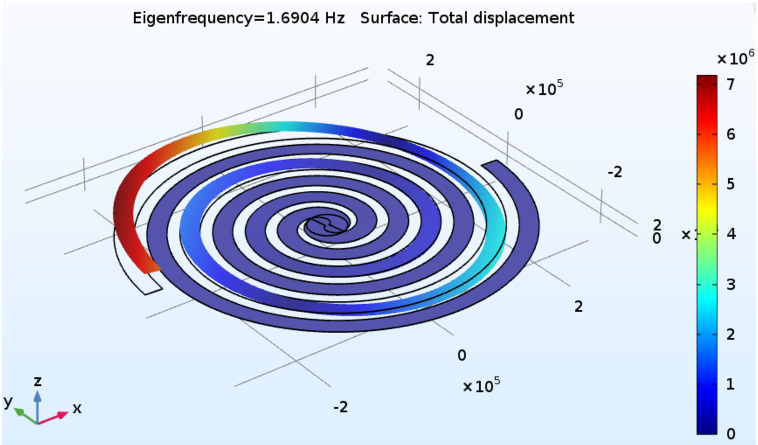
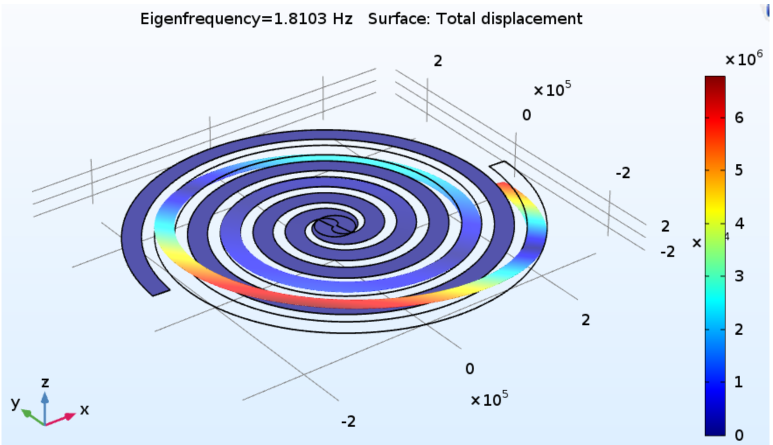


Figure 24: Eigen frequency simulation AlN shim layer


Eigenfrequency=1.4363 Hz Surface: Total displacement


Eigenfrequency=1.6904 Hz Surface: Total displacement


Eigenfrequency=1.8103 Hz Surface: Total displacement

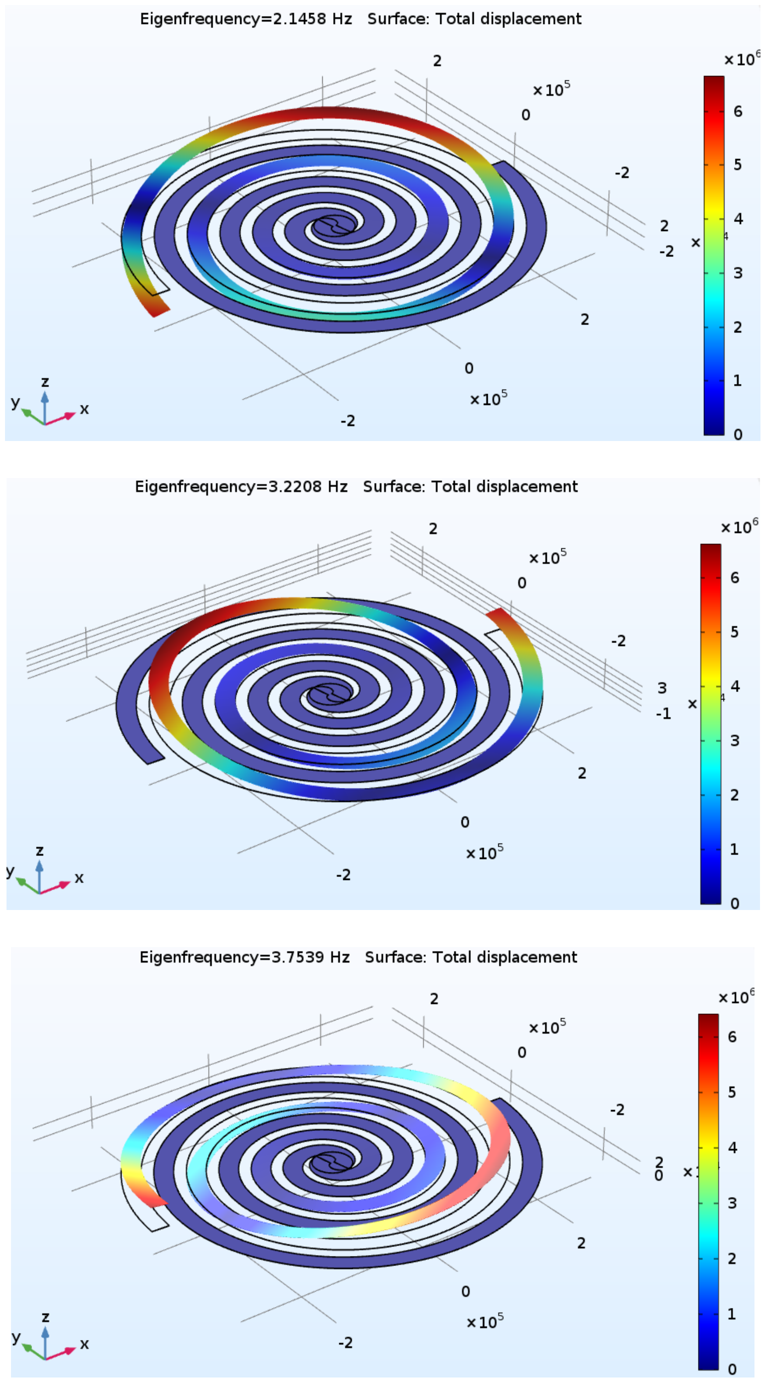


Figure 25: Eigen frequency simulation LiO_3 shim layer

Upon further investigation, new material combination was simulated. This design was simulated by modifying both the shim layer and the piezoelectric layer. For the shim layer, the

Lithium Niobate was used as it showed more displacement amongst Lithium Niobate and Aluminum Nitride. For piezoelectric material, PZT-5H was replaced by PZT-5E. PZT-5E has a lower Youngs modulus compared to PZT-5H. The stationary study was performed on PZT-5E-$LiNbO_3$-Ni structure design. It was observed that the PZT-5E-$LiNbO_3$-Ni design showed higher displacement that PZT-5H-$LiNbO_3$-Ni. Application of same force resulted in higher displacement of about approximately 8.36µm.

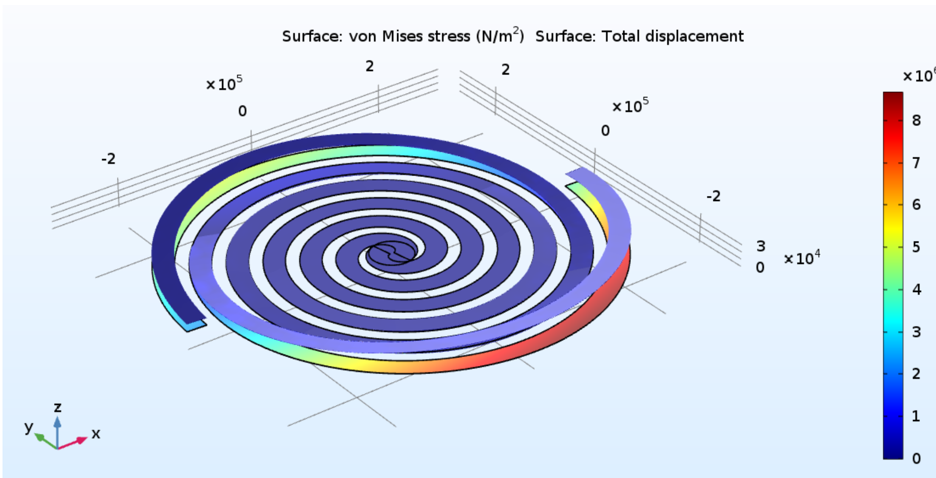


Figure 26: Total Displacement representation in surface plot

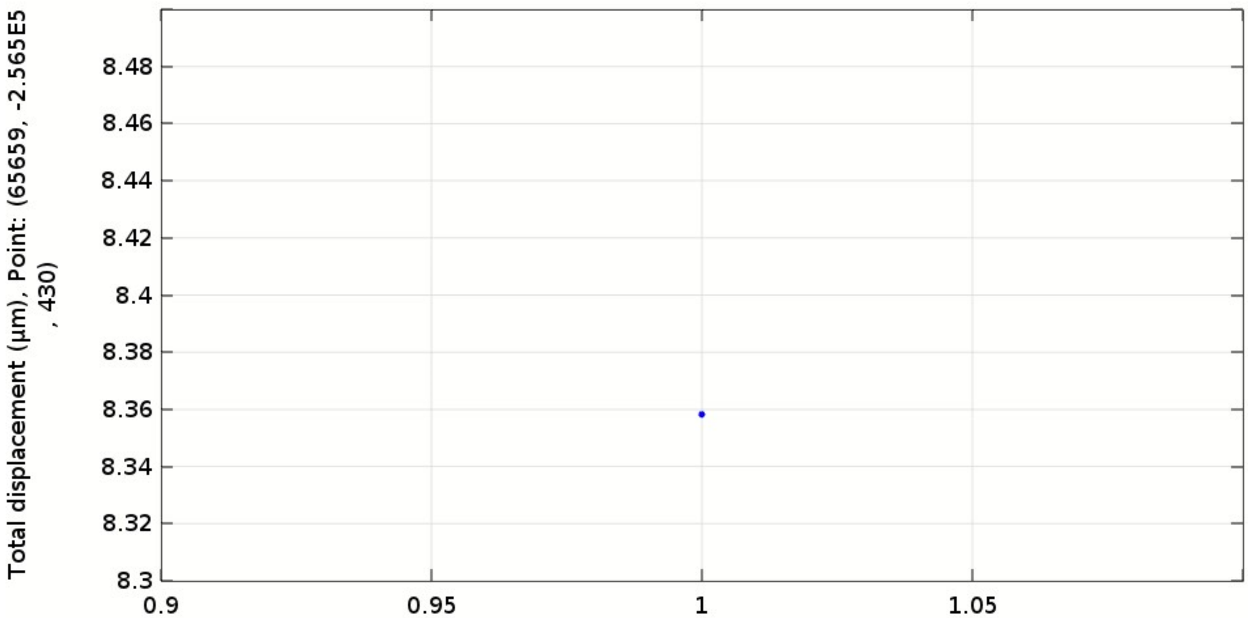
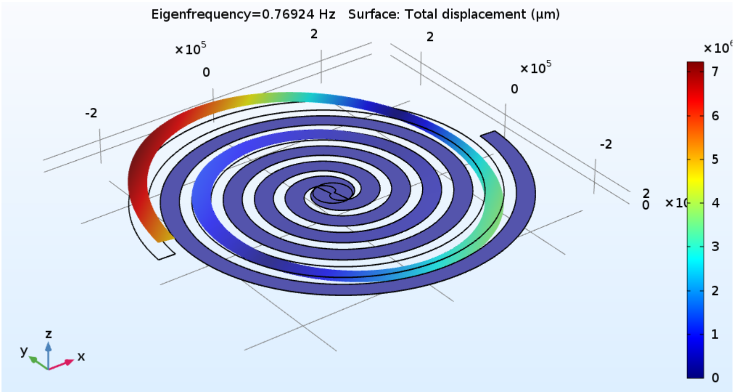
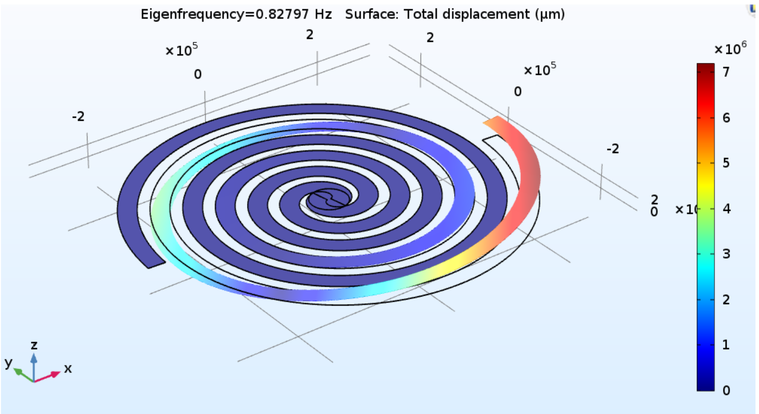
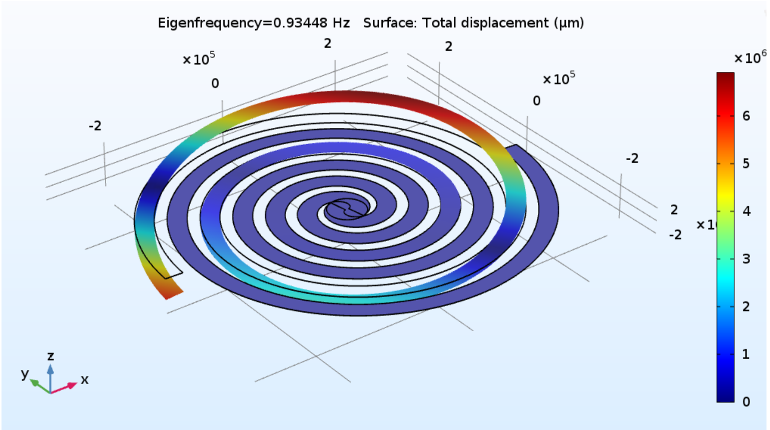


Figure 27: Probe reading representing maximum total displacement.

The figure below shows the eigen frequency obtained from computing Von-stress through stationary study.


Eigenfrequency=0.76924 Hz Surface: Total displacement (µm)


Eigenfrequency=0.82797 Hz Surface: Total displacement (µm)


Eigenfrequency=0.93448 Hz Surface: Total displacement (µm)

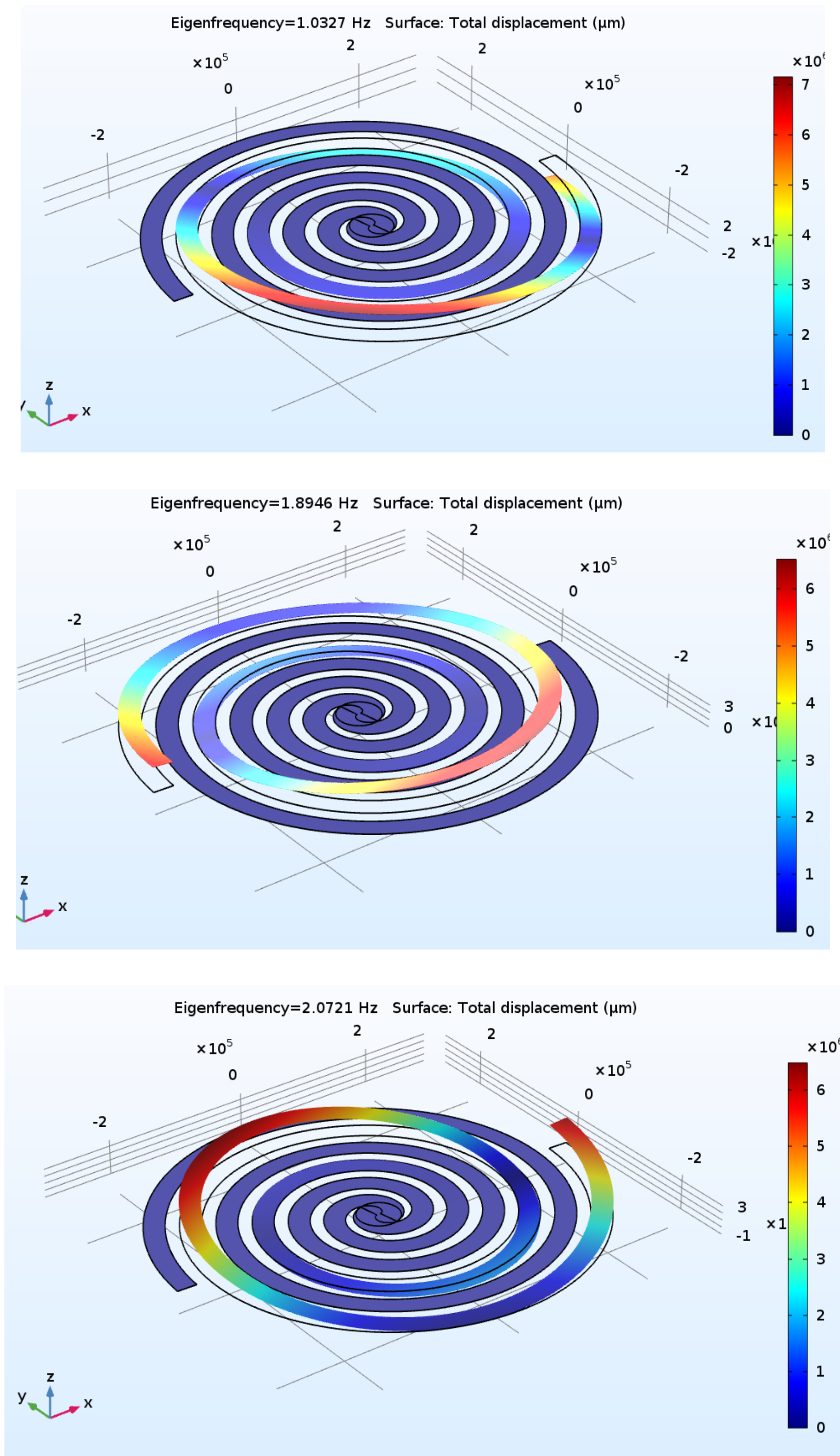


Figure 28: Eigen frequency representations of PZT-5E-LiNbO$_3$-Ni design

The plot shows that PZT-5E has not only increased the maximum displacement obtained but also at a much lower frequency.

CHAPTER 5

RESULT AND DISCUSSION

A. RESULT

The main objective of the project is to model and simulate 2-loop spiral design modeled using several material combinations. To determine the effect of various parameters the energy harvester was designed using a PZT-5H material combination with different shim layers. It was observed that the displacement is inversely proportional to the width and thickness of the shim layer. Whenever the width of the device or thickness of the shim layer is increased, the displacement reduces whereas on contrary the operating frequency increases. Parametric sweep is performed on the length of the design. It has been observed that the displacement of the energy has a direct relation with the length of the device and inversely proportional to the operating frequency. Based on parametric sweep and optimization in COMSOL, the device dimensions are determined.

A spiral-shaped 2-loop human energy harvester is designed. The spiral-shaped harvester is simulated, and a stationary study is performed to obtain six-eigenfrequencies. The surface plot is plotted to show the eigenfrequencies and corresponding displacement at the respective frequencies. The surface plot for overall displacement is also plotted. Since aluminum nitride and Lithium Niobate is used as shim layer for the design.

It has been observed that AlN as a shim layer shows more displacement when compared to traditional beam type design or spiral shaped energy harvester with PZT 5H and Nickel as the shim layer. However, it was observed that the displacement increased significantly, even higher in comparison to Aluminum Nitride as a shim layer when Lithium Niobate has used a shim layer.

Using Lithium Niobate as a shim layer has not only improved the displacement but also resulted in lowering the frequency significantly. As the main goal behind simulation of an energy harvester is to obtain smaller energy harvester with low operating frequency and higher displacement.

In this project, in order to improve the resulting displacement higher, the PZT-5H is further replaced with PZT-5E as this material has lower Young's modulus. This makes the piezoelectric layer less stiff which in turn results in higher displacement. Using PZT-5E-$LiNbO_3$-Ni structure the maximum output obtained is approximately 8.36µm.

B. FUTURE WORK

As it has been observed that materials which are used for designing the energy harvester affect the performance significantly. The research can be extended further into investigation of material for electrode layer which results in higher displacement compared to Nickel. There are several other metals are used for patterning electrodes in MEMS technologies these days which co

Upon performing the parametric seep along the width, certain deviation from the trend line was observed. As the overall displacement reduced upon increasing the with of the energy harvester, at a point in graph it was observed that the total displacement shows deviation from linearly decreasing trendline.

Output of energy harvester is directly proportional to number of loops. To increase the output, we can increase the number loop. However, it could be interesting to see if there would be any constraint to this.

C. CONCLUSION

2-loop energy harvester with Lithium Niobate as shim layer and PZT-5H has showed significantly higher displacement of approximately 7.32 um. The operation frequencies were obtained in the range of 1Hz-7Hz. However, a 2-loop energy harvester with Lithium Niobate as shim layer and PZT-5E has showed much higher displacement of approximately 8.36 um. The proposed design and material combination have shown the better result in simulation using COMSOL Multiphysics.

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APPENDIX A

A COMSOL SETUP

A. INTRODUCTION

COMSOL Multiphysics has been used for designing and simulation. COMSOL Multiphysics is an interactive tool used for modeling and simulation. The design has been modeled using a Model Builder. Using COMSOL's built-in physics interface and library support such as material properties, building model by defining material properties, constraints, load, variables. These expressions and variables can be applied to boundary, domain, edge or point. COMSOL generates the model by solving the equation. Using the built-in physics interface, we can perform a various study on the geometry. Using COMSOL Multiphysics we can perform Stationary, time-dependent study, linear, non-linear study, eigenfrequency, frequency response and modal.

COMSOL uses finite element analysis along with adaptive mesh technique and error control using various numerical solvers. It also facilitates us to run parametric sweep using various studies. A more detailed description is in *COMSOL Multiphysics Reference Guide*.

COMSOL Multiphysics creates *sequences* to record all the steps of creating the geometry, mesh, solver and study setting, visualization, which makes it is easier to modify and parameterize the nodes of the model. Changing the node in the model and simulating it. There are several optional COMSOL modules optimized for a specific application and has discipline-specific parameters and physics interfaces. There are various additional libraries, specialized solvers, element types.

Few of the several available modules are listed below:

• AC/DC Module

• Heat Transfer Module

• MEMS Module

• Microfluidics Module

• Nonlinear Structural Materials Module

• Optimization Module

• Plasma Module

• RF Module

• Structural Mechanics Module

These modules are explained in detail in the COMSOL Multiphysics User's guide (COMSOL Multiphysics Users Guide).

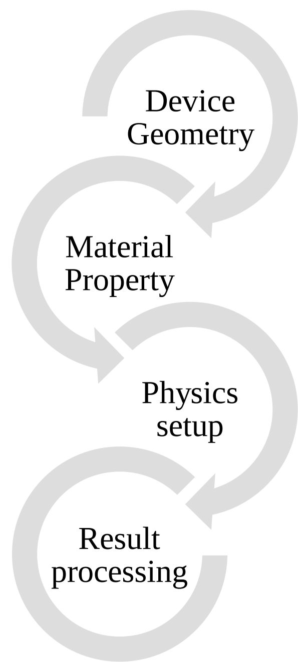

Figure 29: General steps of simulation

MEMS MODULE

MEMS module is a collection of physics interface and built-in models for COMSOL Multiphysics. It includes the interface for modeling with structural mechanics, piezoelectricity etc. In MEMS, the device operation gets affected by the physical mechanism coupled with the mechanism.

STRUCTURAL MECHANICS MODULE

The structural mechanic's module solves problems related to solid mechanics and structural mechanics. The physics interface is Multiphysics enabled, facilitates with combining the other physics interface:

- Solid Mechanics for a 2-D and 3-D stress and plane strain.

- Piezoelectric modeling

B. MODEL LIBRARY

A. Global Definitions:

The *Parameters* defined in global parameter can be used throughout the model. The *Parameters* are scalar quantity same for all geometries and domain. *Parameters* can be used for following:

- Defining dimension of geometry.
- The parameter for mesh generator
- To evaluate a mathematical expression
- Size of mesh

Steps:

- Right-click Global Definitions ( ) to add the following:
- Parameters ( ): global, scalar values that are used to parameterize any part of the model.
- Variables ( ): expression variables that are used anywhere to simplify the specifications of some properties.
- Functions are predefined function templates for common function types such as step

  functions, ramps, and random functions.

B. Local Definitions:

The local definitions are the definitions that are defined for any specific geometry or segment of model builder.

C. The Differentiation Operator

Use the *d* operator to differentiate a variable with respect to another variable. For example, *d(T, x)* means differentiation of *T* with respect to *x*.

D. Material property:

The material can be added to the entire geometry or different material for several layers.

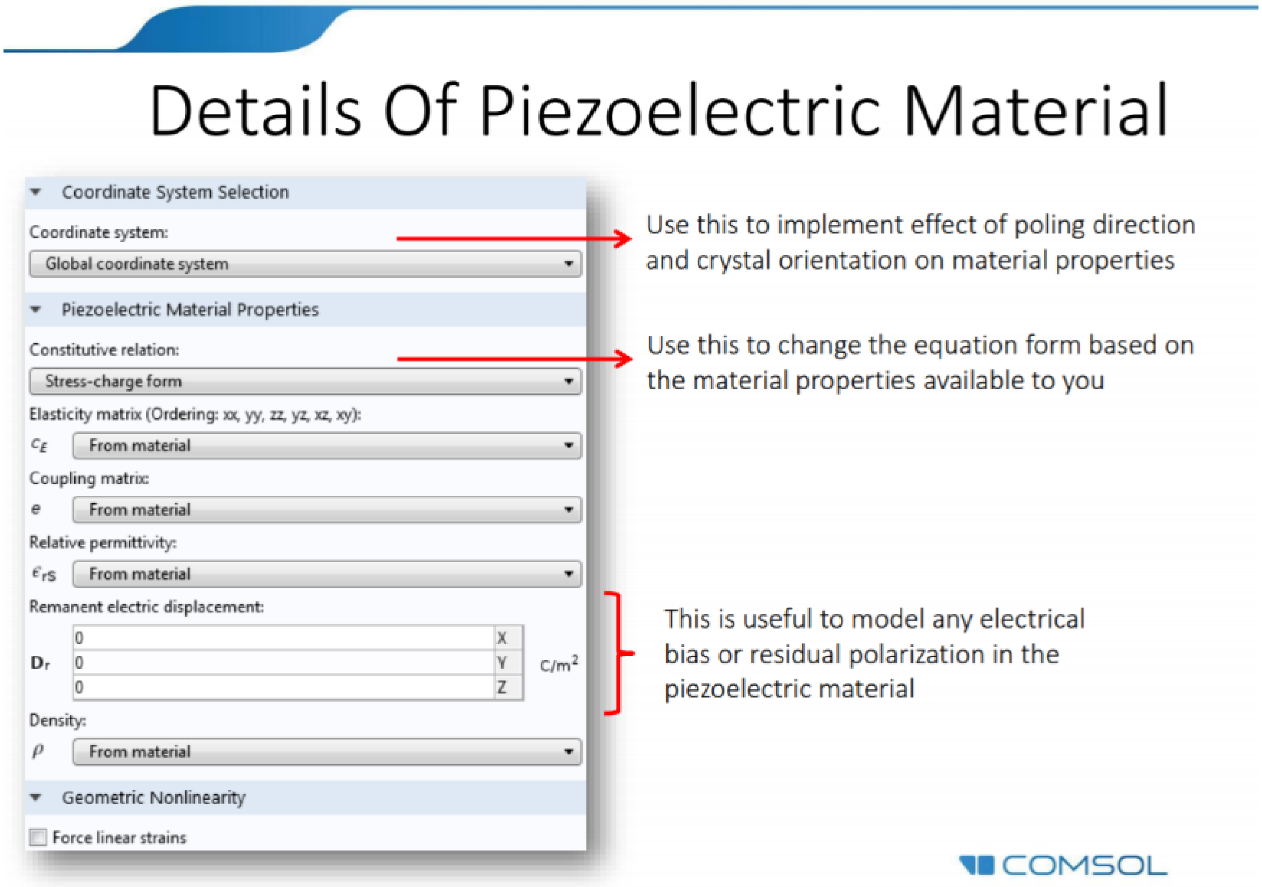

Figure 30: Material property- stress form or strain form (COMSOL, n.d.)

E. **Parametric Sweep:** (COMSOL, Modelling MEMS devices, n.d.), (COMSOL, n.d.)

The modeling workflow includes building the geometry, definitions, adding materials, defining physics, meshing, compute study and post-process result. Using parametric sweep, the variable which could be one or more variables, are varied keeping the rest of the geometry definitions same. This performs the study by varying the variable over the range of values (continuous steps) or discrete.

To perform the parametric sweep :

✓ Right-click the Study under which parametric sweep is performed.

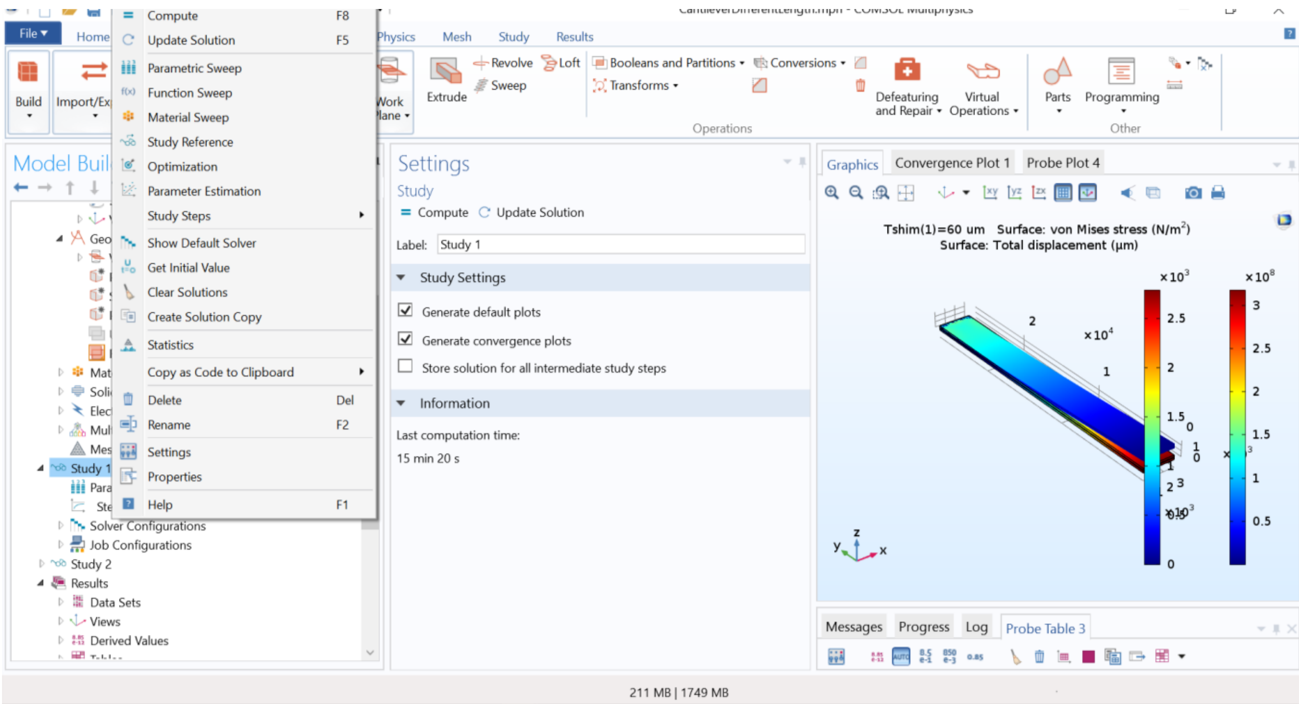

Figure 31: Parametric sweep

- ✓ Select Parametric sweep and select the variable on which parametric sweep is performed.

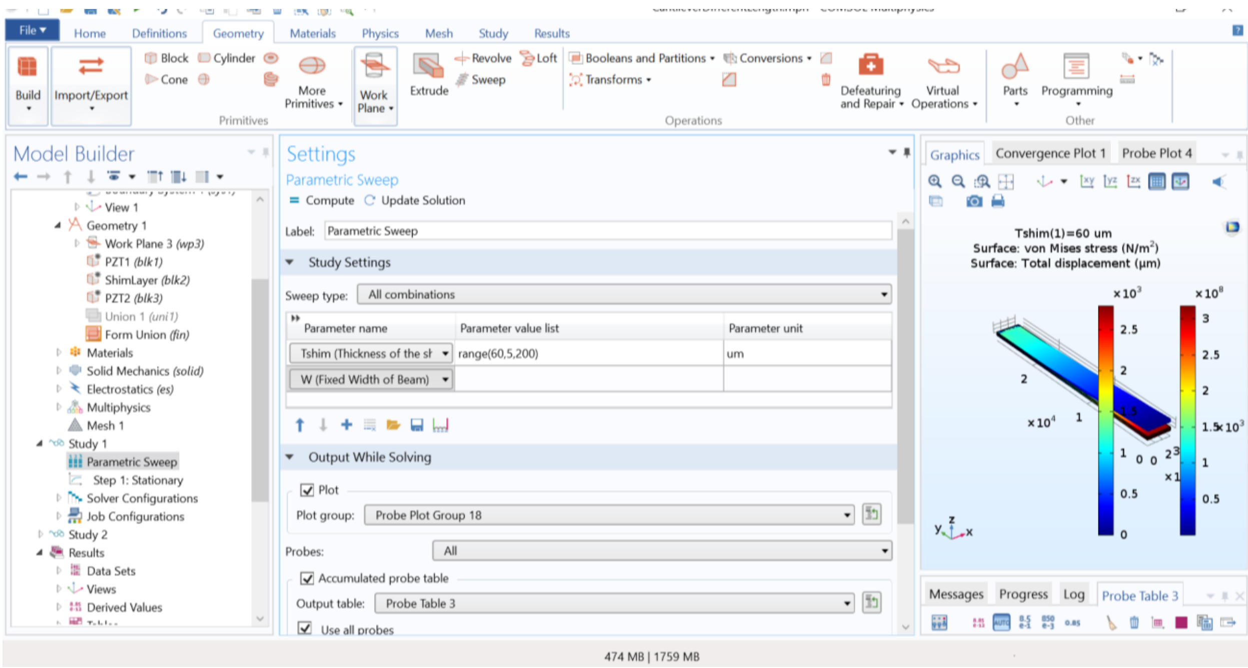

Figure 32: Parametric sweep- parameters

✓ The parameter value list is defined the next.

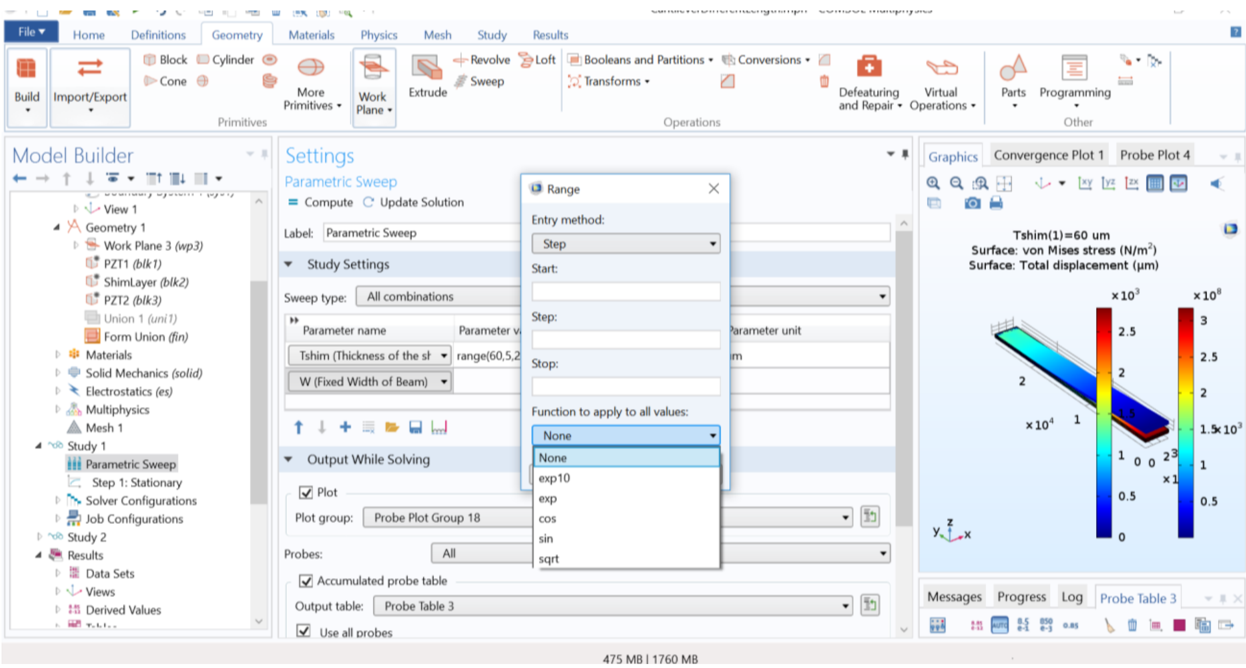

Figure 33:Parametric sweep- range

✓ Compute the study.

C. SPIRAL STRUCTURE

The spiral-shaped structure is first designed using parametric coves based on several equations and functions discussed in the next chapter.

APPENDIX B

MATERIAL PROPERTIES

A. ALUMINUM NITRIDE

Coupling matrix

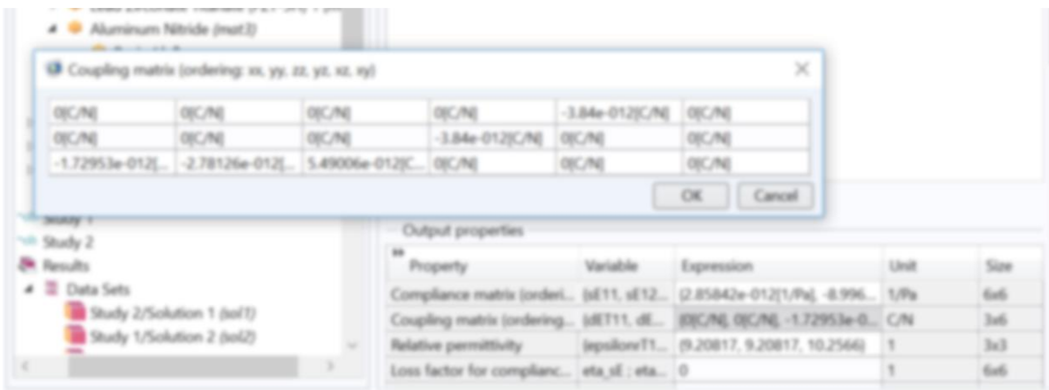

Figure 34: Coupling matrix of AlN

Compliance matrix

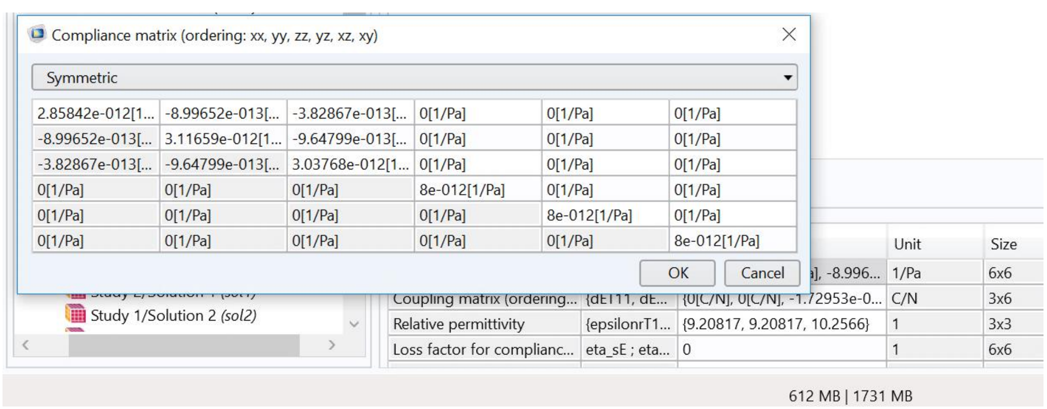

Figure 35: Elasticity matrix of AlN

B. LITHIUM NIOBATE

Coupling matrix

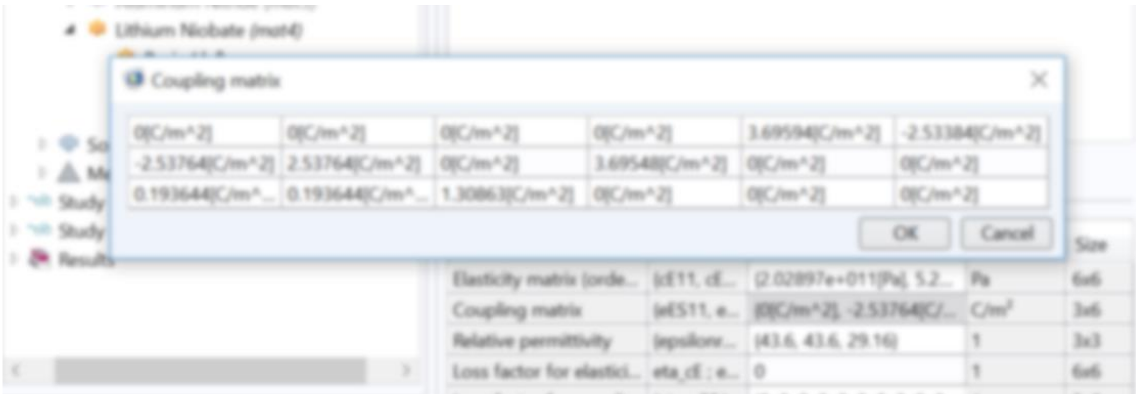

Figure 36: Coupling matrix of $LiNbO_3$

Elasticity matrix

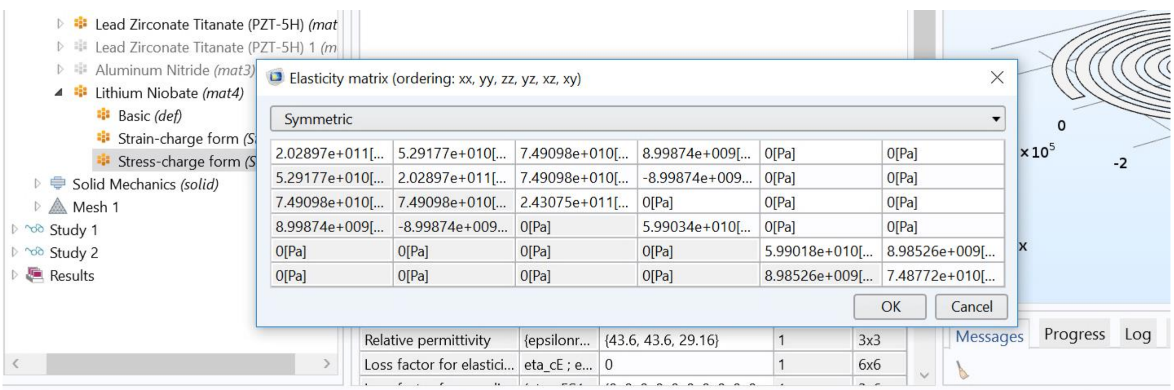

Figure 37: Elasticity matrix of $LiNbO_3$

APPENDIX C

DESIGN PARAMETER FOR SPIRAL SHAPE

A. GLOBAL PARAMETERS

Settings

Parameters

Parameters

Name	Expression	Value	Description
R_i	0.1	0.1	Initial spiral radius
R_f	10	10	Final spiral radius
N	3	3	Number of turns
Thickness	1	1	Thickness of spiral arm
b	(R_f-R_i)/(2*pi*N)	0.52521	Spiral growth rate
Theta_i	0	0	Initial spiral angle
Theta_f	(R_f-R_i)/b	18.85	Final spiral angle
Tshim	60[um]	6E-5 m	Tickness of shim layer
H	400[um]	4E-4 m	Height of the structure
Tpzt	(H-Tshim)/2	1.7E-4 m	Thickness of each PZT layer
L1l	0	0	
L2l	Tpzt	1.7E-4 m	
L2u	Tpzt+Tshim	2.3E-4 m	
L3l	Tpzt+Tshim	2.3E-4 m	
L3u	H	4E-4 m	

Figure 38: Global Parameters(representation of defining global parameters)

B. FUNCTION

- ***X_function***:

X_function is a cosine function which is argument of '*t*' and initial spiral radius (*R_i*) where t= [0,1]

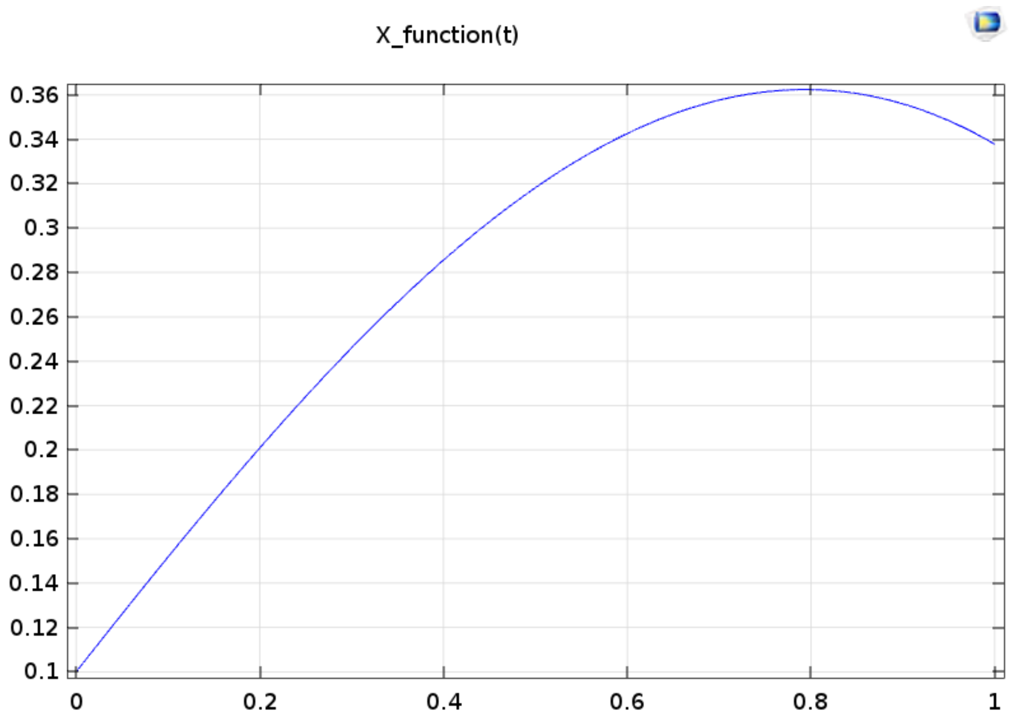

Figure 39: Plot of X_function

- ***Y_function***:

Y_function is a sine function which is argument of '*t*' and initial spiral radius (*R_i*) where *t*= [0,1]

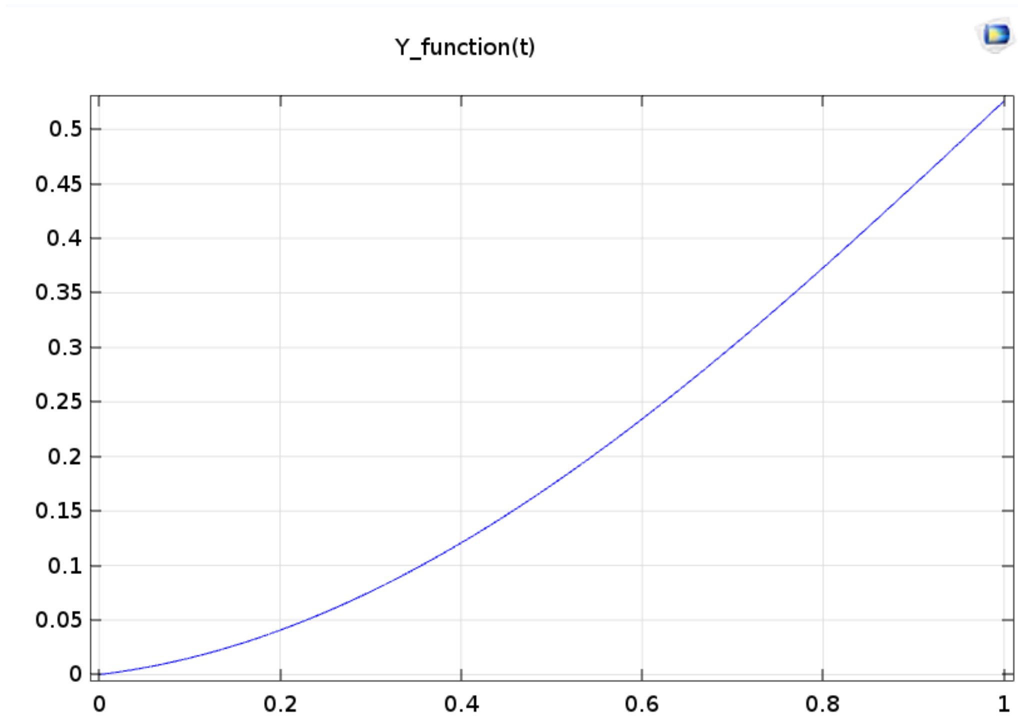

Figure 40: Plot of Y_function

- **N_x(t) function:**

N_x(t) is the base function which has X_function(t) used to design the spiral loop.

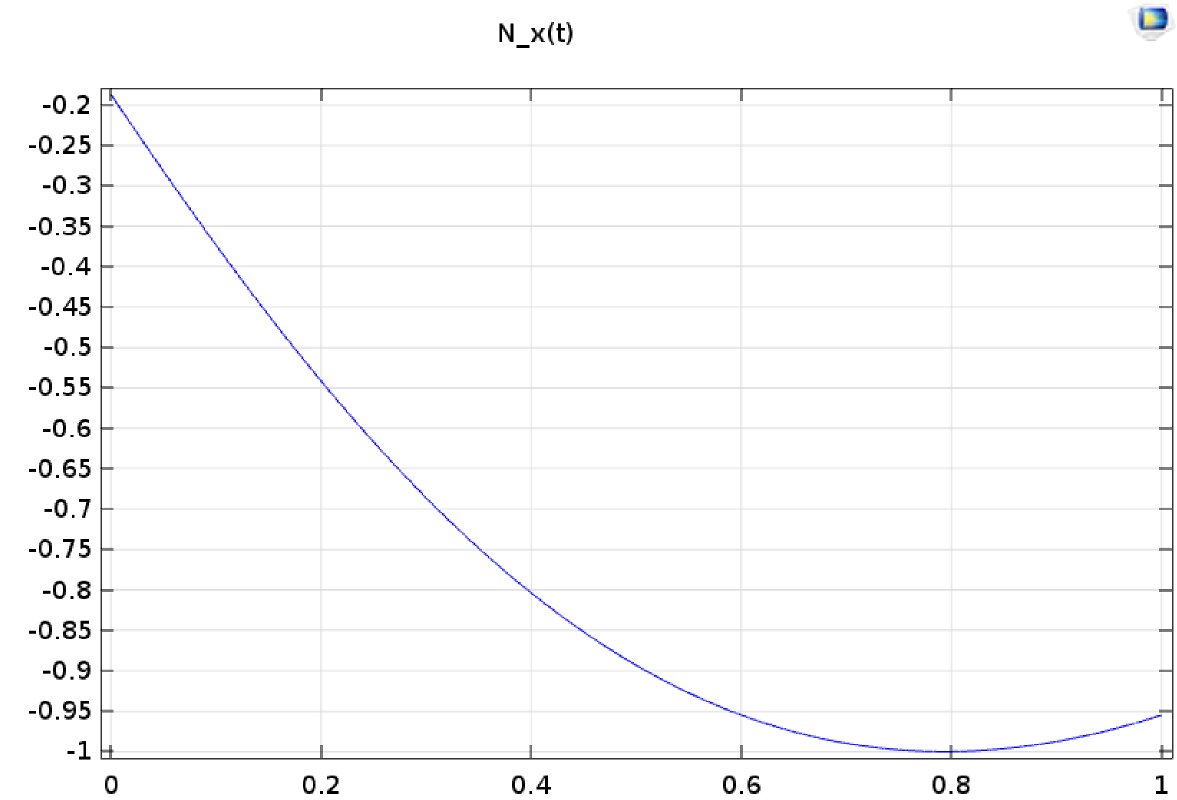

Figure 41: N_x(t) function

- **N_y(t) function:**

N_y(t) is the base function which has Y_function(t) used to design the spiral loop.

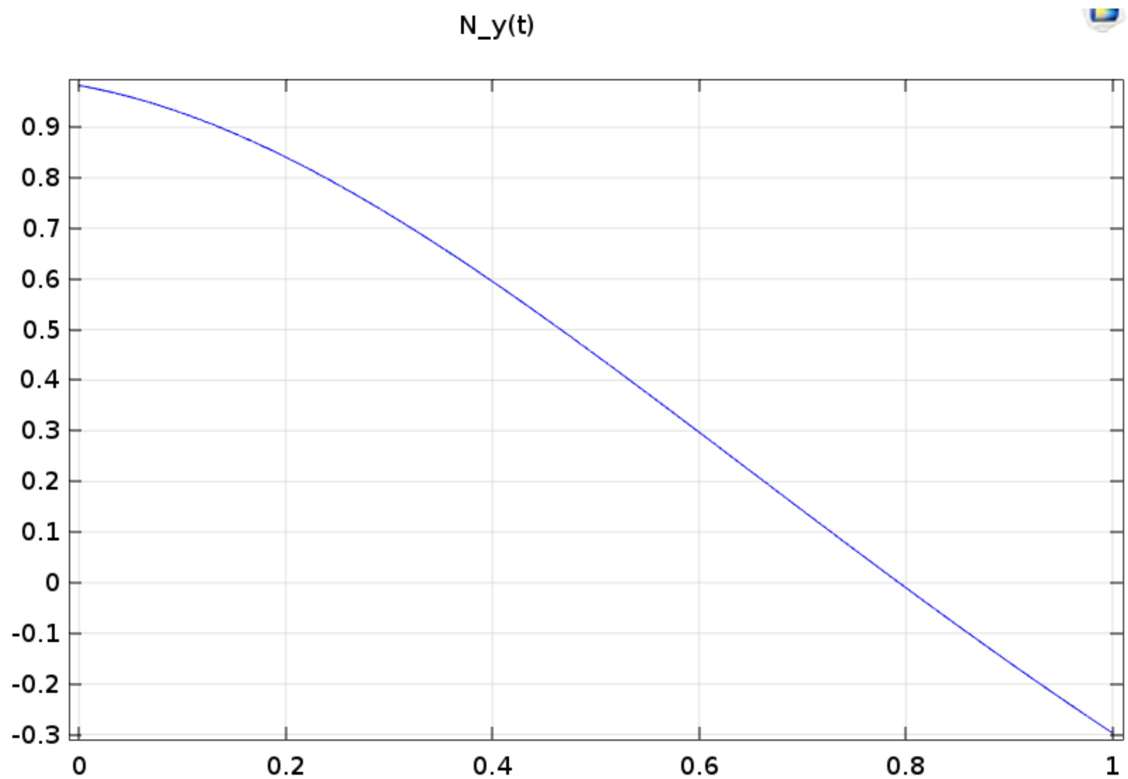

Figure 42: N_y(t) function