

A Comprehensive Study on Effect of Auxetic Structure on Analysis of Piezoelectric Energy Harvesting Systems

Ash Tabak

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Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Murat Özdenefe
Chair, Department of Mechanical
Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Asst. Prof. Dr. Babak Safaei
Supervisor

Examining Committee

1. Prof. Dr. Qasim Zeeshan

2. Asst. Prof. Dr. Mohammed Bsher A. Asmael

3. Asst. Prof. Dr. Babak Safaei

ABSTRACT

Numerous studies have shown that piezoelectric devices are highly effective in harvesting energy. Auxetic materials stand out owing to their exceptional qualities, and this results in an improvement in efficiency when used in piezoelectric systems. Energy harvesting from ambient mechanical vibrations is a universal endeavor because it can sustainably provide wireless sensors and portable electronic gadgets. In comparison to other vibration-based energy collection methods, piezoelectric energy harvesting is now a more widespread technique due to its benefits such as simplicity, scalability, and high-power output. Therefore, the present study investigated an auxetic piezoelectric energy harvester (APEH) system focusing on the structure of auxetic materials along with their behavior and efficiency in the system. In this thesis, four different models were investigated under different conditions with finite element modeling using COMSOL Multiphysics 6.0. This study simulated the models under four different studies such as frequency response, acceleration dependence, R load dependence and eigenfrequency study. Results are evaluated regarding all studies to decide which model is more efficient in under which conditions. This study demonstrated that COMSOL Multiphysics is a powerful tool for engineers and researchers to work on 3D models.

Keywords: Auxetic Structure; Negative Poisson Ratio; Piezoelectric; Energy Harvesting; Vibration.

ÖZ

Çok sayıda araştırma, enerji hasadında piezoelektrik cihazların yüksek verimliliğini göstermiştir. Negatif poisson oranına sahip malzemeler olağanüstü nitelikleriyle öne çıkar ve bu tip malzemeler, piezoelektrik sistemlerde kullanıldığında verimliliğin artmasına neden olur. Ortamdaki mekanik titreşimlerden enerji hasadı, dünya çapında önemli bir uğraş konusudur; çünkü sürdürülebilir bir şekilde kablosuz sensörler ve taşınabilir elektronik cihazlar üretilebilir. Piezoelektrik enerji hasadı, basitliği, ölçeklenebilirliği ve yüksek güç çıkışı gibi avantajları nedeniyle diğer titreşime dayalı enerji toplama tekniklerinden daha yaygın hale geldi. Bu nedenle, bu çalışma, negatif poisson oranına sahip yapıların yanı sıra sistemdeki davranışları ve verimliliklerine odaklanan ve esnetildiğinde kalınlaşma özelliği olan piezoelektrik enerji toplayıcı (EPET) sistemini araştırmıştır. Bu tezde, COMSOL Multiphysics 6.0 kullanılarak sonlu elemanlar modellemesi ile farklı koşullar altında dört farklı model incelenmiştir. Bu çalışma, frekans tepkisi, ivme bağımlılığı, rezistans yük bağımlılığı ve öz frekans çalışması gibi dört farklı çalışma altındaki modelleri simüle etmiştir. Hangi modelin hangi koşullarda daha verimli olduğuna karar vermek için tüm çalışmalarla ilgili sonuçlar değerlendirilmiştir. Bu çalışma, COMSOL Multiphysics'in mühendisler ve araştırmacılar için üç boyutlu modeller üzerinde çalışmak üzere önemli bir araç olduğunu göstermiştir.

Anahtar Kelimeler: Negatif Poisson Oranına Sahip Yapılar; Negatif Poisson Oranı; Piezoelektrik; Enerji Toplanması; Titreşim.

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
APEH	Auxetic Piezoelectric Energy Harvester
AS	Auxetic Structure
AC	Alternate Current
DC	Direct Current
FE	Finite Element
FEM	Finite Element Model
GAEH	Gradient Auxetic Structure Substrate
MPEH	MetaSub Piezoelectric Energy Harvester
NPR	Negative Poisson's Ratio
PEH	Piezoelectric Energy Harvester
PVEH	Piezoelectric Vibrational Energy Harvester
PZT	Lead Zirconate Titanate
UAEH	Uniform Auxetic Structure Substrate

Chapter 1

INTRODUCTION

1.1 Energy Harvesting Technologies

Energy harvesting term implies the operation of collecting energy from the environment or a system in the environment and converting it into an electronic power source [1]. Energy harvesting is a comprehensive method that can help provide clean, renewable energy and increase infrastructure sustainability [2]. Researchers may "harvest" few quantities of dissipating energy from the surroundings and use it to generate usable electric energy and which is known as energy harvesting in the world [3]. As an "enabling technology" that increases IoT (Internet of Things) use options, improves societal resilience, and enriches lives, energy harvesting technology is gaining popularity. This innovation gathers the energy that is formed around people, emitted in the form of heat and vibration, then changes the form into electrical energy which is comfortable to use. [3]. Figure 1 illustrates the general phenomenon of energy harvesting innovation for surrounding targets.

The energy recovered can be utilized to make electricity, ice melting, operate wireless sensors, and monitor structure condition. Each energy harvesting device is thoroughly investigated, including its operating principles, instances of how it has been used, how it has developed as a prototype, and key discoveries [2]. Figure 2 illustrates all available energy harvesting technologies that can be applied in roadways [2].

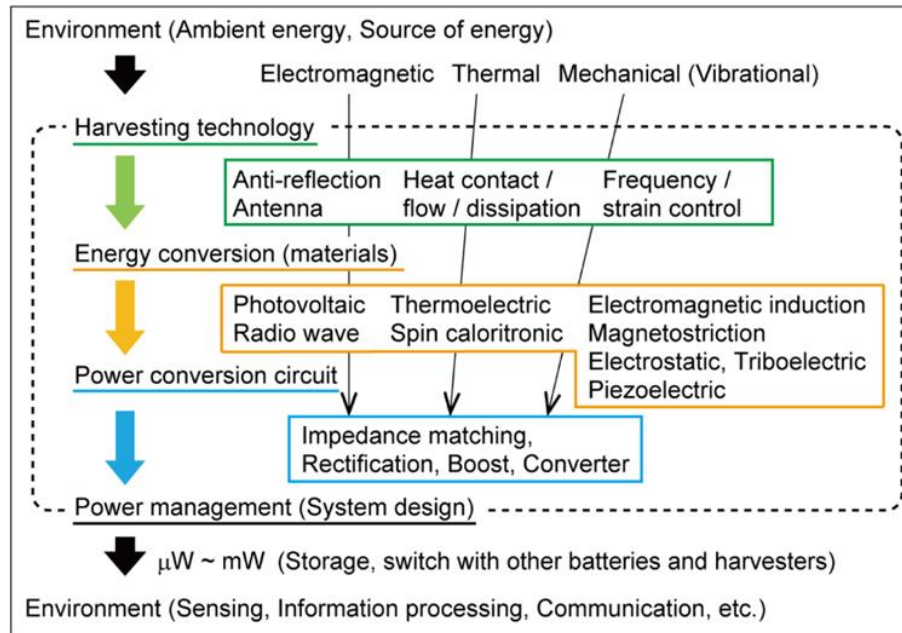


Figure 1: Energy-harvesting technologies [3]

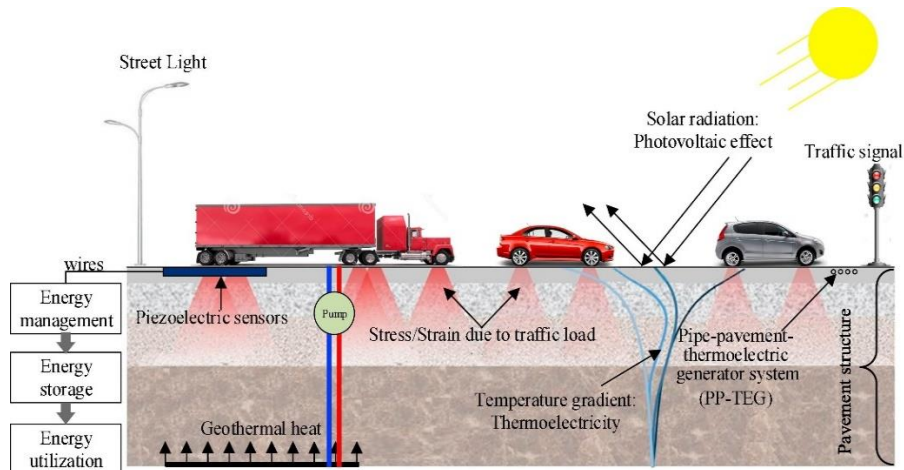


Figure 2: Accessible sources for energy harvesting in roadways [2]

One of the biggest advantages of energy harvesting is that, unlike many types of technology, it has the ability to eliminate energy-related carbon emissions [4]. Solar energy collection technology is a system that has been used for many years and has reached maturity today. Commercially available solar panels are proven electricity generators that make it financially viable to feed the electrical grid [5]. The biggest problem of current solar panel technology is the need for physical space installation [6]. As another type of energy, electricity can be obtained through

mechanical energy, magnetic field for electromagnetic material or strain field for piezoelectric materials. Piezoelectric systems, on the other hand, have been widely used in many situations such as transducers, actuators, vibration sensors, frequency controllers [7].

1.1.1 Piezoelectric Systems in Energy Harvesting

The use of piezoelectric elements to extract energy from ambient vibrations was made possible by the discovery of the effect of these elements in the early 1880s and has attracted great interest for decades [8]. Vibration may be used to generate electricity in three different ways: electromagnetically, electrostatically, and piezoelectrically [9]. This thesis will be considered piezoelectric method as an energy harvesting technology. The surface charges that occur as a result of either mechanical stress and strain or dielectric polarization are expressed with the concept of piezoelectric effect. When vibration is applied to PZT materials, this type of harvesters capture the electric energy that is produced [10]. Piezoelectric transducers have been extensively investigated to produce power from vibration energy sources due to its intrinsic electromechanical coupling and higher power density than electromagnetic and electrostatic transducers [11].

When mechanical forces are applied, piezoelectric materials produce electrical charges or when an electric field is applied, piezoelectric materials undergo geometrical changes. Figure 3 illustrates the operation of piezoelectric energy harvesting. The direct and inverse piezoelectric effects are caused by changes in voltage generated by piezoelectric material over time, which produces an alternative current (AC) signal. [12].

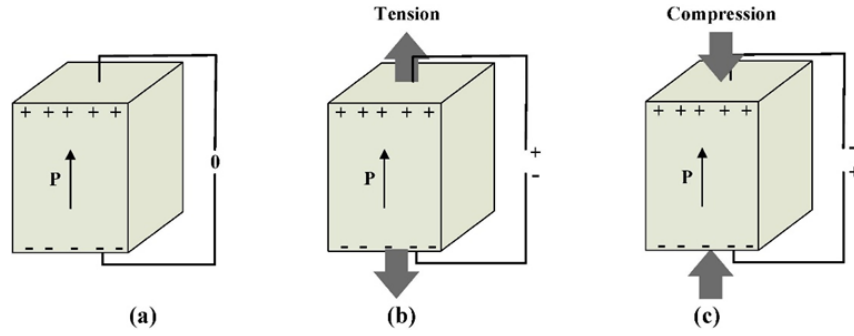


Figure 3: Working principle of piezoelectric effect under (a) zero stress; (b) tension; and (c) compression [12]

Single-crystalline materials, such as quartz, piezoceramics (such as lead zirconate titanate [PZT]), piezoelectric semiconductors (such as ZnO_2), polymers (such as polyvinylidene fluoride [PVDF]), piezoelectric composites, and glass ceramics (e.g., $\text{Li}_2\text{Si}_2\text{O}_5$, $\text{Ba}_2\text{TiSiO}_6$) may all be categorized as types of piezoelectric materials. Although there are many different piezoelectric and mechanical properties in piezoelectric materials, polymers and ceramics are the most often employed materials. Ceramics are stiff, but polymer materials are soft and flexible. Compared to ceramics, polymer materials produce less energy because of their distinct dielectric and piezoelectric characteristics [2]. Examples of situations where piezoelectric vibration energy is gathered; can be used including civil engineering such as buildings and bridges [13,14] aerospace systems [15–19], and the human body [20,21].

1.1.2 Auxetic Material

The term auxetic materials appeared in 1991 [22]. Auxeticity term implies the negative Poisson's ratio (NPR). Usage area of auxetic materials and structures are widely explored thanks to their rare characteristic features [23]. Expressly, with uniaxial extension, they not only do not shrink but rather increase in the transverse directions [24,25]. Auxetic metamaterials have the interesting characterization of negative Poisson; this indicates that the auxiliary metamaterials will expand or contract laterally

when stretched or compressed longitudinally [26]. Figure 4 below illustrates this situation.

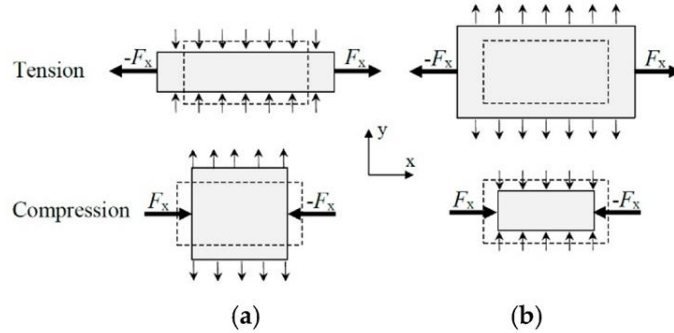


Figure 4: Non-auxetic (a) and auxetic (b) behavior during tensile and compressive loading (dashed lines—undeformed geometry) [27–29]

Auxetic structures have positive influences in converting mechanical energy to electricity because of their properties related to the negative Poisson's ratio [30,31]. The effectiveness of energy harvesters has recently been improved by the introduction of auxetic structures by numerous researchers [32]. AS have been studied in sensing [33], actuation [34], and impact absorption [35], because of this unique property, however, the application of AS for energy harvesting is relatively recent.

1.1.3 Piezoelectric Systems with Auxetic Materials

Auxetic materials are characterized by an NPR that they expand laterally in directions perpendicular to the applied stretching stress and during the compression it works vice versa. Piezoelectric will change their dimensions when exposed to an external electric field [36]. In the field of energy harvesting, approaches examining an auxetic structure directly made of piezoelectric PZT material have been a hot topic today [34]. According to the researchers, they reported a higher than 10 times increase in energy produced from the PZT material placed on the auxetic substrate [37]. Most naturally auxetic materials have internal force, which prevents them from being able to stretch

a stronger material linked to them (such as most piezoelectric materials). Nevertheless, there are a number of configurations that can provide a greater bulk material auxetic behavior, resulting in a lower effective Poisson's ratio while being more powerful [37]. Because of the unusual properties of the auxetic structures, the piezoelectric energy harvesters used with them exhibit more sensitive behavior [30]. Due to its behavior shows a negative Poisson's ratio (NPR), auxetic sheets can boost the power output [38]. Figure 5 shows the applications of auxetic structures and piezoelectric energy harvesting systems.

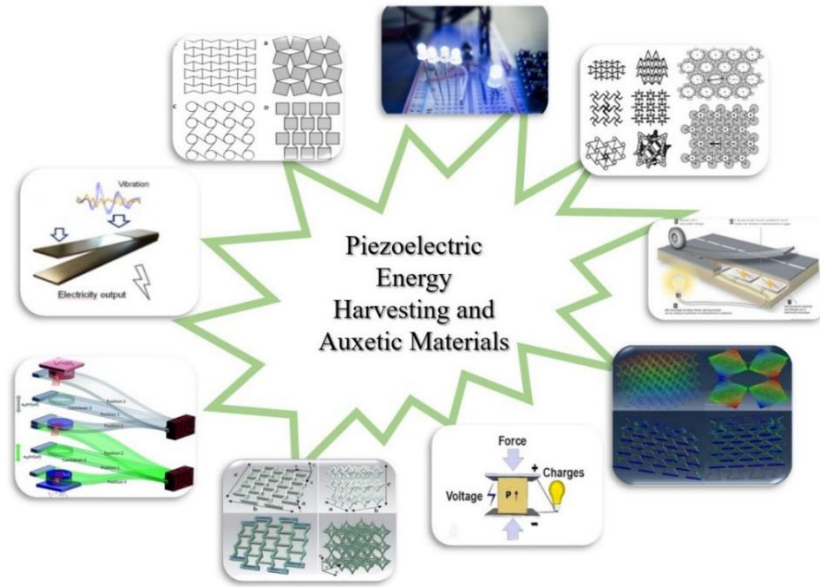


Figure 5: The applications of auxetic structures and piezoelectric energy harvesting systems.

1.2 Definition of the Problem

Although piezoelectric energy harvesting has been widely used and modified in recent years, there are still significant challenges that need to be resolved/changed. As a matter of fact, despite these difficulties, today, the application of vibrational energy in harvesting is frequently encountered. However, in this system low efficiency and low

performance are still achieved in vibration energy harvesting. This means that the output powers for this type of energy converter are generally low and most of the input energy is dissipated in parallel mechanisms [27]. In this thesis, the number of layers has been changed and auxetic structures have been selected to provide high efficiency in energy harvesting by increasing energy collection and absorption to solve the problem.

1.3 Need for Research (Motivation)

According to the research, in piezoelectric systems that are cantilever beams, two layers of PZT material and one substrate layer have been preferred until today. Later, when it was understood that auxetic structures contributed to more voltage generation in energy harvesting, structures with NPR were included in the core parts of piezoelectric systems. As a novelty in this thesis, the piezoelectric layers were increased to three and two auxetic materials were added in between. This system is analyzed and compared with and without auxetic structure in the core part. The aim of the thesis and innovations are presented together with the results of the analysis.

1.4 Scope of This Study

The scope of this study is to investigate the potential benefits of using auxetics in piezoelectric energy harvesters. The study will focus on the design and simulation of conventional piezoelectric energy harvesters and auxetic piezoelectric energy harvesters. The study will compare the energy harvesting efficiency of auxetic and conventional piezoelectric energy harvesters under various loading conditions using both numerical simulations. The study will not address the use of auxetics in other types of energy harvesters.

1.5 Objectives of This Study

In this thesis, the main objective of the thesis is to explore the efficiency of auxetic piezoelectric systems in energy harvesting by vibration energy source.

According to that, the objectives are ordered below as points,

- Development of an auxetic piezoelectric energy harvester will increase power production while utilizing strain energy.
- The APEH consists of a piezoelectric element connected to an auxetic layer. The auxetic part of the model concentrates the applied stress and strain into the region of the piezoelectric element and introduces auxetic behavior in the piezoelectric element, both of which increase the electric power.
- It investigated how changing the number of layers of the piezoelectric energy harvesting system affects efficiency.
- With the simulations to be made in this thesis, a conventional core and an auxetic core in piezoelectric systems will be compared. It is aimed to reveal how the efficiency of the auxetic structured piezoelectric system differs from the conventional structure and the effect of the change in the number of layers on the efficiency with the analysis.

Chapter 2

LITERATURE REVIEW

2.1 Auxetic Materials

The term auxetic materials appeared in 1991 [22]. Auxeticity is defined as the negative degree of Poisson's ratio. Owing to their unique properties, the application of auxetic structures and materials is widely researched [23]. In other words, with uniaxial extension, they not only do not shrink but rather increase in the transverse directions [24,25]. Auxetic structures positively affect mechanical-electricity energy conversion due to their characteristics depended on negative Poisson ratios [30,31].

A negative Poisson ratio denotes that the material is flowing along impact zone direction [39] and unlike standard cellular materials, it is not discharged from impact zone. Flow along impact zone direction is among the most critical advantages of the development materials [39]. When compressing materials on a selected axis, they expand in orthogonal to load application direction. This behavior is due to Poisson's quantitative relationship; this is outlined because of negative transverse to longitudinal strains ratio [23]. The main, well-known benefits of auxetic elastic materials, such as increased fracture toughness, high acoustic damping, indentation resistance, and shear modulus, may be leveraged when using a piezoelectric material resulting in the improvement of piezoelectric behavior [30]. These structures, which have the most severe drawbacks in terms of production challenges, have gotten easier to construct as

3D printing technology has progressed, and have been the focus of numerous research in recent years [40].

Systems with a negative Poisson's magnitude relation (auxetic) exhibits the strange nonetheless helpful property of obtaining wider instead of dilutant once uniaxially stretched. A completely unique mechanism to come up with growth behavior at custom-made values which can be enforced in composites manufacture exploitation promptly offered materials is proposed [41]. As a very important mechanical metamaterial branch, auxetic metamaterials present extraordinary properties of negative Poisson's magnitude relation suggesting that auxetic metamaterials will shrink/expand laterally once compressed/stretched longitudinally [26]. Figure 6 illustrates this situation.

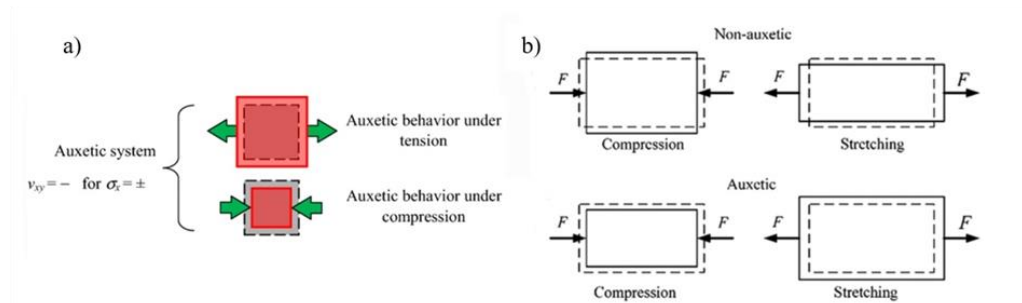


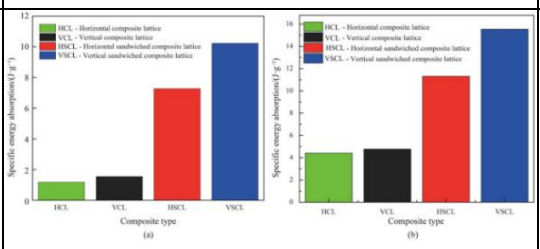
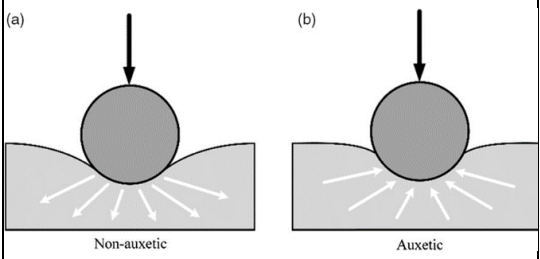
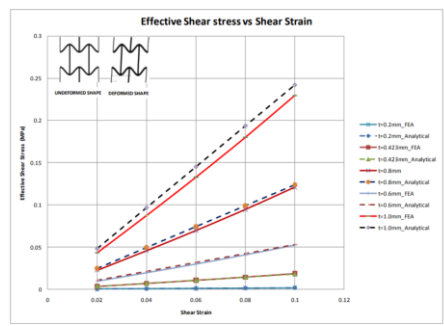
Figure 6: a) Auxetic system is in under tension and compression [42] b) Comparison between non auxetic and auxetic structure [43]

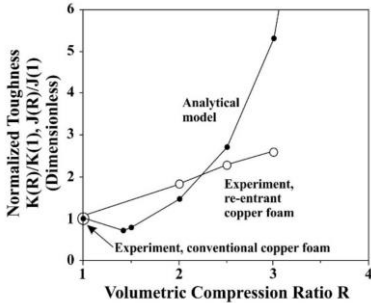
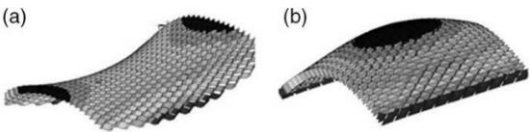
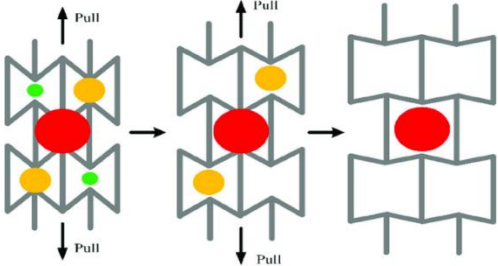
2.2 Auxetic Material's Behaviors in Piezoelectric System

Auxetic materials have been known for over a century [44,45]. Many researchers have recently produced auxetic structures to improve energy harvester efficiency [32]. Auxetic structures have negative Poisson's ratios, which means they laterally expand during extension and transversely contract when compressed. For this unique feature, auxetic structures are applied in impact absorption [35], actuation [34], and sensing

[33]; however, utilization of auxetic structures as energy harvester is very new [46]. Kwon and Phan [47] investigated composites with auxetic inclusions, finding that they exhibited both auxetic behavior and improved mechanical characteristics. Table 1 shows the properties of auxetic materials because of negative Poisson's ratios.

Table 1: Auxetic materials enhancing mechanical characteristics [48]

Mechanical properties	Description	Figures	Ref.
Energy absorption	Experiments reveal that auxetic materials (for example, porous auxetic foams) have better damping and sound absorption than conventional materials.	 At low velocities and high velocities, various auxetic lattices absorb specific energy	[40,49]
Enhanced indentation resistance	This trait results from two main factors: high shear stiffness and when an impactor contacts with their surface, auxetic materials shift toward impact areas, increasing the density of those areas. Many investigations on materials having re-entrant unit cells, composite sandwich panels, and metallic polymeric foams have been accomplished	 Indentation behavior	[43,50,51]
High shear stiffness	For negative Poisson's ratios, the shear modulus increases. For Poisson's ratios of close to -1, shear resistance increases considerably and shear modulus approaches infinity. Structures having chiral and re-entrant unit		[52–54]

	cells have been investigated for this characteristic.	Analytical and computational solutions for the sinusoidal auxetic unit cell are compared.	
High fracture toughness	According to researchers, crack propagation in auxetic material takes more energy, and change of Poisson's ratio changes toughness, making the material extremely tough with Poisson's ratio approaching - Structures containing solid foams, composite sandwich panels, and re-entrant unit cells have all been the subject of several investigations.	 Experimentally normalized fracture toughness. Open symbols: conventional solid and foam symbols: re-entrant foam	[55–58]
Synclastic curvature in bending	Auxetic surfaces experience synclastic deformation when bending loads are applied on two opposed sides. This feature enables the production of structures with a variety of shapes using a limited number of machining stages, reducing material waste and, as a result, lowering manufacturing costs. Structures with re-entrant unit cells are most likely to have this property.	 Bending deformation. Reproduced with permission. a) Conventional hexagonal structure. b) Re-entrant hexagonal structure.	[59,60]
Variable Permeability	Auxetic materials with pores are good for altering permeability. This characteristic enables filter permeability to be controlled. The size of their pores changes when applying load in a specific direction. When subjected to a tensile load, their size expands. From macroscale to nanoscale materials, this	 Intelligent filters with variable permeability	[43,61,62]

	variable permeability can be employed. This feature is present in all porous auxetic materials		
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Auxetic structures, in contrast to conventional materials, laterally expand and contract under uniaxial stress and axial compression, respectively. This is the most important aspect of creating an effective auxetic structure [63]. Shape transformations in auxetic materials can be programmed by taking use of nontrivial deformation modes associated with elastic instabilities [64–67]. However, creating strong and stable shape changes is difficult since the structure must maintain a pre-stressed state [68]. Chen et al. [69] examined the use of a gradient auxetic structure to boost PEH power output. According to their findings, gradient auxetic energy harvesters can generate more power compared to uniform ones while reducing concentration of stress. As shown in Figure 7, the energy harvesters fabricated using three substrate types are offered for comparison: uniform auxetic structure substrate (UAEH), gradient auxetic structure substrate (GAEH), and traditional plain substrate (PEH) and Figure 8 shows the developed PEH [69]. Chen et al. [69] found that the gradient auxetic structure slightly raised stress concentration but could greatly boost power output with uniform strain distribution when compared to uniform auxetic structure. Their outcomes are displayed in Figure 9.

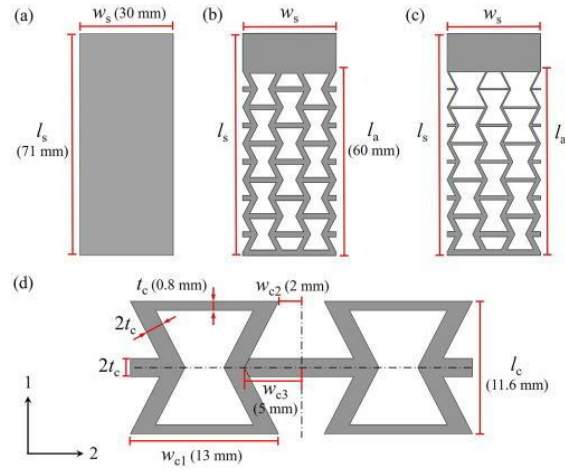


Figure 7: Geometries of (a) conventional plain substrate, (b) uniform auxetic structure substrate, (c) gradient auxetic structure substrate, and (d) unit cell [69]

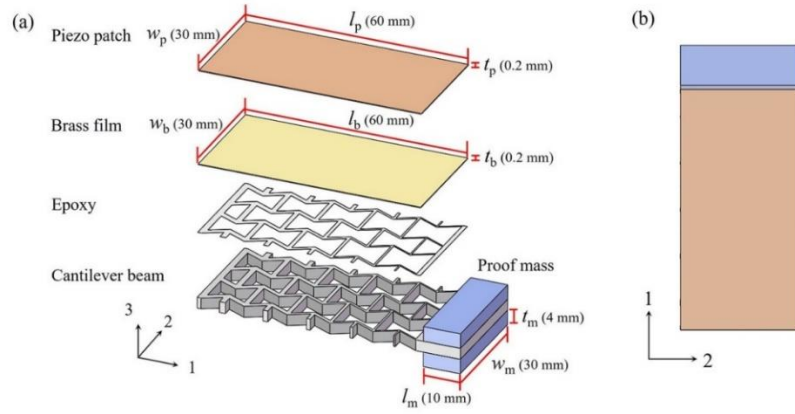


Figure 8: (a) Exploded and (b) top view of the developed PEH [69]

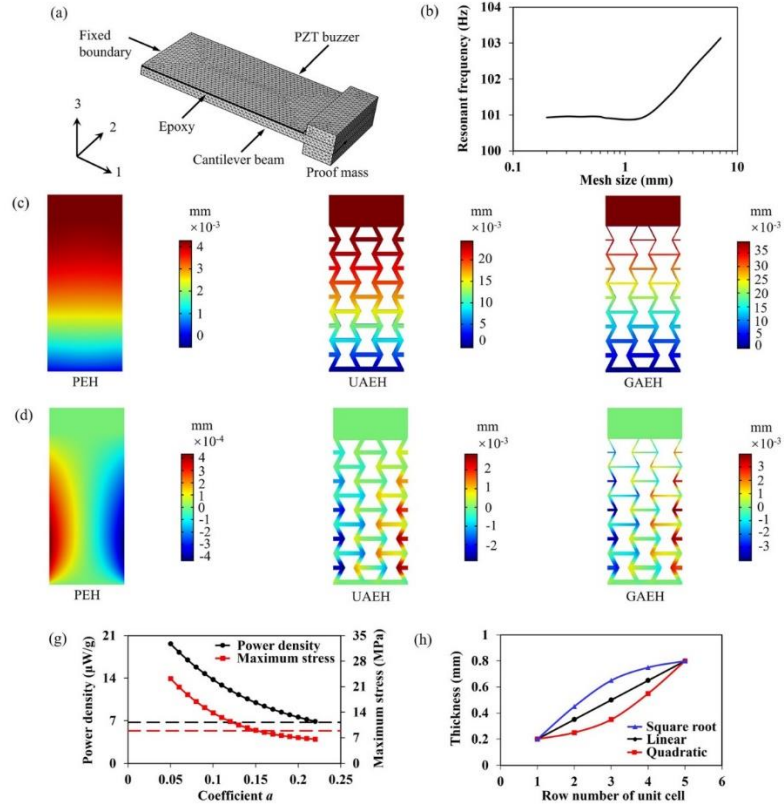


Figure 9: (a) Energy harvester FEM simulation model; (b) relationship of resonant frequency of PEH and mesh size; distributions of substrate displacement in GAEH, UAEH and PEH along (c) longitudinal and (d) lateral directions; (e) strain and (f) stress distributions of piezoelectric patches in GAEH and UAEH; (g) GAEH working performance with various gradient auxetic structures; and (h) various thicknesses of unit cell

Energy harvester performance in COMSOL is examined using an electromechanical coupling model that makes use of the electrical circuit, solid mechanics, and AC/DC. The model's components include an epoxy coating, a cantilever beam, a proof mass, and a PZT buzzer, as seen in Figure 9 (a). Additionally, the beam's terminus is subjected to a set boundary condition. Sweeping meshing and free triangular meshing are both utilized in mesh. The maximum mesh size is changed to guarantee simulation correctness because energy harvester modal analysis is performed first. The link between resonant frequency and the maximum grid size in PEH is depicted in Figure 9 (b). The resonance frequency essentially remains unchanged when the maximum size of mesh is less than 1 mm. Therefore, 1 mm is chosen as the maximum mesh size.

PEH, UAEH, and GAEH have been found to have respective first resonant frequencies of 100.91, 46.06, and 39.16 Hz. 1 m/s^2 base excitation along three axes at the resonant frequencies is used to examine how well energy harvesters operate in resonant modes. Figures 9 (c) and 9 (d) present substrate displacement distributions in PEH, UAEH and GAEH, respectively. As seen in Figure 9 (c), substrates' longitudinal deformation (along one axis) is entirely positive, indicating that the substrates are being stretched. The substrate compresses laterally (along two axes) in Figure 9 for PEH, exhibiting the typical positive Poisson's ratio. Unlike PEH, substrates in GAEH and UAEH extend laterally demonstrating the feature of NPR. When GAEH and UAEH are put side by side, GAEH exhibits larger average stresses. Piezoelectric patch strain distributions in Figure 9 serve as an example of this phenomena (e). The maximum strains of the two energy harvesters are comparable, but GAEH has a larger average strain because its strain distribution is more even than UAEH's. Additionally, Figure 9 (f) shows that the maximum stress in GAEH and UAEH is 8.90 MPa and 9.03 MPa, respectively.

Li et al. [70] reported piezoelectric material Poisson's ratios and substrate has positive and roughly the same magnitude, ordinary bimorphs transversely narrow at almost similar rate. In this scenario, no force acts on piezoelectric layer along transverse direction. Hence, σ_{22} is almost zero and has no effect on electricity generation. That is, only 31-mode affects the power output of typical bimorph. However, for negative Poisson's ratios of substrate and transverse expansion, the piezoelectric layer generates a transverse force since piezoelectric layer presents various and positive Poisson's ratios. For big enough forces, the piezoelectric layer transversely expands, indicating that piezoelectric layers also exhibit auxetic characteristics. Therefore, σ_{22} is increased

and will have the same sign as σ_{11} , resulting in the contribution to power generation. Under such a situation, power creation is affected by both 31- and 32-modes at the same time, resulting in higher power output. Figure 10 shows a conventional piezoelectric bimorph for energy harvesters, as well as a 2D auxetic substrate for replacing bimorph's typical substrate.

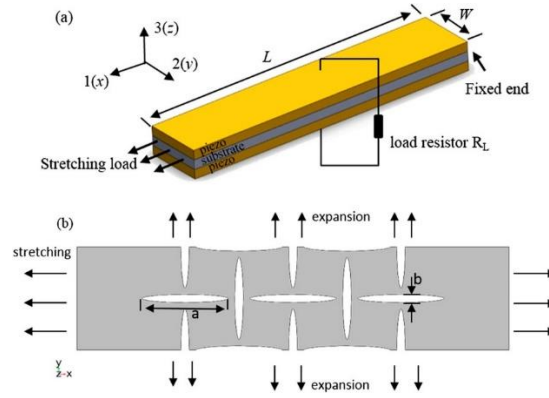


Figure 10:(a) A typical piezoelectric bimorph to be applied in energy harvesting and (b) a 2D auxetic substrate for replacing conventional substrates in bimorph [70]

Farhangdoust et al. [71] has investigated due to the general improved auxetic and kirigami properties introduced to the design of Meta Sub cell, a greatly increased power output is anticipated from any PEH that uses Meta Sub as substrate. It has two reasons: As mentioned earlier, thanks to NPR, it extends the stress concentration (σ_A) occurring in PZT simultaneously along two directions as seen in Figure 11 a. Hence increasing electric power output. Meta Sub presents higher flexibility and higher strain capacity because of its kirigami cuts, resulting in the production of stress concentration (σ_K) in PZT (Figure 11 a) boosting polarization for the generation of more power and Figure 11 b illustrates Metasub PEH (top) and the conventional PEH (bottom) [71].

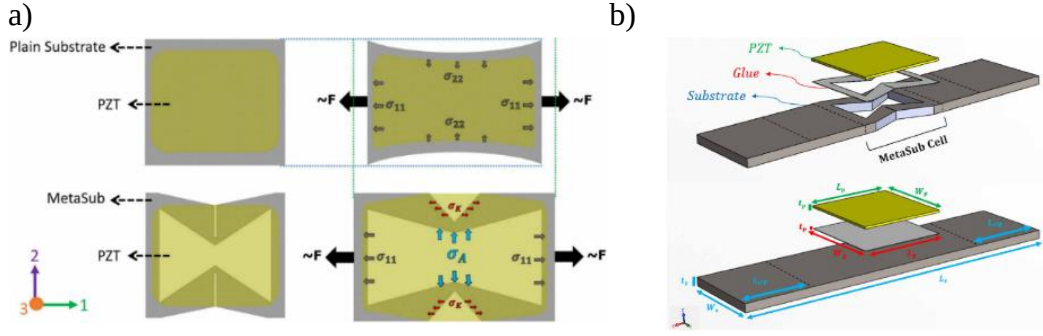


Figure 11: a) Deformed (right) and undeformed (left) states of plain cell (top) and Meta Sub cell (bottom). b) MPEH (top) and the conventional PEH (bottom) [71]

Various combinations of high and low frequency stimulation were investigated in order to examine the MPEH's performance. At high frequencies (100-1500 Hz), 18.1 times more power was produced by MPEH than a comparable conventional PEH. Two experiments for auxetic and conventional PEHs have been used to assess the power augmentation of the MPEH. Even while the MetaSub significantly increases the longitudinal and transverse stresses in PZT-element, it nevertheless has lower stress distribution than corresponding plain substrate of a traditional PEH. In contrast to conventional PEH, only applying 7.1 percent of the capacity of PZT, the MPEH is able to employ 82.6 percent of PZT capacity, representing a considerable efficiency improvement.

According to Fey et al. [34] report, piezoelectric ceramics having auxetic structures are a new class of multifunctional composite materials integrating piezoelectric effects and auxetic structure behavior to obtain high stiffness-to-weight ratios and strength, as along with extraordinary strain responses that outperform individual components. To improve specific electromechanical coupling characteristics such as hydrostatic voltage coefficient (g_h), and hydrostatic strain (d_h), introduction of porosity, changing piezoceramic microstructure by adding a second phase, or periodical cellular design formation is envisaged [72,73]. In comparison to monolithic piezoelectric

ceramic materials, piezoelectric composites have higher electromechanical coupling efficiency, lower specific acoustic impedance, and suppress undesired vibration modes [74]. The receiver sensitivity was improved by an order of magnitude when composite constructions with piezoceramic rods locate in auxetic polymer matrices were used [75]. The AS depicts orthotropic deformation response with negative in-plane Poisson's ratio which is -2.05 [63]. Figure 12a illustrates machined and sintered piezoelectric auxetic PZT ceramic and Figure 12b shows in-plane strain amplification factors for conventional and auxetic hexagonal honeycomb structures in terms of rib slenderness obtained for unit cell deformation dominated with rib bending using cellular material theory [73].

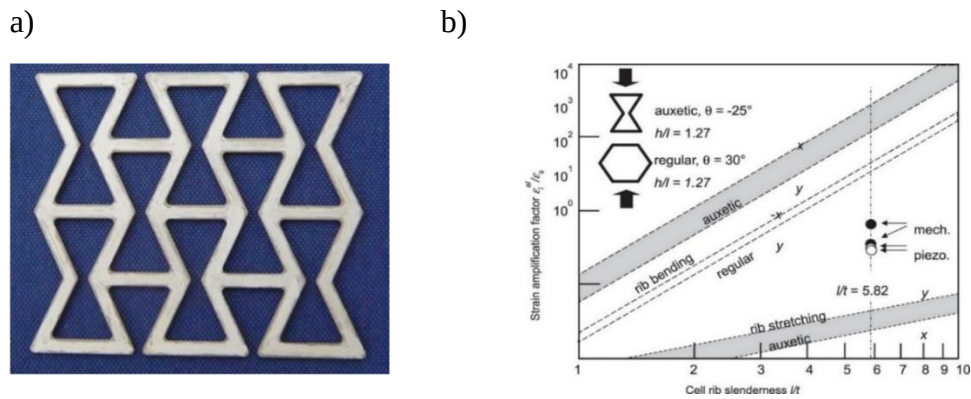


Figure 12: a) Sintered piezoelectric auxetic PZT lattice, b) Auxetic and regular hexagonal honeycomb structures in terms of rib slenderness [34,76]

As was presented in Figure 13, auxetic structure I (AS I) and auxetic structure II (AS II) were calculated in this study by Eghbali et al. [77]. A cantilever beam with an AS and a connected piezoelectric layer is schematically shown in Figure 14. The AS I shows a negative Poisson ratio and has been evaluated for a strip in a tension application [37]. This meta structure is called re-entrant honeycomb and AS II is a

wearable skin sensor with customizable mechanical characteristics that is inspired by ancient geometric shapes [78].

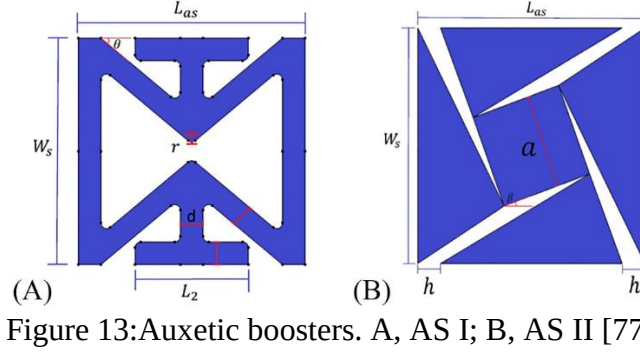


Figure 13: Auxetic boosters. A, AS I; B, AS II [77]

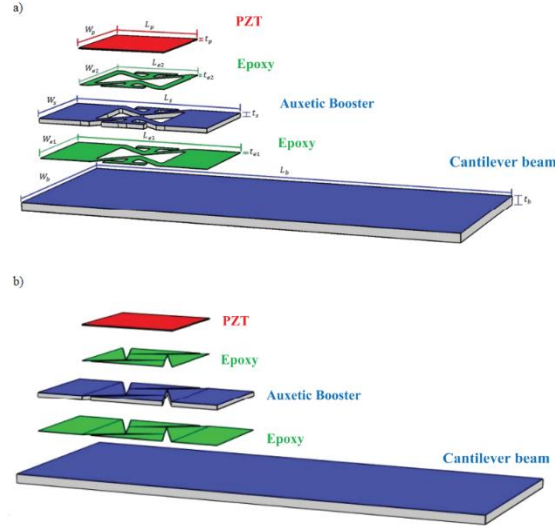


Figure 14: Components of an auxetic booster. A, AS-I; B, AS-II [77]

In the recent study by Ferguson et al. [37], an auxetic structure has been produced in the substrate region sandwiched between piezoelectric components. The auxetic zone has two pros: first, it may stretch piezoelectric elements along two directions simultaneously, enhancing electric power output; second, it is less rigid than the remaining sections of the substrate, concentrating stress on piezoelectric components. Their studied (APEH) is schematically represented in Figure 15.



Figure 15: Schematic diagram of APEH bonded on a host structure. A second piezo element can be added on auxetic region underside [37]

Chen et al. [79] study that is suggested comparing energy harvesters with two substrate types: auxetic structure substrate (AEH) and conventional plain substrate (PEH). Conventional plain substrate with width (w_1) and length (l_1) is shown in Figure 16(a). Figure 16 (b) shows the auxetic structure containing single rotating square unit cell consisting of four square elements [80]. In Figure 16 (b), w_2 connecting hinge width and l_2 is unit cell length. In addition, a/b aspect ratio of rotating square unit cell hole greatly affects unit cell equivalent young's modulus, further influencing harvester characteristics [79]. The suggested harvester achieved both wide working bandwidth and high output power by adjusting unit cell number and parameters, which reduces trade-off of these characteristics in earlier auxetic nonlinear energy harvesters. The qualities of the suggested design are investigated using FEM modeling. The suggested harvester is theoretically examined using a dynamic model that closely reflects the outcomes of testing. Additionally, when compared to the traditional nonlinear energy harvester, the suggested harvester's bandwidth and output power are enhanced by 14 and 268 percent, respectively. Figures 17 and 18 also show the auxetic structure of the beam design. Krishnaswamy et al. [81] examined that auxetic designs could present piezoelectric enhancement effects of more than 300% in comparison to non-auxetic reference models with the same non-auxetic rigid backbone and volume as auxetic backbones. It presents a new possibility of material design employing auxetic matrices either optimally structured for auxetic behavior or inherently auxetic great improvements in piezoelectric behavior are possible, because of enhanced mechanical

connection of the strain applied to piezoelectric inclusions locate in matrices as is seen in Figure 19.

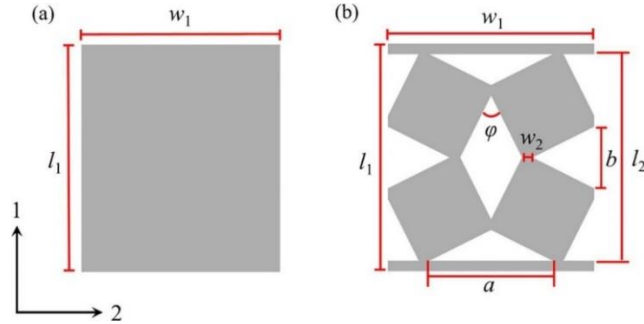


Figure 16: Geometries of (a) conventional plain substrate and (b) auxetic structure [79]

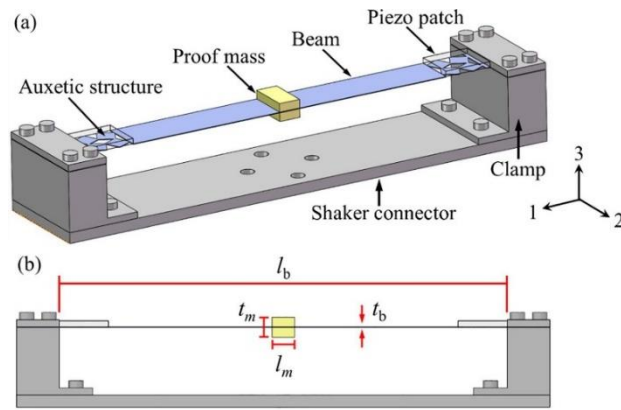


Figure 17: (a) Isometric and (b) side views of the design [79]

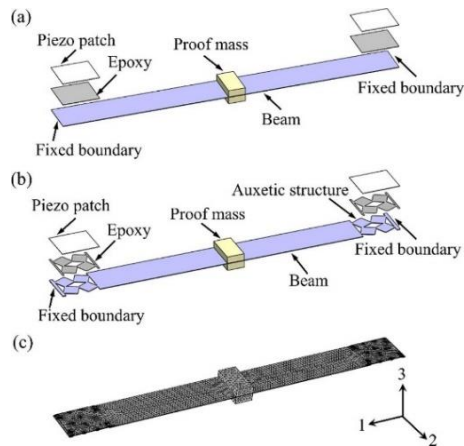


Figure 18: Exploded views of (a) PEH and (b) AEH and (c) meshing in FEM simulation [79].

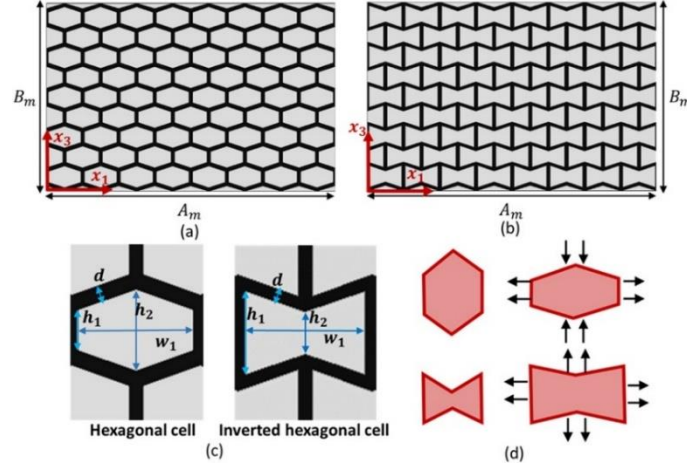


Figure 19: The improved structure has a soft main matrix (grey in color) with a reasonably hard polymeric backbone either (a) hexagonal (nonauxetic) or (b) inverted hexagonal (auxetic). (c) geometric parameters that determine the unit cell of the backbone. (d) Behaviors of hexagonal and inverted-hexagonal structures as non-auxetic and auxetic structures, respectively, with arrows indicating net strain directions [81]

2.3 Auxetic Structures in Piezoelectric System

Beyond the capabilities of state-of-the-art techniques, the utilization of structured materials with such unique qualities opens up new tuning options for material characteristics and performance. It has been observed that auxetic materials' behavior contributes to the piezoelectric response on simple 1-3 topologies [33,82] and simple bimorphic [70] designs. Therefore, these kinds of structures have become promising structures and have attracted attention to them. As a result, the primary focus of Krishnaswamy et al. [81] research's was on creating an auxetic matrix design where piezoelectric lead-free inclusions with random shapes are placed, just like practical composite materials. Bellis and Bacigalupo [30] proposed periodic anti-tetrarchical auxetic lattice structures with a variety of geometries investigated, then piezoelectrical and mechanical responses are first studied, shown in Figure 20. They worked on the strain sensor illustrated in Figure 21(a), and a periodic cell exhibits a sandwich structure, as depicted in Figure 21(b).

Auxetic microstructured strain sensors are more sensitive than their equivalent square beam lattice microstructured counterparts. Additionally, the sensitivity of non-auxetic strain sensors is higher than that of bulk PZT strain sensors. Applications involving sensors and actuators may benefit from an improved strain capacity [30]. Furthermore, Bellis and Bacigalupo [83] studied the characterization of a different type of anti-tetra chiral cellular solids considering both static and dynamic response.

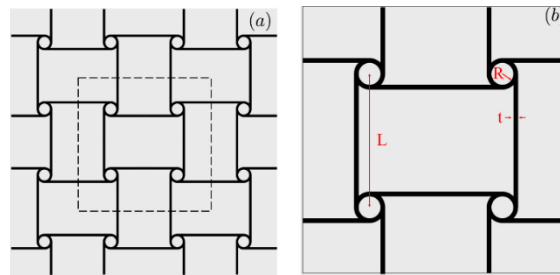


Figure 20: (a) Periodic anti-tetra chiral cellular materials (b) Close view of periodic cell [30]

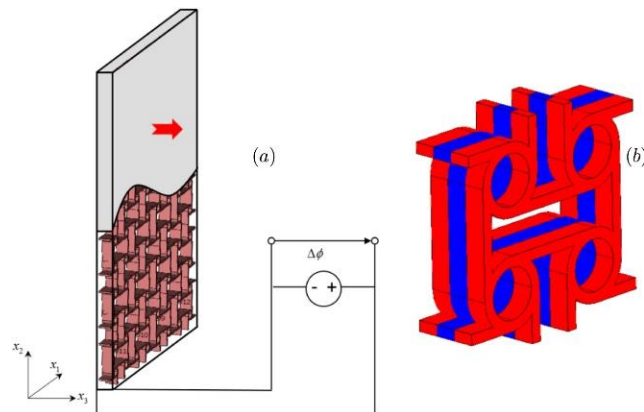


Figure 21: (a) Schematic diagram of 3D strain sensor sandwich structure; (b) a periodic cell with sandwich structure [30]

Auxetic and kirigami topologies are coupled to build a new metamaterial-based substrate (Meta Sub) for PEH, according to Farhangdoust et al. [71] work. The kirigami was created using symmetric and incised periodic cuts on plates and shells to

increase deformation capability and breaking strain [84,85]. Poisson's ratio (Equation (1)) is defined as the ratio of two axial and lateral strain parameters of a structure [66].

$$\nu = \frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \quad (1)$$

Figure 22 shows re-entrant uniaxial kirigami design in the Farhangdoust et al. [71] study as one of the most commonly discussed kirigami topologies [29,86–90].

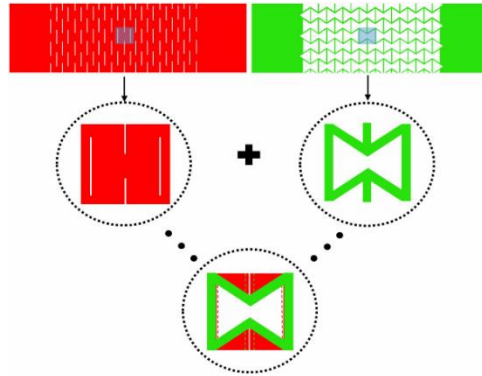


Figure 22: The Meta Sub cell design (bottom) combining uniaxial kirigami (red) and re-entrant hexagonal auxetic (green) topologies [71]

A mesh of four interconnected triangles with two opposing inwards thrust Kirigami forms the basis of this design. As shown in Figure 23, the meta subunit cell arrangement with details is illustrated. Additionally, by outward bending of the first four triangle elements along opposite transverse directions, the bowtie shape approaches rectangular.

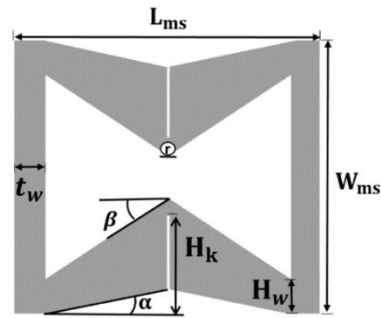


Figure 23: Schematic diagram of Meta Sub unit cell design with details [71]

Sun et al. [91] made by a highly ductile and soft PEH with a substrate based on kirigami resulting in an about 2.5-times rise in voltage output. In other engineering applications using more rigid substrates such as steel, kirigami-based PEHs have been developed for biomedical applications with highly deformable and soft substrates such as polyethylene terephthalate (PET) and polydimethylsiloxane (PDMS) [92,93]. Fey et al. [34] developed a piezo-ceramic with a auxetic lattice structure of hexagonal honeycomb type to enhance strain energy from an applied voltage. Two auxetic structure types are examined to study auxetic structure effects on the nonlinearity and efficiency of energy harvesters. Figure 24 shows the geometric properties of auxetic structures. The type I auxetic structure (Figure 24 a) is composed of re-entrant hexagonal unit cells. However, type II auxetic structure, shown in Figure 24 (b), is created by the addition of ribs to re-entrant hexagonal unit cells, increasing auxetic structure rigidity. The energy harvester's performance may be harmed as a result of this rigidity [46].

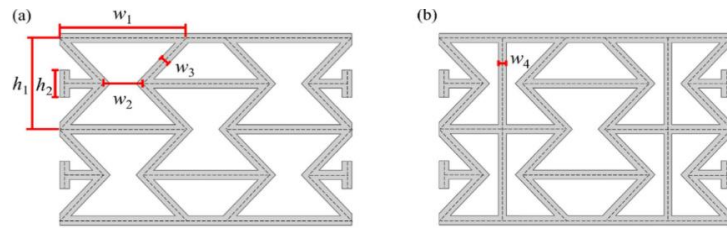


Figure 24: Geometry of auxetic structures: (a) type I and (b) type II [46]

2D honeycombs, a unit cell of which is illustrated in Figure 25 a, have been proposed auxetic structures [63]. It was extended laterally by the application of uniaxial tension along longitudinal direction, as shown in Figure 25 b, and compressed laterally by applying uniaxial pressure along x direction (Figure 25 c). This indicates that auxetic structure's elements should be placed in such a way that the poison ratio is negative.

This concept is used in this article, especially in the circular layouts. Figure 26 depicts the proposed circular auxetic designs' aberrant negative poison's ratio behavior. Figures 26 a, c shows the auxetic structures' lateral (y direction) growth when applying uniaxial tension along x direction. When strain is applied to inclined ligaments, they shift towards the out of the circle. Figures 26 b, d depict lateral compression along x direction under uniaxial pressure. The two unique auxetic geometries were created specifically for PZT buzzers with circular shapes (Figure 27).

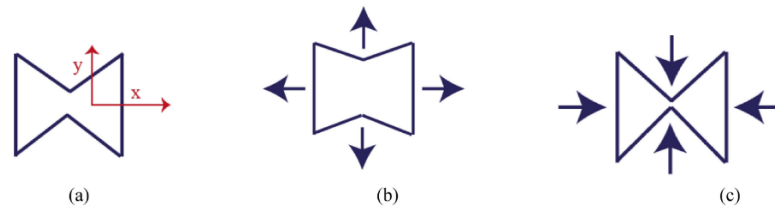


Figure 25: 2D auxetic structures (a) free mode, (b) lateral (y direction) expansion under uniaxial tension along x direction, (c) lateral (y direction) compression under uniaxial pressure along x direction [63]

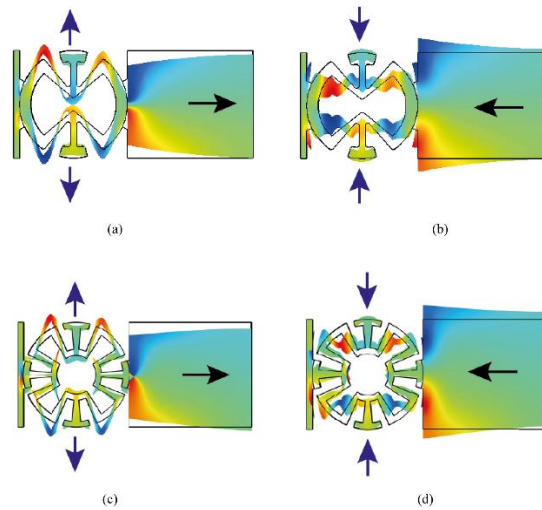


Figure 26: The developed circular auxetic layouts, colored presentation reveal deformed shapes (a), (c) auxetic region lateral expansion under uniaxial tension (b), (d) auxetic region lateral compression under uniaxial pressure [63]

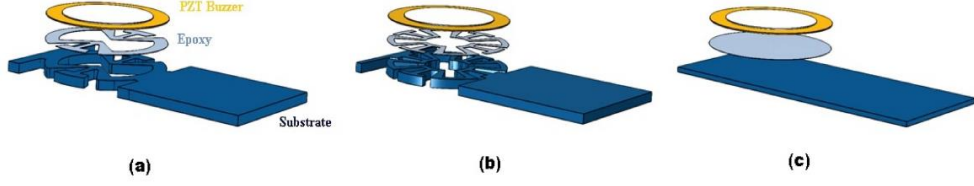


Figure 27: Cantilever beam energy harvester with auxetic structures (a) AEH-I, (b) AEH-II, (c) PEH [63]

Eghbali et al. [63] report that the use of auxetic structures is motivated by two primary characteristics of them;

1. The significance of this property will be underscored when the following equation is considered. The combined influences of stress concentration and auxeticity of the area result in the power increase in the APEH and the relation is shown in equation 2 [37].

$$\text{power} \propto (\sigma_{11} + \sigma_{22})^2 \quad (2)$$

2. The average of stress in the vertical direction, as well as longitudinal direction, are defined with σ_{11} and σ_{22} . In comparison to the plain structure, where σ_{11} and σ_{22} have different signs, this equation indicates that auxetic structure output electrical power is increased when σ_{11} and σ_{22} have the same sign. Because stress buildup near the corners and geometrical singularities, power density is increased. For the piezoelectric material, we have constitutive equations as follows [94].

$$\begin{aligned} S_1 &= s_{11}^E T_1 + d_{31} E_3 \\ D_3 &= d_{31} T_1 + \epsilon_{33}^T E_3 \end{aligned} \quad (3)$$

In which S_1 , T_1 , E_3 , and D_3 indicates the longitudinal strain, stress, electric field, and charge density of the piezoelectric element, respectively. s_{11}^E , d_{31} and ϵ_{33}^T represent the

electric cohesion in a constant electric field, the piezoelectric stress constant, and the dielectric constant under constant voltage, respectively. Using the foregoing constitutive equations, it can be observed that raising T_1 due to stress concentration increases the charge density D_3 . When compared to ordinary resonators, mentioned as 1 and 2 descriptions show the pros of auxetic structures result in increased captured power.

Three distinct auxetic patterns employed in energy harvesting systems are presented by Moayedizadeh and Younesian [95]. The strategy of the new design is to increase the pattern's stress concentration zones and design parameters. By comparing the findings of Auxetics I and III, it is demonstrated that both in theory and in practice, these two concepts significantly boost harvested energy amount. According to Moayedizadeh and Younesian, stress concentration in auxetic material increases PEH power density. The corresponding equation for this property is shown in equation (2). Bertoldi et al. [115] and, Eghbali et al. [63] drove the same equation with their studies. Iyer et al. [96] concentrate on the latter instance (auxetic piezoelectric), which has applications in sensing and actuation. Another justification for including piezoelectric composites showing auxetic properties is underlying deformation mechanisms that cause NPR in auxetic materials. For both transverse and longitudinal poling, piezo ceramic typical convention is to keep direction 3 as poling direction (Figure 28). As a result, in the case of transverse poling, the direction of poling is in-plane, whereas it is out-of-plane for longitudinal poling.

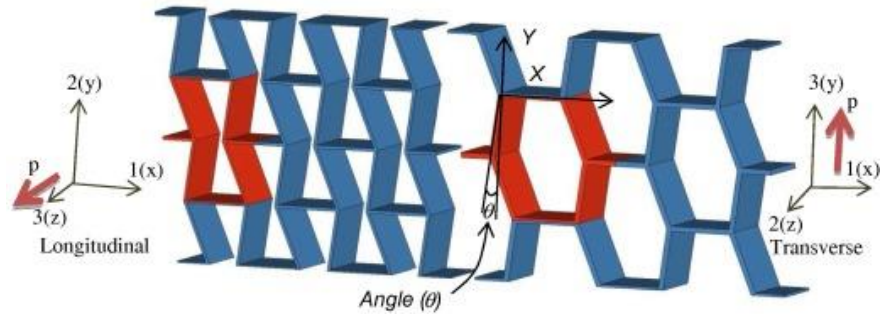


Figure 28: The schematic diagrams of a conventional structure with positive Poisson's ratio (right) and an auxetic structure (left) are shown in cellular hexagonal geometry. For both transverse and longitudinal poling conditions, the figure depicts basic representative unit cells (in red), coordinate systems and angle employed. In all cases, poling (red arrow) is done in three directions, as is typical in piezo-ceramics [96]

Chandrasekharan and Thompson [97] studied to shows that replacing solid continuous substrates of existing bimorphs with honeycomb structures of similar materials leads to a great boost in the piezoelectric harvester's power to weight ratio at low excitation frequency ranges. It has been demonstrated that, contrary to typical piezoelectric bimorphs with solid continuous substrates, honeycomb substrates bimorphs may keep optimum global design parameters by manipulating the parameters of honeycomb unit cell at higher driving frequency ranges. Honeycomb structure unit cell parameters could be manipulated to adjust stiffness and mass properties of substrates, which greatly affect power generation and increase design flexibility and operating lifetime of honeycomb core piezoelectric bimorphs [97]. Based on the inlaid geometrical patterns, Kabirian et al. [98] constructed three different latticed designs to be auxetic piezoelectric resonators. Figure 30 depicts several geometries. Each cantilever resonator has three layers, as indicated in this figure: PZT, Brass, and PZT. According to the auxetic pattern, all three layers are latticed and through-bored. Figure 29 also shows top views of the three structures, as well as their geometrical parameters [98].

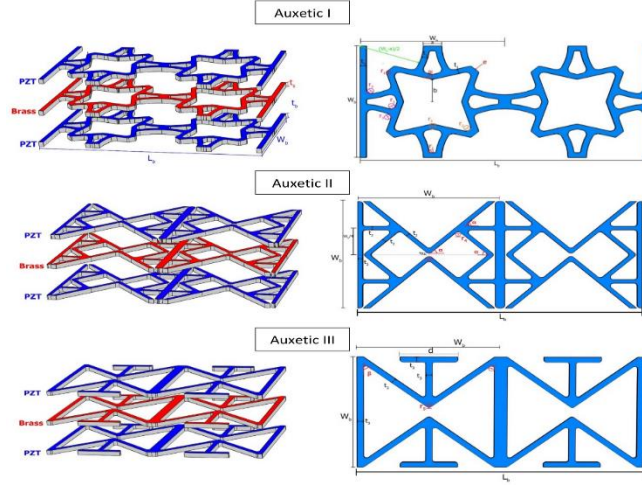


Figure 29: Auxetic patterns and geometrical parameters [98]

Ichige et al. [99] enhance power production capability while retaining low resonance frequency (≤ 30 Hz), button battery size, and device footprint, structural parameters of metamaterial were designed for PVEH elastic layer. The suggested PVEH is seen schematically in Figure 30. Strain is created in piezoelectric layer when bending the beam, which causes piezoelectric effect to produce electricity. Increase of strain and reduction of the stiffness of bending can be used in the cantilever-type PVEH to reduce driving frequency and boost power generation. The material's characteristics and cross-sectional shape affect the material's bending stiffness. Therefore, the elastic and piezoelectric layers in this investigation were made of a flexible polymer material. The distance of neutral axis from piezoelectric layer is lowered in a technique to reduce the stiffness of bending by decreasing thickness, and strain may be minimal even if the deformation is substantial. Therefore, to increase flexibility without reducing thickness, they developed metamaterial structures as elastic layers.

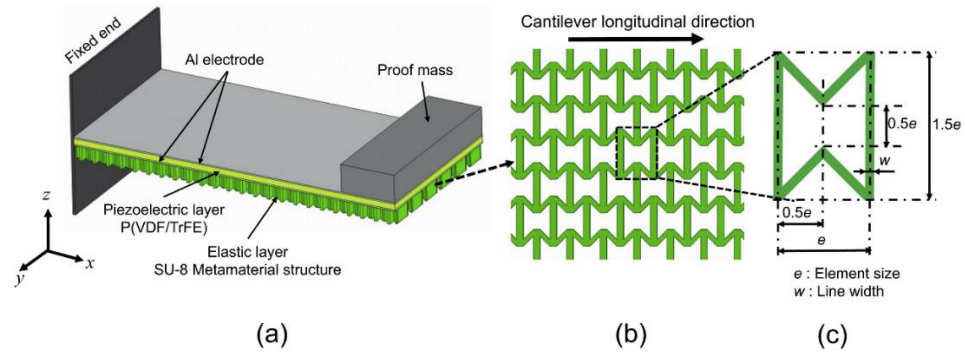


Figure 30: Schematic diagram of the developed PVEH. (a) unimorph cantilever configuration consisting of a metamaterial elastic layer and piezoelectric layer, (b) metamaterial elastic layer, and (c) the element of metamaterial structure [99]

Based on the literature review, Table 2 shows the summarized comparison of APEHs and PEHs. Number 2 and number 9 studies have the same auxetic structure, therefore the efficiencies are close to each other.

Table 2: Efficiency comparisons of several APEH with PEH

No	Auxetic Structure Type	Efficiency Comparison with Conventional PEH	Ref
1	Gradient auxetic structure	356 % higher	[69]
2	2D auxetic substrate	276 times higher	[70]
3	Meta sub	82,6 % higher	[71]
4	Re-entrant honeycomb	3,9 times higher	[77]
5	Single rotating square unit cell	77 % higher	[79]
6	Auxetic backbones	300 % higher	[81]
7	Periodic anti-tetrarchal auxetic lattice structures	2,5 times higher	[30]
8	Kirigami	2.5-times higher	[91]
9	Auxetic porous structure	259 times higher	Current study

Chapter 3

METHODOLOGY

3.1 Simulation of the Piezoelectric Cantilever Beam with Different Substrate Layers

The finite element (FE) approach is used to study the piezoelectric laminated constructions under certain presumptions. When exposed to background vibrations, the cantilever beam experiences slight deformations. Piezoelectric material is thought to behave linearly. Furthermore, there is a constant load distribution across the model setup and a flawless link between the piezoelectric and substrate layers. Additionally, in this thesis, the efficiency of AS with piezoelectric materials in cantilever beam energy harvesters was investigated.

In the research, finite element simulations are driven to investigate the performance of the created models. An example of piezoelectric bimorph cantilever beam for verification has been given by Wang et al. [100]. In this thesis, a piezoelectric cantilever beam with the same material parameters as the example was used, then number of layers increased and some of the layers were converted into auxetic structure, and the length and width dimensions of all models were adopted to auxetic structure. Furthermore, four models of beam were created in the system. They are called Structure 1, Structure 2, and Structure 3, and Structure 4. They were compared with each other by using finite element models at COMSOL Multiphysics 6.0. The aim of this thesis is to reach voltage and power values depending on frequency

response, acceleration dependence, load dependence, eigenfrequency study and to show that energy harvesting efficiency is increasing in which model more. Moreover, the flowchart of the model shown in Figure 31.

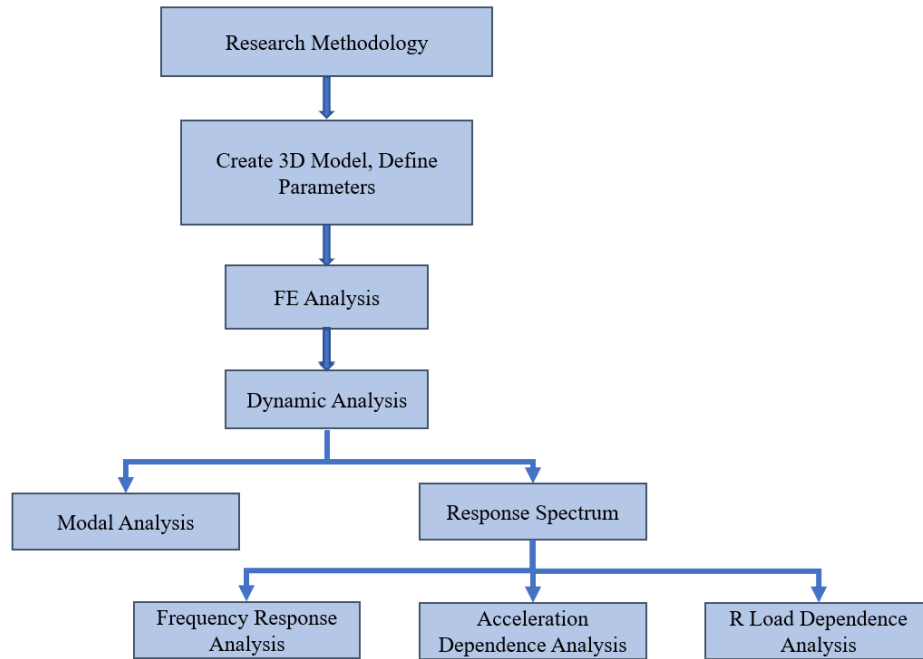


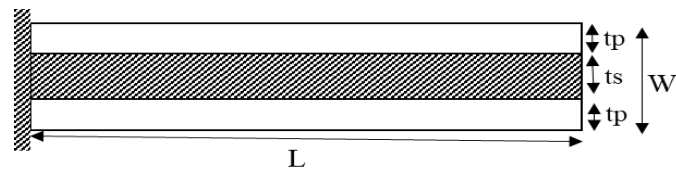
Figure 31: Flow Chart of PEH modeling using COMSOL.

3.2 Geometry

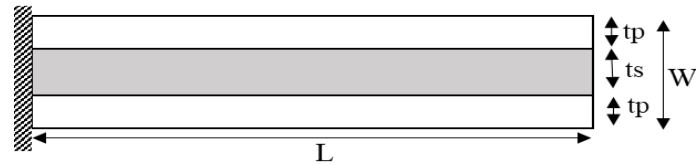
A 3D cantilever beam model was created and simulated in COMSOL Multiphysics 6.0 using specific values such as length, width etc. in response to changing input parameters including frequency response, acceleration dependence, load dependence and eigenfrequency study. Moreover, this thesis includes four types of cantilever beam models. The first one consists of 2 layers of piezoelectric material 1-layer auxetic substrate, second one has 1 layer of brass substrate and 2 layers of pzt material, third one has 3 layers of piezoelectric material 2-layer auxetic substrates, and the fourth one consists of 3 layers of piezoelectric material and 2 layers brass substrates. Models are

shown in Figure 32. Furthermore, the dimensions of the models shown in Table 3 such as the thicknesses (t_s) of the auxetic substrate and piezoelectric layers (t_p).

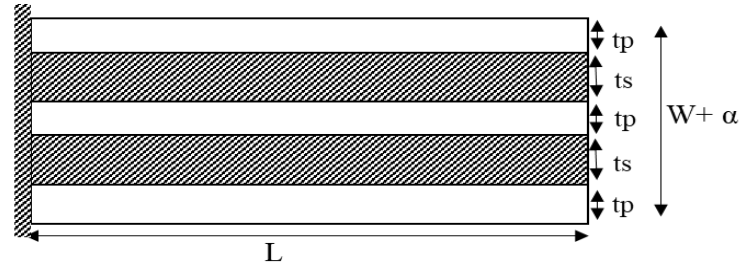
The auxetic design is shown in Figure 33 and is created by making elliptic rounds along the length of the substrate layer. Major and minor axes of the ellipse are denoted by a and b , respectively. The L represents the length of the sheet and W is the width of it also they illustrated in Figure 33. The model was a fixed free cantilever beam, it oscillated with the applied body load. The voltage and electrical power of the beam were authorized to be examined using this simulation. Boundary conditions for the cantilever beam have been established using the solid mechanics settings of COMSOL Multiphysics 6.0. A fixed, free end beam model was used for this study. The remaining components of the cantilever beam were in a free state, which means that displacement is always a possibility anytime the vibrations being applied are noticed. Furthermore, boundary conditions were built up for all structure and electrostatics settings. After that, the useful studies are determined for the models and simulation was ran.



a) Structure 1: 1-layer auxetic substrate 2 layers PZT-5H



b) Structure 2: 1-layer brass substrate 2 layers PZT-5H



c) Structure 3: 2-layer auxetic substrate 3 layers PZT-5H



d) Structure 4: 2-layer brass substrate 3 layers PZT-5H

Figure 32: Geometry for four created structures

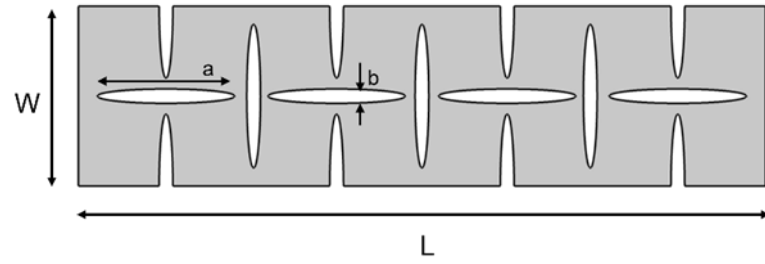


Figure 33: Schematic of auxetic sheet

Table 3: Cantilever beam and auxetic sheet parameters [70]

Description & Name	Value	Expression
Width -W	0.05 m	50[mm]
Length - L	0.2 m	200[mm]
Major axis - a	0.02 m	20[mm]
Minor axis - b	0.002 m	2[mm]
Piezoelectric layer thickness - tp	5E-5 m	0.05[mm]
Substrate thickness - ts	2E-4 m	0.2[mm]
Load resistance - R_load	12000 Ω	12[kohm]
Acceleration (g) - acc	1	1

3.3 Material Properties for Brass

Brass substrate was used for all configurations, however, Structure 2 and 4 did not include an auxetic structure. Therefore, Poisson's ratio has a positive value for Structure 2 and 4 but Structure 1 and 3 has negative value. The properties for brass are given in Table 4 below.

Table 4: a) Properties of brass in auxetic structure b) Properties for brass in conventional structure [100]

a)			b)		
Name	Value	Unit	Name	Value	Unit
Density	9000	kg/m ³	Density	9000	kg/m ³
Young's modulus	105	GPa	Young's modulus	105	GPa
Poisson's ratio	-0.35		Poisson's ratio	0.35	

3.4 PZT 5H Properties

All structures have PZT-5H material as piezoelectric material. The best piezoelectric material, PZT 5H, has somewhat narrower temperature range and is sensitive to temperature changes [101]. The important features of PZT 5H are shown in Table 5 and the data provided from COMSOL Library.

Table 5: The important properties of PZT 5H

Density	7500 kg/m ³
Relative permittivity	{1704.4, 1704.4, 1433.6}

3.5 Mesh

Finite element analysis and finer triangular mapping meshing were used to enable the cantilever beam to be discretized smoothly. The cantilever beam's eigenvalue was

calculated using eigenfrequency analysis, and also three other studies were run. The mesh divides the structure into many parts and runs for each part and aim of that to get accurate results by using finer mesh. For Auxetic sheet mesh is shown in Figure 34 and the beam meshes shown in Figure 35.

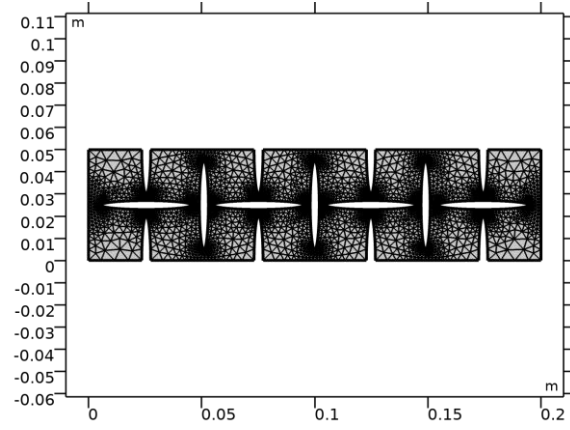
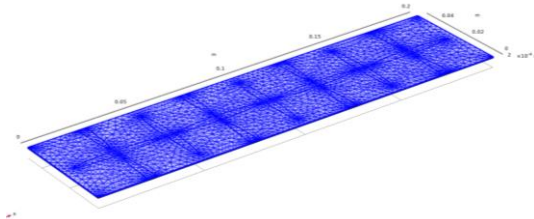
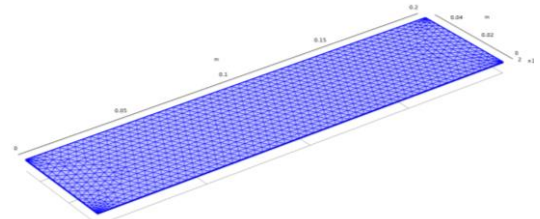


Figure 34: auxetic sheet mesh

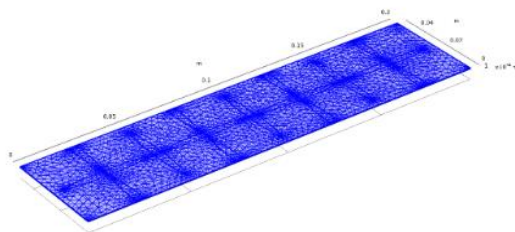
a) Structure 1



b) Structure 2



c) Structure 3



d) Structure 4

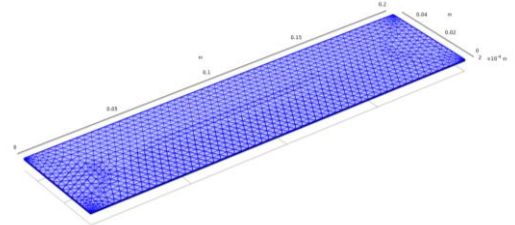


Figure 35: Meshes for beam structures

3.6 Solid Mechanics and Electrical Circuit Interfaces

The Solid mechanics interface can be driven to structures the mechanical behavior of the PZTs, while the electrical circuit interface can be used to structures the electrical circuit that is connected to the piezoelectric material. First, piezoelectric coefficients are specified for the piezoelectric material, as well as the mechanical and electric boundary conditions for the structures. The mechanical boundary conditions can include applied forces or deformations, while the electric boundary conditions can include applied electric potentials or currents.

The Solid Mechanics interface is achieved by solving equations of motion and a solid material's structural models. Results are computed as strains, stresses, and displacements. Depending on the tools, the Solid Mechanics interface offers different capabilities. Thus, in this section some parameters were defined for the structures. For example, boundary conditions, body load, piezoelectric material, linear elastic material etc. COMSOL provides the equations from itself which are given in equations 4,5,6,7,8 and 9. Equation 4 describes the behavior of a piezoelectric cantilever beam, which is a type of mechanical structure that is used in a variety of applications. The first equation is the general equation for the system. ρ is the density, ω angular frequency or periodic function, u is the velocity of the particles. Moreover, S is the stress tensor, which is a measure of the internal forces acting within a material, F is force, v is velocity, e is the base of the natural logarithm (also known as Euler's number), i is the imaginary unit, which is equal to the square root of -1 and ϕ (phi) is a scalar function or a phase angle. Additionally, ϵ (epsilon) is the strain tensor, which is a measure of the deformation of a material. The strain tensor is a second-order tensor that describes how the shape of a material changes under the action of external forces.

Equation 5 is related to the permittivity of the material and COMSOL generates the equation according to which commands were defined to it.

$$\rho\omega^2\mathbf{u} = \nabla \cdot \mathbf{S} + \mathbf{F}e^{i\phi} \quad (4)$$

$$\mathbf{S} = \mathbf{S}_0 + \mathbf{C} : \epsilon_{el} - \mathbf{E} \cdot \mathbf{e}, \quad \epsilon_{el} = \epsilon - \epsilon_{inel} \quad (5)$$

$$\epsilon_{inel} = \epsilon_0 + \epsilon_{th} \quad (6)$$

$$\mathbf{C} = \mathbf{C}(c_E) \mathbf{e} = \mathbf{e}(e_{ES}) \quad (7)$$

For the electrostatic section COMSOL used its equations which are 5,6 and 7. The equations of Piezoelectricity combine the momentum equation with the charge conservation equation of Electrostatics, and it creates the fifth equation. ρ_v is the electric charge concentration. $\mathbf{D}$ comes from piezoelectric constitutive relations.

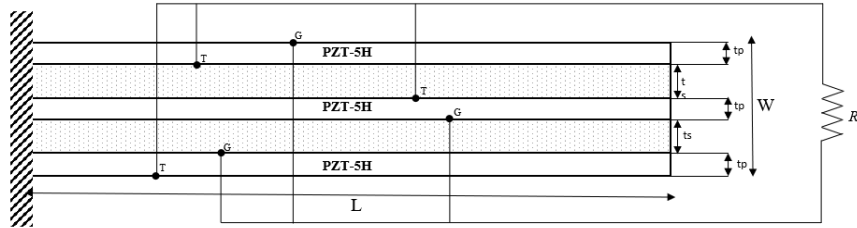
$$\nabla \cdot \mathbf{D} = \rho_v \quad (8)$$

$$\epsilon = \frac{1}{2} [(\nabla \mathbf{u})^T + (\nabla \mathbf{u})] \quad (9)$$

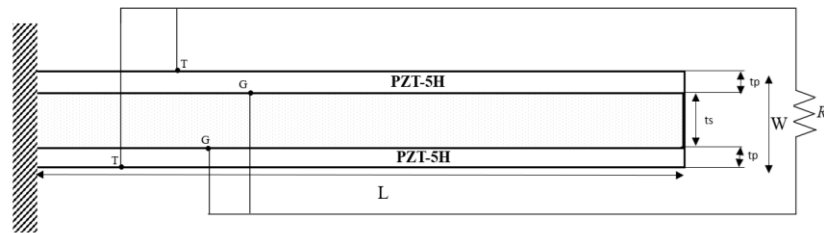
3.7 Electrical Circuit

In this thesis electrical circuit arranged in parallel type for both type of number of layers, the polarization directions of the PZT materials in the top and lower layers are identical. For the electrostatic field, the top electrode of the upper PZT part and the bottom electrode of the lower PZT part are both known as terminals, while the bottom electrode of the upper piezoelectric PZT part and the top electrode of the lower PZT part are both known as ground of the circuit. This arrangement is for Structures that have 2 layers of PZT material and 1 layer of substrate in between. However, when the layer was increased terminal and ground boundaries were adopted again and for

both layer type, electrical circuits depict in Figure 36. This electrical connection creates a piezoelectric circuit that uses the host structure's vibration to produce electricity. This is to assure that anytime there is mechanical vibration, the cantilever beam may respond electrically.



a) 5 layers cantilever beam circuit



b) 3 layers cantilever beam circuit

Figure 36: Electric circuits for both type of structure

Chapter 4

RESULT AND DISCUSSION

4.1 Modeling Validation

The structure presented by Wang et al. [100] is used to examine the validity of the present simulations through verifying the experimental and FE simulation results. In Ref. [100], the structure is a piezoelectric bimorph beam with 2 PZT-5H layers, a substrate layer made of brass, and subject to an acceleration of 1 g, which is similar to the cantilever beam described in Chapter 3 for this study. In the present simulation, changes made in material and layer thickness only affect the initial structure setup and do not affect the validity of other structures. However, parameters including beam length, thickness, etc. will affect the magnitude of resonance and stress distribution and not the overall structure accuracy.

The effective parameters and quantities utilized by Wang et al. [100]. for the suggested cantilever beam are utilized in current research, where the first order eigenfrequency is computed to verify the structure. The results in Table 6 show that the first order eigenvalues are close to each other, which validates the simulation results and is consistent with results provided by Wang et al. [100].

Table 6: First order eigenfrequencies comparison

Structure (3D) [100]	Current Structure (3D)
First order eigenfrequency	First order eigenfrequency
513.55 Hz	522.62+1.1499i

4.2 Frequency Response

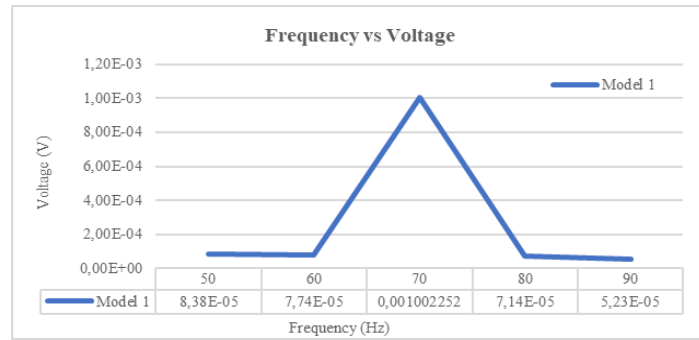
The frequency response of a piezoelectric energy harvester is an important result to study in a COMSOL Multiphysics simulation because it can provide insights into the performance and efficiency of the energy harvester under different operating conditions. The change of voltage and power output of the energy harvester varies with changes in the frequency applied on the energy harvester. Therefore, energy harvesters work best when their resonance is in coherence with the applied frequency, as frequency is the key factor in piezoelectric energy harvesting [102,103].

The frequency response can also reveal the resonant frequencies of the energy harvester, which are frequencies at which the energy harvester exhibits a particularly large or small response. The resonant frequencies of an energy harvester are important because they can affect its performance and efficiency. For example, an energy harvester that is designed to vibrate at its resonant frequency will can generate the maximum amount of electrical energy, whereas an energy harvester that is subjected to vibrations at frequencies that are significantly different from its resonant frequency may not be able to generate as much electrical energy. By understanding the frequency response and resonant frequencies of a piezoelectric energy harvester, you can design or optimize the energy harvester for a particular application, such as for harvesting energy from specific types of vibrations or at particular levels of intensity. The frequency response can also be used to troubleshoot problems with the energy harvester or to identify opportunities for improving its performance.

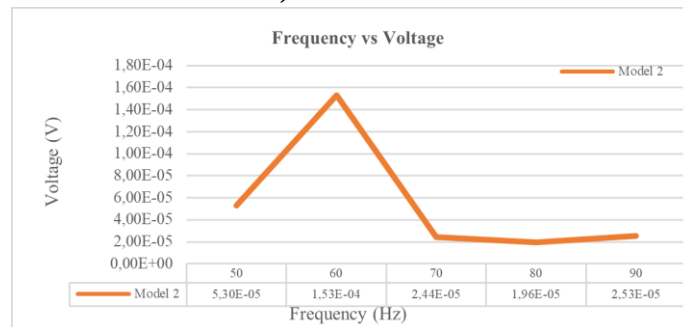
4.2.1 Frequency Voltage Response Comparing with Structures 1, 2, 3 and 4

The harvester was subjected to an excitation signal in the frequency range from 20 Hz to 140 Hz. The results of the voltage frequency response study showed that the voltage output of the harvester increased with increasing frequency, reaching a maximum value at a resonant frequency of around 50 to 80 Hz for two-layer PZT Structures Figure 37 a and b, and 30 to 70 Hz for three-layer PZT Structures which are Figure 37 c and d. The voltage output then decreased at higher frequencies, due to the loss of energy through the internal resistance of the harvester. However, Structure 1 and Structure 2 consist of two piezoelectric layers. Structure 1 has an auxetic structure as a core and Structure 2 has conventional brass core layer. Figure 37 a and b show the frequency between 50 and 90 and the voltage values in that range. According to the peak values of the two Structures, it was observed that Structure 1 released approximately 6 times more voltage than Structure 2. This result is expected and desired since Structure 1 contains an auxetic layer. Structure 3 (Figure 37 c) and Structure 4 (Figure 37 d) have three layers of piezoelectric materials and 2 layers of core materials. As in Chapter 3, Structure 3 has auxetic layers and Structure 4 created by conventional structures. Regarding the last two Structures, Structure 3, which includes auxetic structure layers has significantly higher voltage output than Structure 4 because of the auxetic cores.

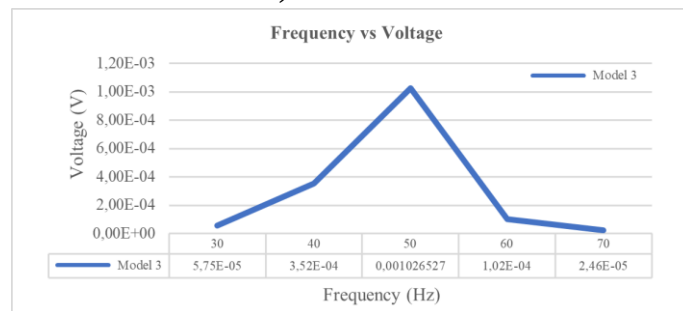
a) Structure 1



b) Structure 2



c) Structure 3



d) Structure 4

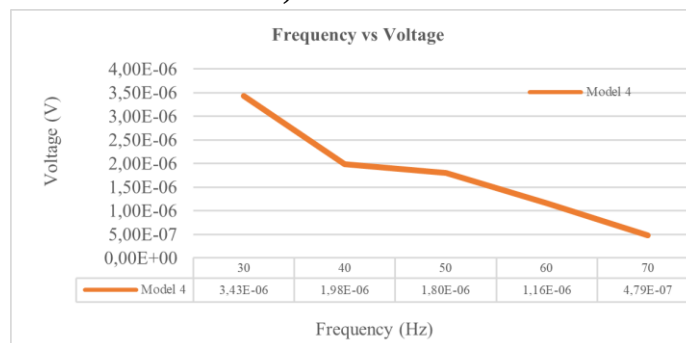
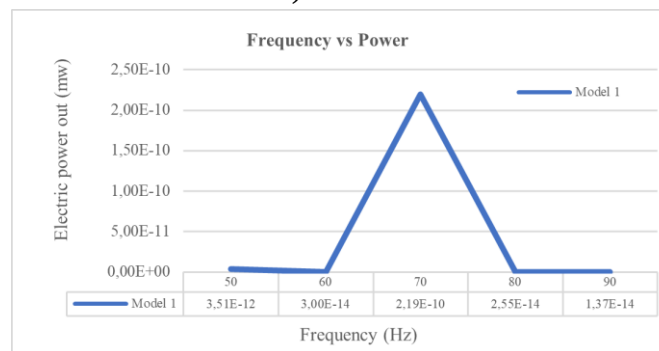


Figure 37: Frequency vs voltage graphs for all structures

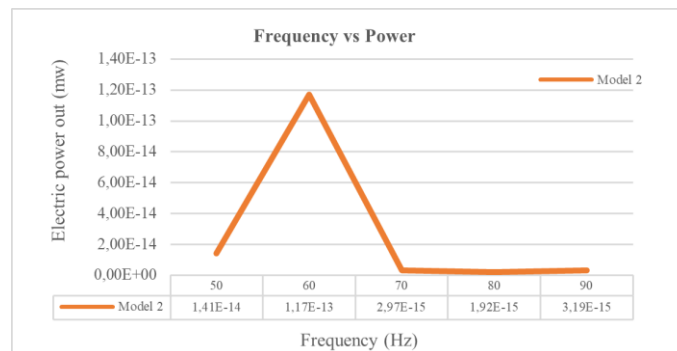
4.2.2 Frequency Power Response Comparing with Structure 1, 2, 3 and 4

The power frequency response is directly proportional to the voltage frequency response. The higher the voltage generation in a system, the higher the power output should be. Comparison of Structure 1 and Structure 2 in Figure 38 a and b illustrated as Figure 37. At the peak points auxetic structure affects power like voltage and the same situation occurs in Structure 3 and 4 as well.

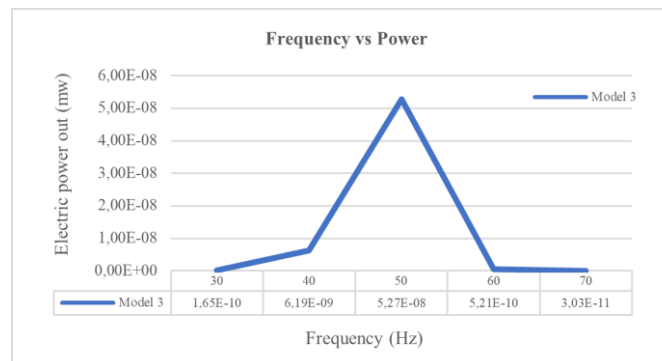
a) Structure 1



b) Structure 2



c) Structure 3



d) Structure 4

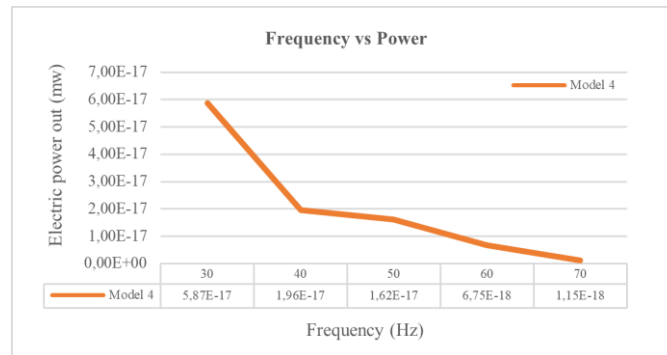
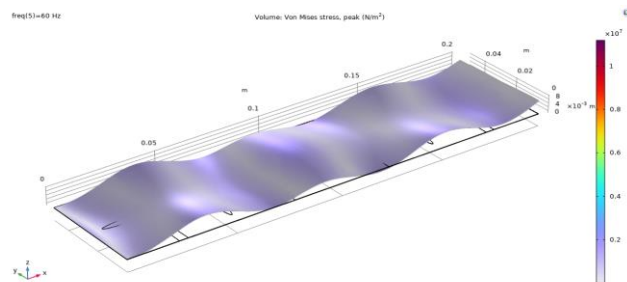


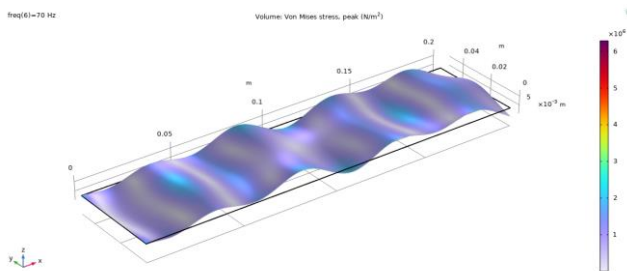
Figure 38: Frequency vs power graphs for all structures

In this present study, the stresses that the structure is exposed to at different frequencies were calculated by Von Misses and COMSOL in order to analyze the response of the structures varying with frequency. As shown in Figure 39, the structures were analyzed thoroughly and the structures with the auxetic materials are far from failing in the appropriate structure according to von Misses. The Structures which contain the auxetic layer are more stable than the conventional energy harvester.

a) Structure 1



b) Structure 2



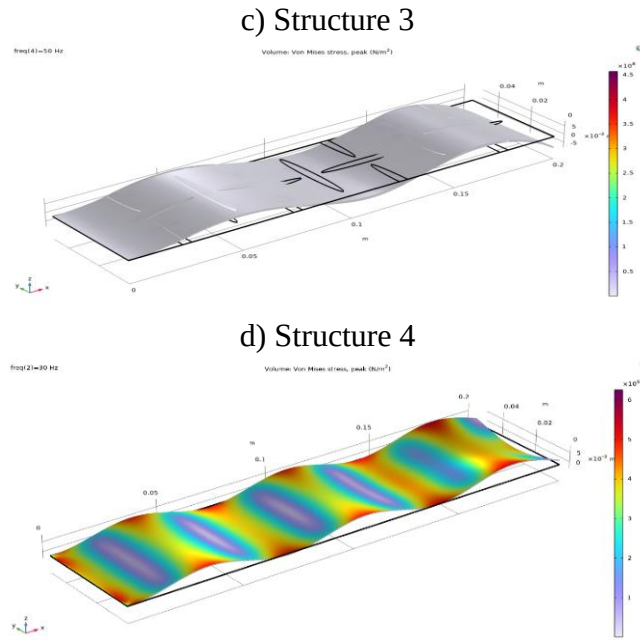


Figure 39: Von Misses stresses regarding to frequency response

4.3 Acceleration Dependence

A COMSOL simulation of a piezoelectric energy harvester involves modeling the mechanical and electrical behavior of the PZT material as well as the energy harvesting and conversion process. The simulation ran for various accelerations to see how the performance of the harvester changes under different circumstances. In this study, the acceleration dependence was studied by applying a range of acceleration levels to the device and measuring the corresponding voltage and electric power output. By analyzing the results of the study, it is possible to determine the optimal acceleration range for the device, as well as any factors that may affect the efficiency of the device at different acceleration levels.

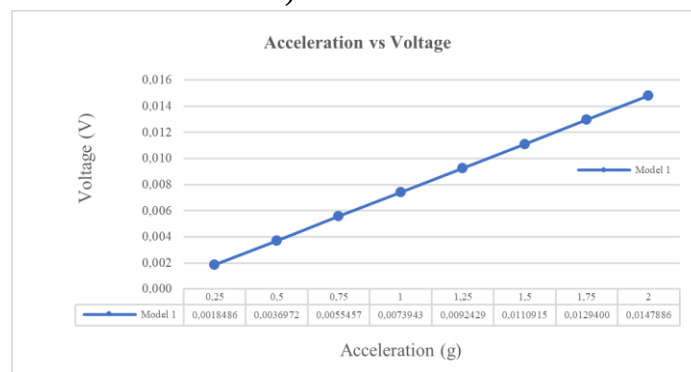
In this thesis, the energy harvester was subjected to a range of acceleration levels, from 0,25 to 2 g, in increments of 0.25 g. The results of the acceleration dependence study

showed that the voltage and electrical power output of the energy harvester increased with increasing acceleration.

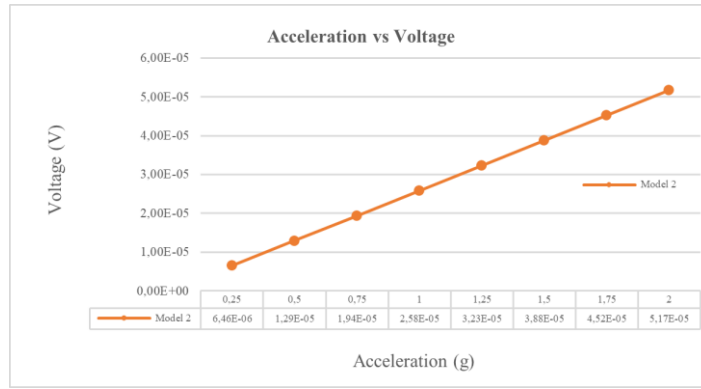
4.3.1 Acceleration-Voltage Relationship for Structures 1, 2, 3 and 4

Figure 40 shows the acceleration versus voltage graphs for Structure 1 to Structure 4. As it is reached in the voltage acceleration graph, it is seen that the voltage output increases with the increase in acceleration. However, while Structure 1 produced more voltage than Structure 2, Structure 3 generates less voltage than Structure 4 in this study. Thus, an adverse effect on voltage generation was observed when the number of layers increased compared to the frequency response study. For example, at 1 g of acceleration, the voltage of with auxetic layer harvester became about 259 times higher than the conventional energy harvester for two layers of piezoelectric structure whereas for Structure 3 and Structure 4 at the same level of acceleration, the conventional harvesters' voltage output 5 times higher than other. According to this study type increasing the number of layers did not affect the voltage output considerably.

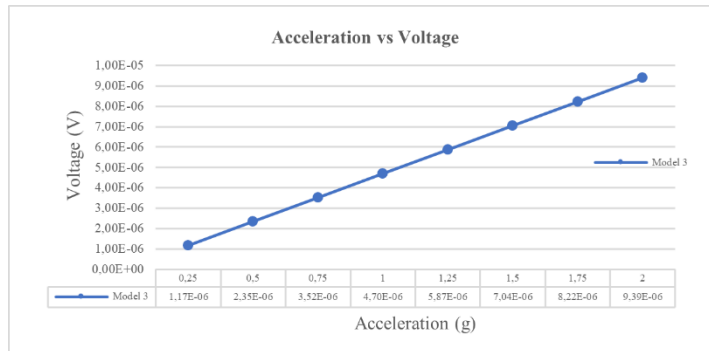
a) Structure 1



b) Structure 2



c) Structure 3



d) Structure 4

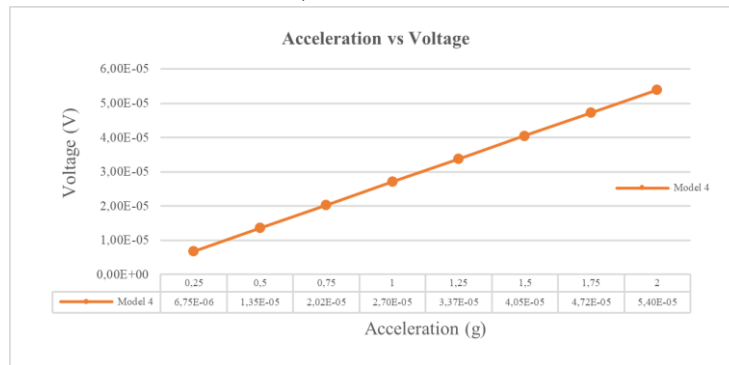


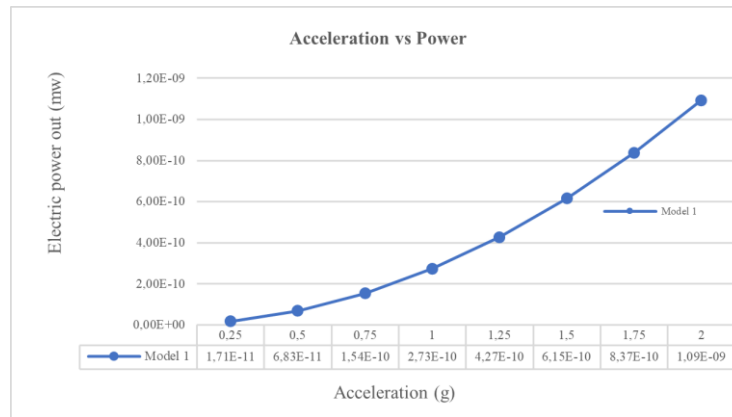
Figure 40: Acceleration vs voltage graphs for structure 1-4

4.3.2 Acceleration–Power Relationship for Structures 1, 2, 3 and 4

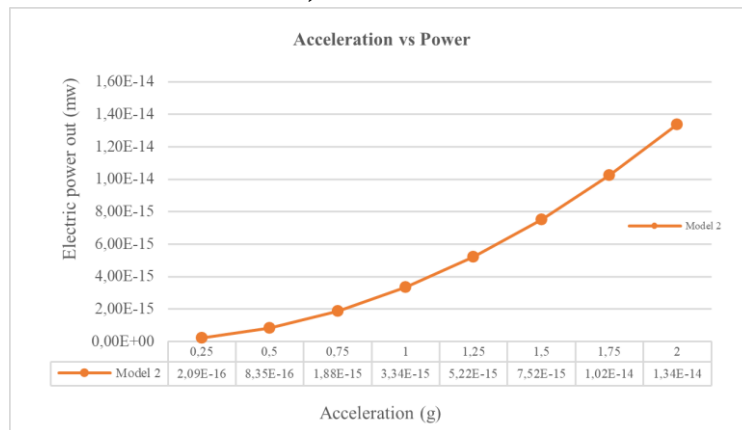
The acceleration power graph shows a more quadratically increase than the acceleration voltage graph. Due to the direct proportionality of voltage and power, the resulting power was higher for the structure with two PZT-5Hs with auxetic materials, while higher power output was found for the structure without auxetic one with three PZT-5H materials. There is a serious difference in the first two structures compared to

the last two Structures. As can be seen in the graphs in Figure 41, their multi-layered structures were not as efficient as expected.

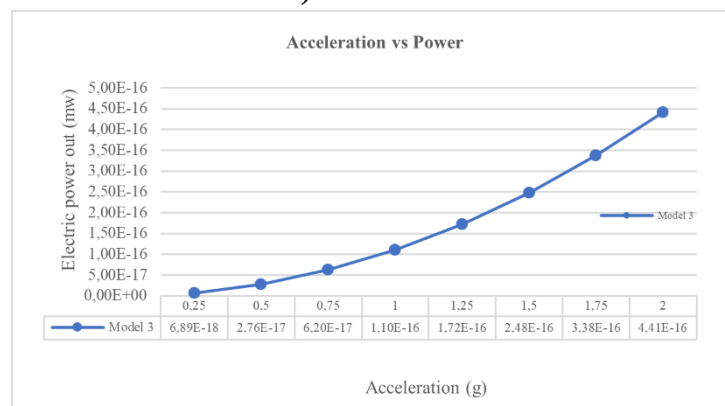
a) Structure 1



b) Structure 2



c) Structure 3



d) Structure 4

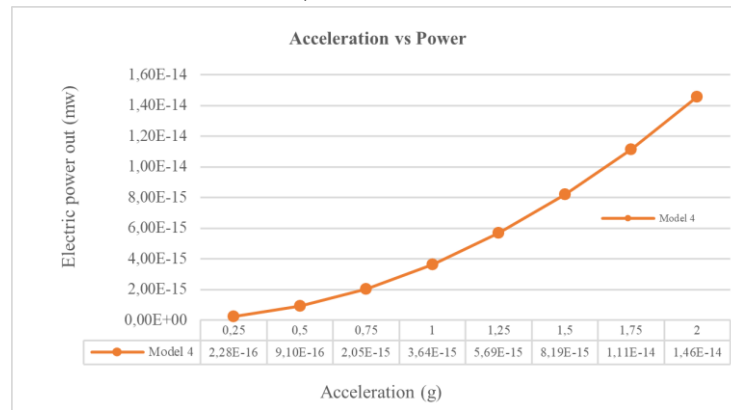
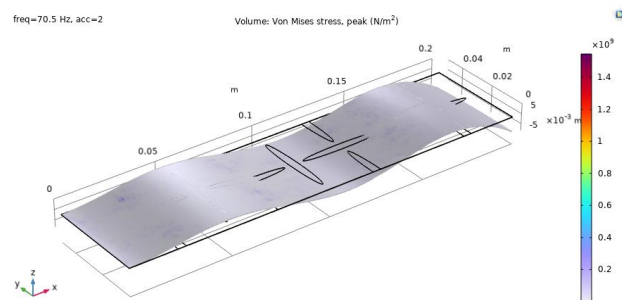


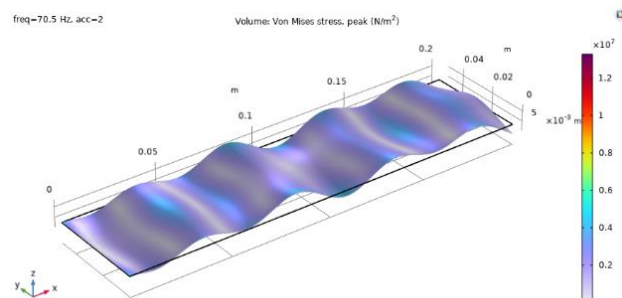
Figure 41: Acceleration vs power graphs for structure 1-4

The acceleration dependence Von Misses stresses are shown in Figure 42. They are calculated according to acceleration of structures. Furthermore, for all structure's frequency and acceleration are levelled up and the results reveal that the first structure is more yield than the others. Additionally, structure 1 has minimum failure and maximum efficiency rather than the other three Structures which appear the efficient structure for this study.

a) Structure 1



b) Structure 2



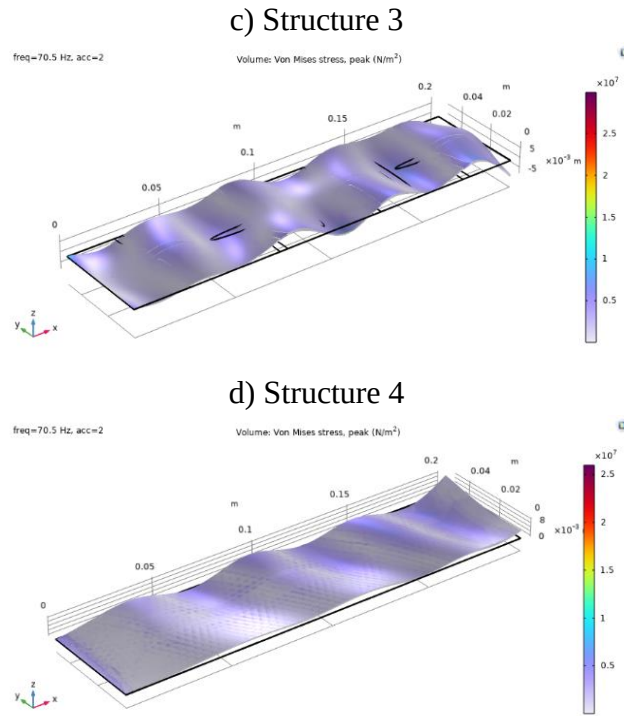


Figure 42: Von Misses stresses regarding to acceleration dependence

4.4 Resistance Load Dependence

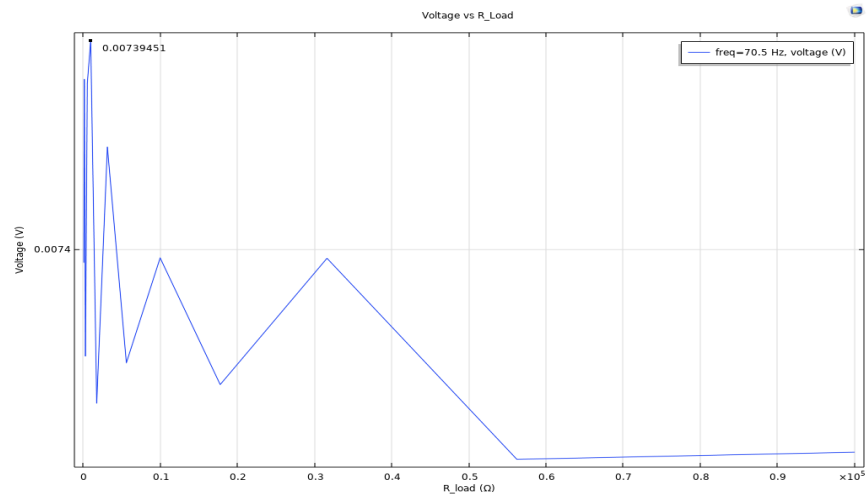
Resistance load dependence allows the user to simulate and analyze how changes in the R_{load} applied to the models affect the output voltage and power generated by the energy harvesters. 75 Hz frequency was used for each structure as a constant parameter and voltage and power results were investigated under varying R_{load} resistance values.

4.4.1 R_{Load} Dependence–Voltage Relationship for Structures 1, 2, 3 and 4

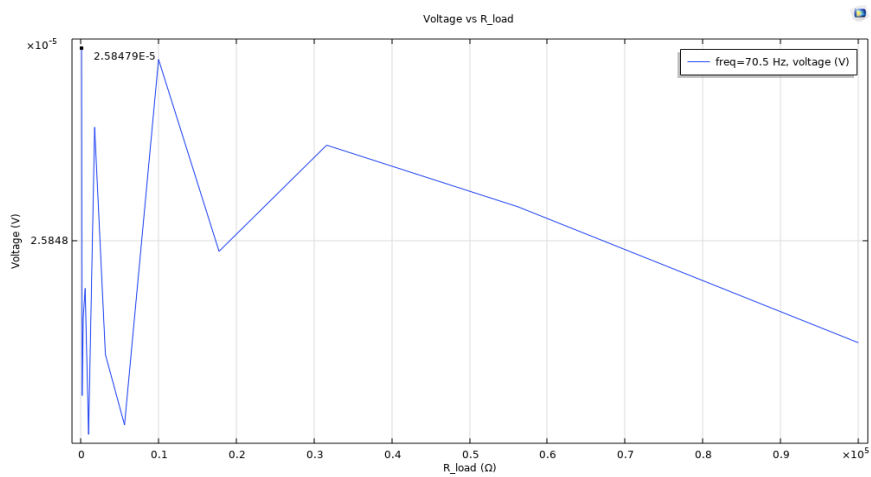
From the R_{load} dependence voltage study result in Figure 43, it was observed that the voltage is sharply increasing and decreasing but from one of the points there was a significant drop in the voltage versus R load. Structure 1 to 3 voltage movements are almost similar depending on the R load, however, In Structure 4, the rapid reduction occurred while under a slightly heavier R load. In addition, Structure 1 produced more voltage than other structures. Although structure 1 had the most voltage, structure 3

revealed higher voltage than structure 4. According to this study, meaning that those with auxetic layers in structures at the same layer level had greater efficiency.

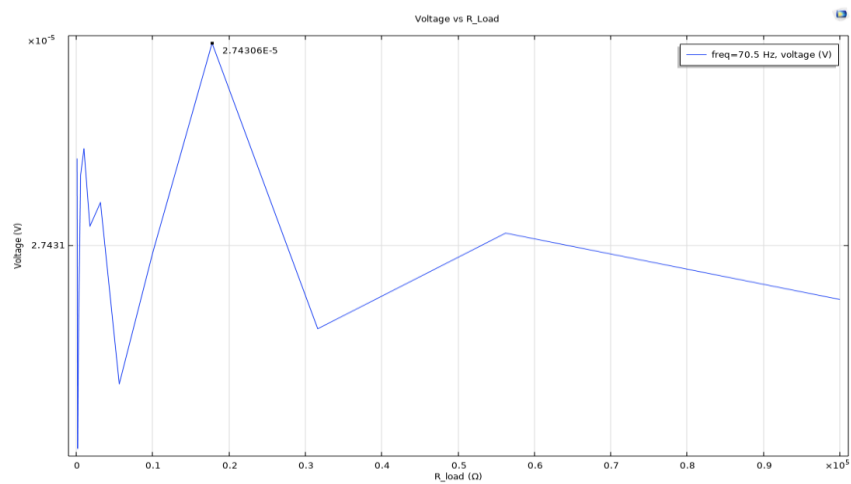
Structure 1



Structure 2



Structure 3



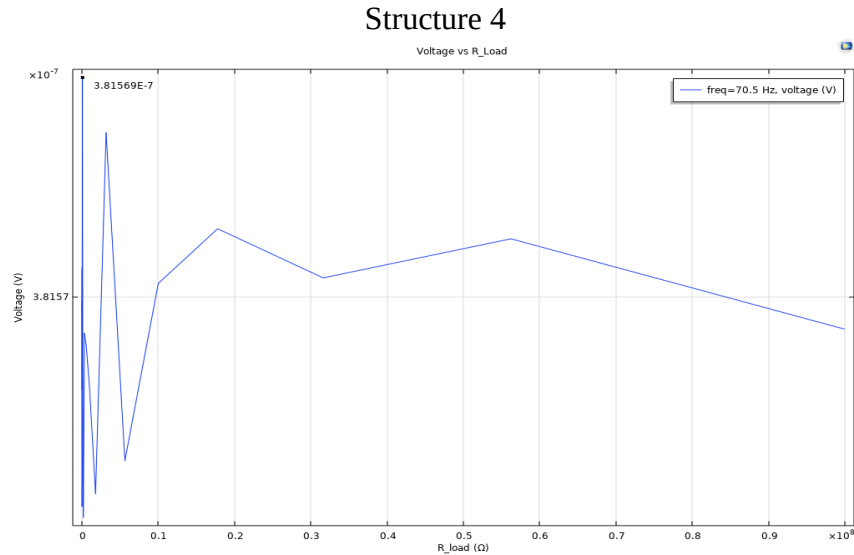
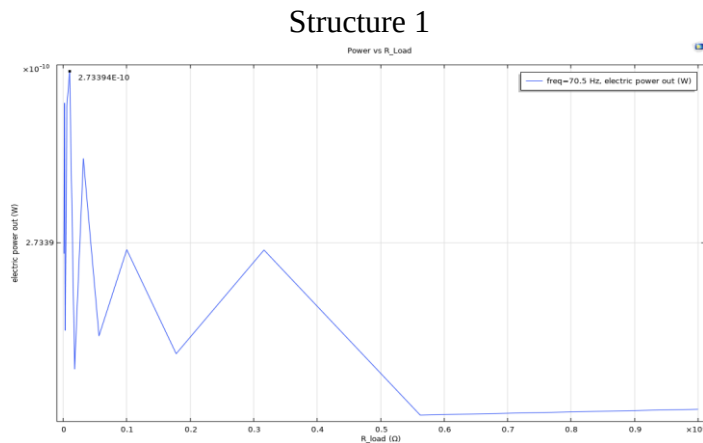


Figure 43: Voltage vs R_Load graphs for structure 1-4

4.4.2 Resistance Load Dependence–Power Relationship for Structures 1, 2, 3 and 4

The R load dependence power graph shows a similar increase and decrease movements with voltage graphs since there is the direct proportionality of voltage and power. The resulting power was higher for the structures with auxetic material. As can be seen in the graphs in Figure 44, Structure 1 is the one that generates the most power. Furthermore, APEHs reveal higher power than PEHs in this study because auxetic structure helps current flow, hence power can increase.



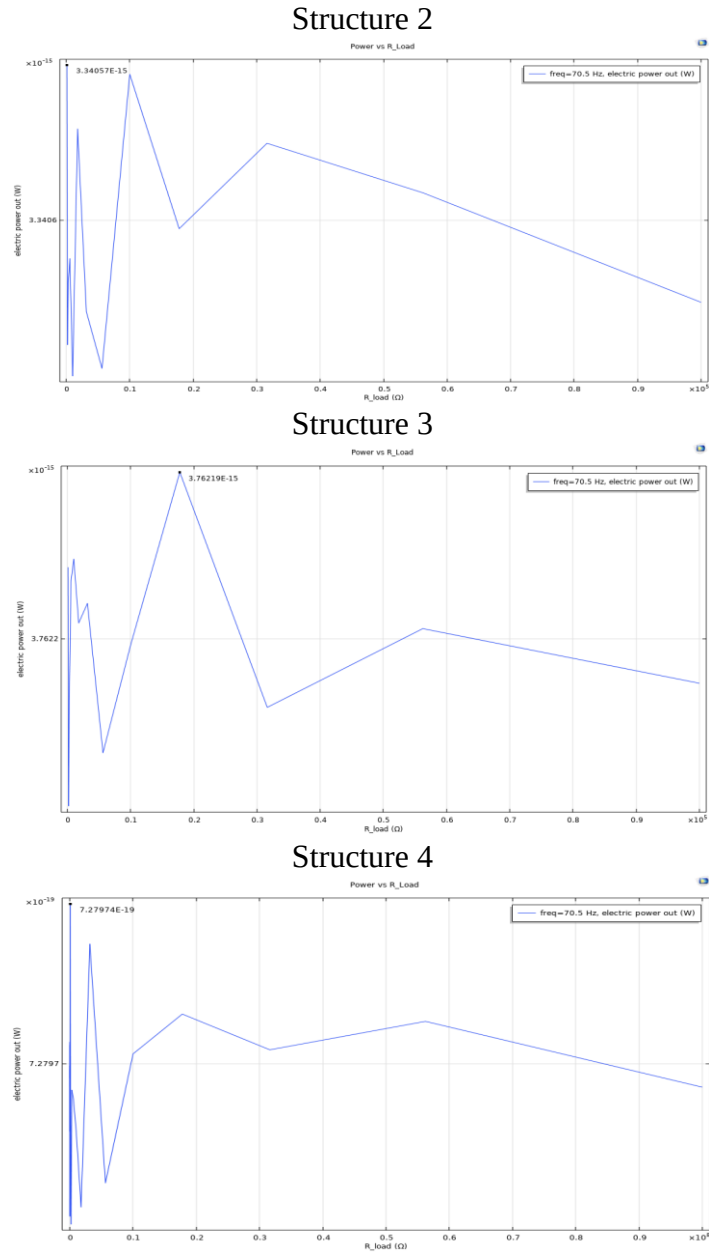


Figure 44: Power vs R_Load graphs for structure 1-4

The R load dependence Von Misses stresses are illustrated in Figure 45. They are calculated according to resistance loads connected on the structures. Moreover, for all structure's frequency and resistance loads are levelled up and the results produced that the first structure has higher efficiency than the others. Additionally, APEHs have minimum failure due to auxetic material properties. Although structure 1 is the most

efficient one, structure 3 is less than structure 4. Hence, when the number of layers increases the efficiency of models changes.

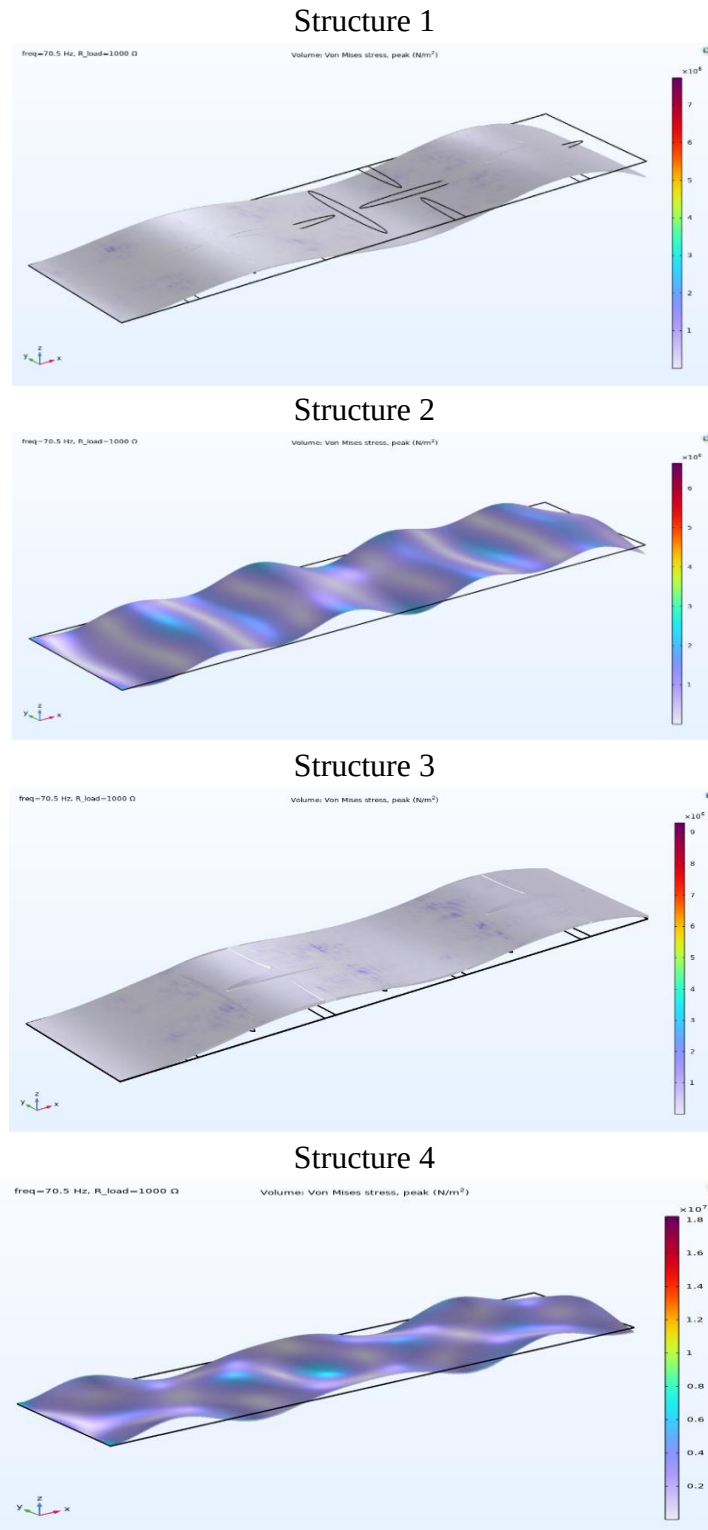


Figure 45: Von Misses stresses regarding to R Load dependence

4.5 Eigenfrequency

In this thesis, the FEM analysis of the harvester is evaluated under eigenfrequency study, and which are important in piezoelectric energy harvesters because they determine the resonant frequencies of the system. They use piezoelectric materials, which generate a voltage when they are subjected to mechanical stress. The frequency of the vibrations is close to the natural resonant frequency of the piezoelectric material. When the material is in resonance, it will oscillate with a larger amplitude, which leads to a more output voltage and greater power output generation. By determining the eigenfrequencies of the piezoelectric material and the mechanical system, it is possible to optimize the design of the energy harvester for maximum power generation.

The relationship between eigenfrequency and mode shape is important in the study of the dynamic behavior of systems, as it allows us to understand how a system will respond to external perturbations and how it will vibrate under different conditions. Figures 45,46,47 and 48 show the mode shapes according to their eigenfrequencies for each Structure. The mode shapes for Structure 1 are shown in Figure 46. The first, second, third, fifth and seventh mode shapes of a cantilever beam is a bending mode in which the beam deflects in a sinusoidal shape along its length. The fourth mode shape is a torsional mode in which the beam twists about its axis. The sixth mode shape is a bending-torsional mode in which the beam both bends and twists simultaneously. Therefore, most energy generated with mode 6 in this Structure as seen in Figure 46f since the rotation is much more than others.

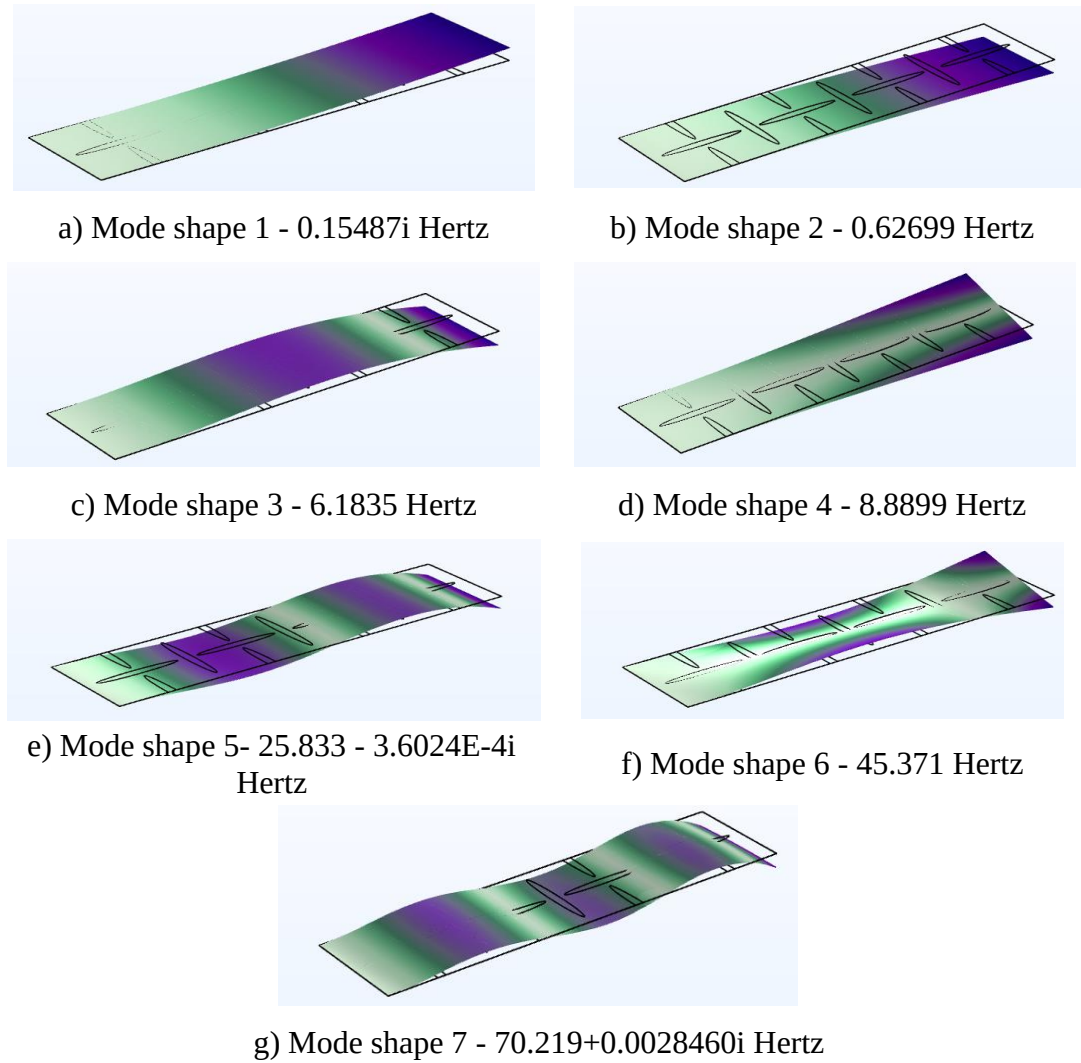


Figure 46: Mode shapes and eigenfrequencies for structure 1

Figure 47 displays the Structure 2 mode shapes. A cantilever beam's first, second, third, fourth, fifth and seventh mode forms are bending modes in which the beam deflects in the shape of a sinusoidal along its length. The beam simultaneously bends and twists in the sixth mode form, known as a bending-torsional mode. Thus, most energy generated with mode 6 in Structure 2 as seen in Figure 47f because the motion is higher than others.

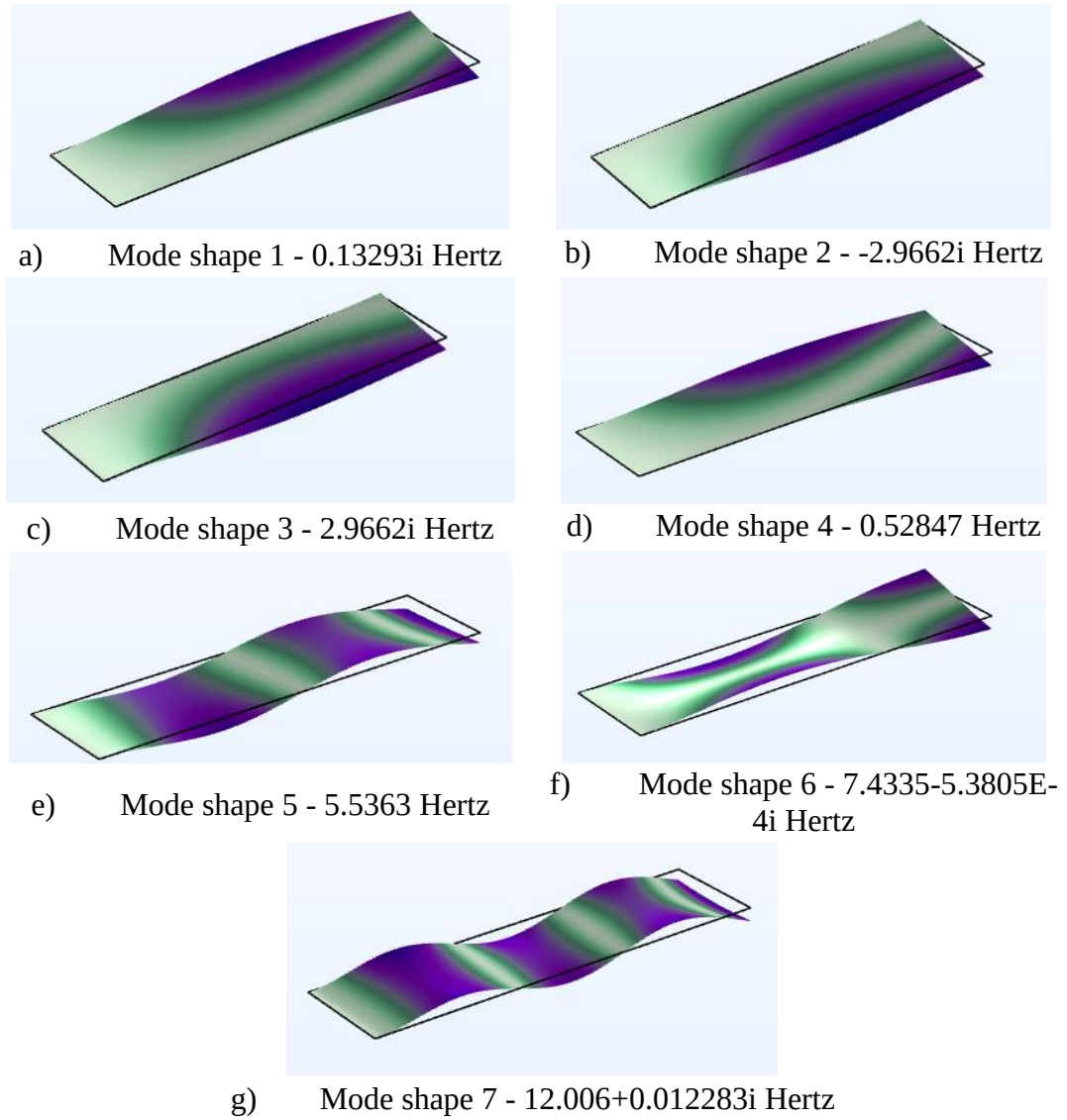


Figure 47: Mode shapes and eigenfrequencies for structure 2

The Structure 3 mode shapes are depicted in Figure 48. The first, second, third, fifth, and seventh mode shapes of a cantilever beam are bending modes in which the beam deflects along its length in the form of a sinusoidal. Torsional modes, in which the beam twists around its axis, are represented by the fourth and sixth mode shapes. Hence, most energy produced with mode 6 in this Structure as seen in Figure 48f because of the highest motion at that mode in this Structure.

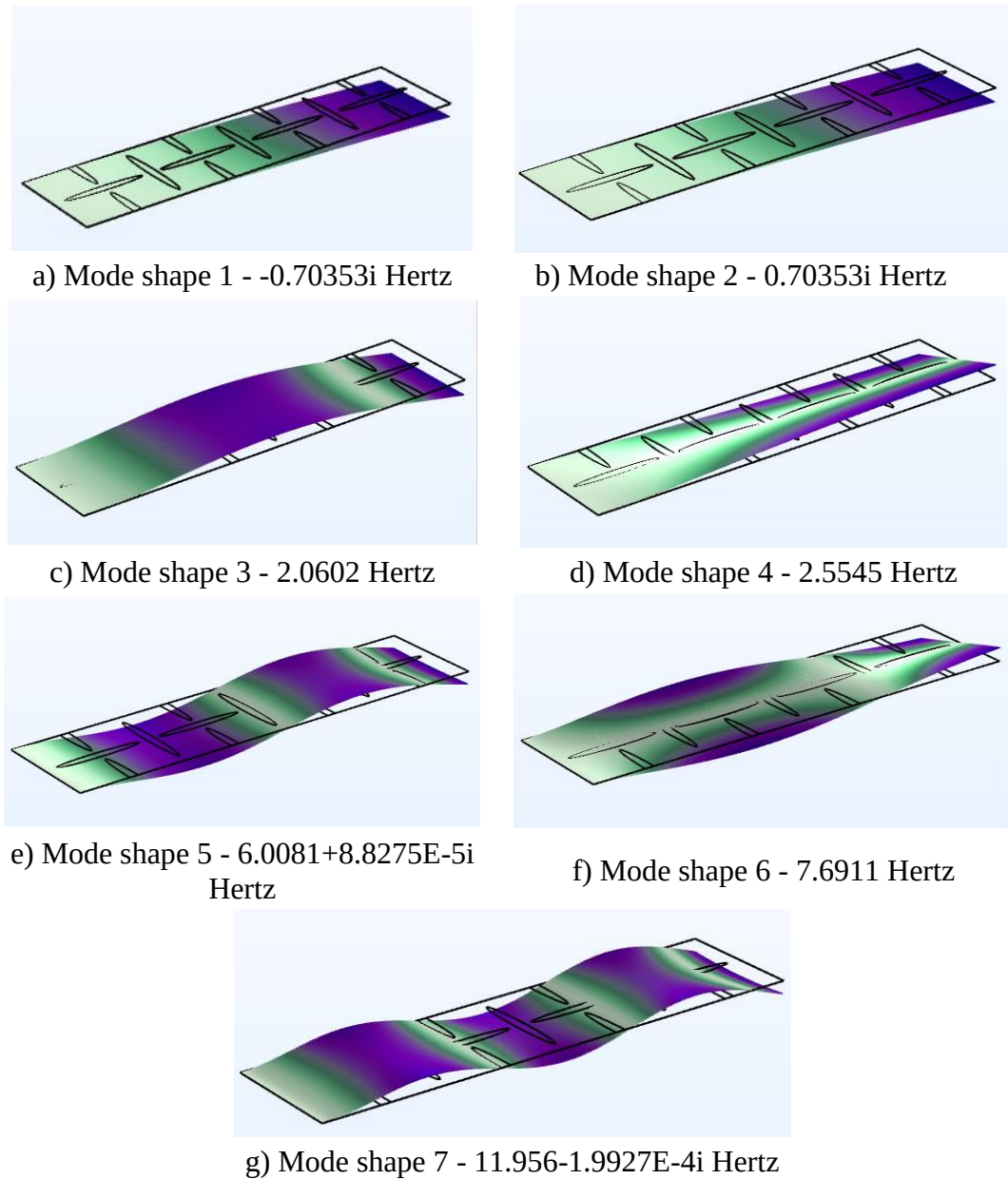
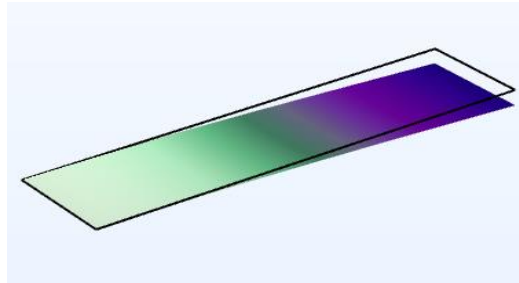


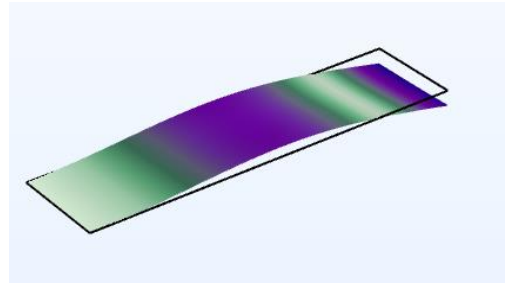
Figure 48: Mode shapes and eigenfrequencies for structure 3

Figure 49 depicts the mode shapes for Structure 4. A cantilever beam's first, second, fourth, and sixth mode shapes are bending modes in which the beam deflects sinusoidally along its length. The third mode shape represents torsional modes, in which the beam twists about its axis; the fifth mode shape, or bending-torsional mode, represents torsional modes, in which the beam simultaneously bends and twists.

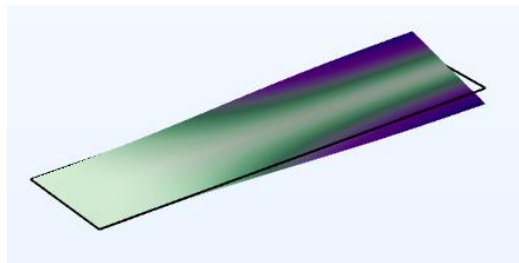
Therefore, most energy generated with mode 5 in this Structure shown in Figure 49e since the rotation is much more than others.



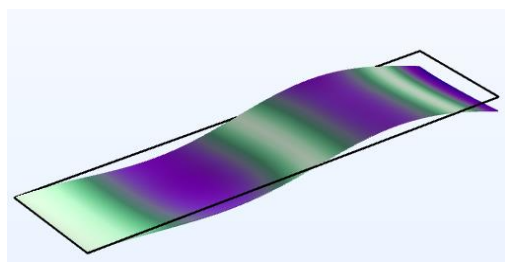
a) Mode shape 1 - 0.35797 Hertz



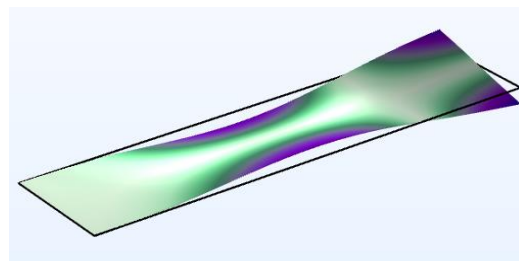
b) Mode shape 2 - $2.5641+4.3928E-5i$ Hertz



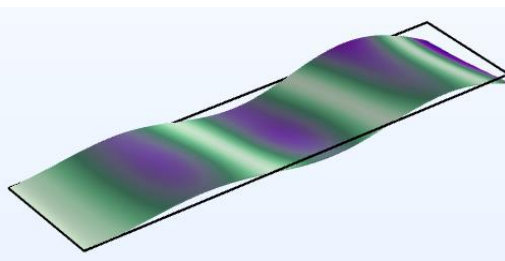
c) Mode shape 3 - $3.0332+6.5123E-5i$ Hertz



d) Mode shape 4 - $7.5796+5.7915E-4i$ Hertz



e) Mode shape 5 - $9.1963+0.0015863i$ Hertz



f) Mode shape 6 - $16.244+0.0011797i$ Hertz

Figure 49: Mode shapes and eigenfrequencies for structure 4.

Chapter 5

CONCLUSION

The current work used COMSOL Multiphysics 6.0 software and developed four different 3D simulation structures. The necessary commands were assigned to the structure using COMSOL tools, and simulations were carried out over four different studies and data were obtained. These are frequency response, acceleration dependence, resistance load dependence and eigenfrequency studies. According to frequency response, Structure 4 is the most efficient, while structure 1 is the most efficient one according to the acceleration dependence and R load dependence. It is accepted that the models give different results under different conditions, and it is understood that the structures should be designed based on the conditions. According to the eigenfrequency study, when the modes are examined, the highest frequency was obtained in Structure 1 and therefore it was observed that it was more efficient.

In addition, it is seen that the auxetic structure of the current study provided about 10 times higher yields than the re-entrant honeycomb, single rotating square unit cell, anti-tetrachiral auxetic lattice structure, and kirigami structure with three layer of energy harvester. However, GAEH, auxetic backbone structure generates 15%- 20% more power than present research. In current configurations of multilayer auxetic piezoelectric energy harvesters generate significantly less power than 85 percent of other research because multilayer APEH creates higher damping. On the other hand, changing the parameters or materials of the energy harvester directly affected the

efficiency. Therefore, in that case different results can appear and finalization may change.

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