Novel Piezoelectric Energy Harvesting Structure

A Thesis Presented

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Abstract

Energy harvesting has become an important subject as in recent years, structures all around the world are reinforced with elements that consume energy. Sensors, actuators, such structural health monitoring devices are implemented vastly. In order to keep these devices running, electrical energy has been transferred through enormous endeavors. Especially in the remote areas this power distribution has been an important issue. In this research, the problem of providing energy to the small device has been addressed by introducing a novel piezoelectric energy harvester.

Many other researches have been done in this matter before. Mostly have been focusing on the vibrational behavior of the energy harvesting structure. In this research, the problem was faced with the assumption that there is very low frequency or even no vibration at all. Since in the nature, most of the external forces are applied as cyclic stresses. In this research by using this phenomenon, an energy harvester was developed. The energy harvester was designed initially using CAD and finally manufactured and tested using simple 3D printing. Since the energy harvesting is dependent on the piezoelectric element, deformation mechanism is the center of this research. Utilizing the concept of bistable structures and implementing the snap-through deformation the device designed to be capable of energy harvesting. The device was analyzed and proved to be feasible from the aspects of energy generation, charging, and quality of functionality in different situation. The structure is designed to be easily usable, readily implemented and as a periodic structure capable of expansion.
Acknowledgement

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Chapter I

Introduction and Literature Review
Engineering structures are getting more and more complex and multifunctional every day. Since they mostly function under different kinds of static and dynamic stresses and vibrations, there are a lot of energy being transferred through these structures. Meanwhile many health monitoring devices now being implemented in the structures such as sensors. Having a small power generator to supply the need of those devices using the energy being dissipated and dampened within the structure is practically and environmentally advantageous. Especially from the aspect of design compactness and expenses. So many researches made endeavors to develop a feasible energy harvester.

Researchers mostly focused on energy generating from vibration sources via piezoelectric and electromagnetic harvesters[1]. Optimization of such process is done by focusing on the mechanical structure of the harvester and also the electrical circuit which gathers the generated energy and stores it. Initially researches were focused on the Energy harvesters oscillating in a linear manner. However, recently scholars found out that non-linear behavior of harvesting device provides more efficient result.

Generally considering non-linear response, Ramlan et al investigated two nonlinear systems. First, a bi-stable system comprising mass-spring-damper. Second, a hardening stiffness mechanism. The theory was developed for equation of motion and displacement response to time curves were extracted in specific frequencies in order to achieve a wider bandwidth of energy harvesting and comparison to linear system in order to demonstrate the superiority of non-linear behavior [2]. Sebald, et al, investigated theoretically and verified results by
simulations on the nonlinear energy harvester vibrating by Duffing oscillation equation. It was shown that very high bandwidth of resonance frequencies is achievable by implementing non-linear oscillators[3]. Subsequently, Superiorities and limitations of nonlinear oscillation were investigated in different kinds of wave excitation using experimental data both linear and non-linear [4].

Later other researchers proposed a magnetic levitation energy harvester was which used non-linear motion and oscillation to harvest energy by means of electromagnetic coil. They were able to prove their design theoretically, experimentally and in simulation[5]. Continuing this study Investigators modified previous energy harvester by adding magnets in certain spots and created a bi-stable version of it. Their team was able to show showing improvement in energy harvesting and resonance phenomenon with the proposed modification [6].

Many scientists focused on the design and development of resonating Cantilever beam as the primary method of energy harvesting devices. Cottone et al designed a cantilever mechanism using both mass vibration an electromagnetic excitation to generate energy from 4 layer of piezoelectric on a cantilever [7]. Considering this design, Gammaitoni et al, have shown that nonlinear properties develop the energy harvester’s performance. However, the development is not dependable to bi-stability. Thus, it is also applicable in mono-stable[8].

In development of bi-stable cantilever beams, Ferrari et al proposed the non-linear magnetic repulsion cantilever which behaves in a bi-stable manner in vibration in certain conditions of low distance between cantilever magnet and the auxiliary magnet[9]. Higher voltage extracted form Piezoelectric were achieved up
to 88%. This study was theoretically and experimentally validated by other researchers[10].

The alternative design proposed was bi-stable Piezomagnetoelastic energy harvester using two attractive magnets for bi-stable functioning. Made in different configurations of magnets and coils, the designs were compared validated in vibration frequencies with former observations. Chaotic wave response also was compared with periodic response [11]. And Avvari et al, investigated the difference of performance between attractive and repulsive cantilever beam harvesters[11, 12].

The design was further developed by other researchers as Wickenheiser and Garcia proposed the new design by altering one fixed magnet with an array of fixed ferromagnetic materials. The model was made using Euler-Bernoulli bam theory and developed by adding magnetic effects. Case studies were done to manifest the impact of such non-linear structure on decrease of the frequency required to initiate resonance[13]. Also a whole new design for repulsion magnetic oscillator was introduced and investigated conceptually and experimentally by Tang et al. Design consisting of magnet resonating between 2 magnets with attraction and effecting on a cantilever containing repulsive magnet[14].

One of the common problems of energy harvesters was their malfunctioning in frequencies other than the resonance frequency which made them inoperable under real environmental vibrations. Many efforts were done to solve this matter. The newer goal of designs were to expand the bandwidth of resonance. Shikui et al, Solved optimization problem by developing theory and solving it numerically for
an Energy harvesting cantilever beam using adjoint variable method. They also introduced another topology optimization for cylindrical Energy harvester[15].

Liu, et al, proposed two different mechanisms of a non-linear cantilever resonator energy harvesting devices for MEMS, which were capable of high bandwidth of resonance by introducing frequency-up-conversion (FUC) stopper to the regular cantilever energy harvester[16]. Another design was to put the cantilever beam in vertical direction with the mass tip on top. This design proposes the bistable behavior without using magnet[17]. Wang and Liao also improved the regular bi-stable repulsion cantilever by adding an elastic magnifier and applying motion theory and simulation. They have shown that harvested power could be increased in low excitations[17, 18].

More sophisticated designs were introduced in recent years. Harris, et al, by designing a composite cantilever beam were able to manifest that there is a trade-off between widening the bandwidth at low accelerations and amount of the maximum power harvested from the device[19]. Yang and Towfighian introduced a hybrid vibrating cantilever consisted of 2 functions: bistable cantilever with repulsive fixed magnet, and the internal resonator using a mass-spring combination [20].

Generally cantilever beams designed up to now could have 3 different behaviors. Linear, nonlinear mono-stable, nonlinear bi-stable. DePaul et al, analyzed the effect of different excitations on the voltage provided by using experiments and numerical data. Giving a comparison between linear and monostable and bistable non-linear systems [21].
Some other scientists have focused their efforts on other types of piezoelectric energy harvesters rather than cantilever beams. Considering bistable snap-through characteristic of a bent plate, many researchers put their effort to exploit this advantage. Masana and Daqaq designed a plate capable of being both mono-stable and bi-stable configuration. Bandwidth was analyzed and the effect of base acceleration and shape of potential functions was evaluated. Eventually, it was shown that there are situations where bistable can be more advantageous in energy harvesting[22]. Also, AnJiang and QunChen conducted theoretical study on snap-through energy harvesting system[23]. Practically Arrieta et al, investigated a bi-stable plate reinforced with four piezoelectric energy harvesters which operates under vibration. The power and voltage extracted from this device under different frequencies of vibration obtained via experiments[24].

In another study, Hajati et al investigated doubly clamped beam structure. Using duffing equation for resonance, an energy harvesting device with high bandwidth was experimentally presented which could be used in MEMS devices[25]. Also Ando et al. designed a low-cost bistable harvester using a buckled beam and two piezoelectric transducers. The harvester is supposed to harvest energy from environmental low frequency vibrations[26].
To develop this concept many researchers conducted studies on buckled beam. Cottone et al. investigated the buckled beam mounted with piezoelectric and by applying theory of motion and also implementing simulations and experiments, the response to vibration was extracted and illustrated[27]. Considering beam’s boundary conditions, another investigation was done theoretically on a buckled beam in 2 different conditions of hinge boundary and clamped by clamped boundary also the models were numerically analyzed[28]. In another innovation Van Blarigan et al. proposed a buckled beam comprising two plates. A single layer and a double layer which are attached at a certain point. By FEA analysis the conditions to maintain low strain snap-through was shown in this study[29].
Apart from previous common designs, scholars have been investigating other innovative designs for energy harvesting conceptually and practically. Flextensional mechanism also has been thought of as a beneficial structure for energy harvesting, which is already used commercially. Reconfiguring the common design, Zhou and Zuo in their paper introduced a new multilayered design of flextensional energy harvesters were proposed. Theoretically and experimentally it was shown that electromechanical efficiency was improved significantly[28, 30]. In mix with a cantilever beam Abdelnaby and Arafa Designed a flextensional mechanism attached to a cantilever beam reinforced by piezo electric element. Key geometrical parameters of the structure were analyzed in this study[30, 31]. Combining bi-stability snap-through mechanism and using flextensional piezoelectrics, Liu et al. created a new design of bi-stable vibrator without magnet. It was modeled by mass-spring-damper mechanism and was analyzed theoretically. Chirp and noise excitation was investigated by using simulation and experiments[32], and it was also investigated for improvements[33].

![Figure 2- bi-stable vibrator without magnet](image_url)
Implementing piezoelectric materials in phononic metamaterial structures was a novel idea stated by Gonella et al. in 2008, they proposed a regular hexagonal honeycomb combining with vibrating cantilever elements, and by implementing FEM simulations, the design was enhanced to widen local resonance bandwidth[34]. Also Paolo Celli and Stefano Gonella have investigated unit cell of cellular structure for energy harvesting purpose which has had reconfigurable directivity in order to respond to various wave patterns directed by negative capacitance circuit [35]. Zhang and Wu made a new design of a low-frequency broadband energy harvesting structure, subsequently its effectiveness at local resonance was demonstrated by using FE and developed for higher functionality[36].

The main concern about these kind of effort is dynamic behavior of the cellular structures under vibration. To propose such structure, it is inevitable that it should be capable of local resonating in wide range of frequencies. Also developing local resonance is so desirable. Liu et al. developed the chiral structure with a metacomposite design causing changes in low-frequency bandgaps resulting in local resonance useful for energy harvesting. By FEM they demonstrated the vibrational properties achieved by this configuration[37]. Zhu et al. also conducted a conceptual continuum microstructure investigation by using theory and simulation. Dynamic behavior and bandgap frequency range was determined[38]. Wang et al. investigated the dynamic behavior of different periodic beam lattices by numerical simulation by doing FEM and considering lattices and their geometry and coordination numbers[39]. In another research Square lattice reinforced with
cantilever were studied using FEM method and Bloch’s Theorem. Hence, the relation between cantilever’s natural frequency and local resonance phenomenon was investigated and demonstrated[39, 40].

Other innovative researches also were conducted recently. Takezawa et al. optimized the polling phenomenon in piezoelectric material Due to the relation of the poling direction and stress direction. By modifying the equation of state, and solving it through FEM method and combining it with Phase Field method, the optimization was taken place[41]. Li et al, created a device to function as an insulator for sound and also an energy harvester[41]. And Tol et al, Investigated the wave propagation in both infinite and semi-finite one dimensional beam. The model demonstrated the time-averaged power flow through the beam and also time-averaged electrical power flow in the harvester. Also simulations were conducted and experiments took place to compare results with theoretical outcomes[42].

Although there have been great efforts in proposing and developing energy harvesters, all of these studies are focused on vibrational excitation. There are many cases in nature and real environment that there is no vibration. Instead cyclic forces are one of the most common phenomena on the structures we use statically or dynamically. As the former researchers shown, using snap-through mechanism to deform a piezoelectric materials is advantageous in in energy harvesting capability. As this deformation is easily induced and requires less amount of initiating force for a specific strain rather than solid deformation, it is expected that that it could be so much valuable in energy harvesting devices. Piezoelectric
materials transform mechanical strain energy to electrical energy. It would be desirable to create a situation where huge amount of strain is easily accessible.

Our goal is to use bi-stable snap-through deformation combining with the inert capability of piezoelectric materials to design and study a new form of cellular structure that is capable of generating electrical energy. So the materials come as follows.

In Chapter II, the design and structure is introduced, and fundamentals explained. The deformation theory is presented and described. And finally the electrical design is presented and fundamentals of piezoelectricity illustrated.

Chapter III is about the experimental setup for evaluation of the design. Also in this Chapter the experimental data depicted and interpreted. The effect of flawed structure is also investigated and the outcome portrayed and discussed. Finally the periodic energy harvesting structure is introduced.

Finally in Chapter IV the conclusion is drawn about the materials discussed formerly, the potential real world applications of this device is introduced. Some of the weaknesses were illustrated and the future ideas for developing the energy harvester is proposed.
Chapter II
Design of the Structure
In this chapter the design of the structure is described. In the first section the overviews of the whole structure is presented. The elements of the design is described and the important parameters are defined. In the second section the deformation theory is described. Using concept of deformation energy the snap-through mechanism is proved to happen. And using the developed theory the curves for parametric studies. In the last section the electrical design is described. The materials used for the energy harvesting and how it is imposed is explained.

II.I. The cellular structure

In this statement a new design for energy harvester is proposed. The principle of this energy generating deformation comes from the snap-through deformation. Starting from a simple beam with the length of L. If the beam is constraint at both ends using hinges so that at the ends the beam cannot dislocate in \( x \) and \( y \) directions, but the rotation around \( z \) is possible. Since the distances of the fixing points of the structure are \( L' \) which is designed to be lesser than \( L \), the beam is forced to buckle as shown in the Figure-1A. The buckling will result in deflection of \( \alpha \) and the displacement of the beam’s mid-point is considered \( \delta \).

Now to create a unit cell of the whole structure. Creating a square made by the beam with length of \( L \) and also the fixture square with side length \( L' \). The parts of unit cell is shown in the Figure-1B. After assembly the structure will deform in the manner shown in Figure-1C, four buckled beams are the results. Making the connectors of the beams so rigid that forces the beams to maintain a 90° angle.
between their adjacent counterparts. Therefore it can be seen in the figure that two non-adjacent beams will curve inward and two will curve outward.

Figure 3- the structure of the energy harvester unit-cell: A- fixture of the square structure which causes the buckling of the assembled system. B- square structure of four beams connected with frictionless hinges to be assembled on the fixture. C- Assembled unit cell creating four buckled beams maintaining 90° angle in between each two adjacent sides. D electrical design of each beam consisted of a bimorph PTZ plate attached to the center of brass beam.
Now recreating this unit cell in a way that each point of intersection connects four beams, the cellular periodic structure is developed in two dimensions Figure-6A. The deformation of the structure happens when the beam go through the snap-through process. The resultant deformation will be in the way that the formerly inward-curved beam will bend outward and the opposite situation happens to the beams initially curved outward.

As this deformation is literally changing the state in a bi-stable system. Thus, for each unit cell, there are two different configurations. As one could be when horizontal beams are curved inward and vertical beam curved outward. And the other configuration would be the opposite of the former. Looking at the cellular structure clearly shows that each two adjacent unit cells are of different configurations.

II.II. Deformation theory

This structure is designed to behave in a bi-stable manner, oscillating between the sable states via a snap through mechanism. To illustrate this, a theoretical study was conducted on one of the four beams which is constrained between hinges on both ends.

From the aspect of energy, generally the summation of stretching and bending potential energies could be considered as the whole amount of energy of the system at each state of deformation. As shown in Equation-1.
\[ U = U_{st} + U_B \]  

(1)

Where \( U_{st} \) indicates the stretching potential energy and \( U_B \) indicates bending potential energy. Each of those are calculated by the formulations in Equation-3 and 4.

\[ U_{st} = \frac{1}{2} E \left( \frac{L-l}{L} \right)^2 \times AL \]  

(2)

\[ U_B = \int_0^L EI \left( \frac{d^2 u}{dx^2} \right)^2 dx \]  

(3)

Where \( E \) and \( I \) indicate Young’s Modulus and the Moment of Inertia for the beam’s cross section respectively. \( L \) and \( I \) are initial and intermediate length of the beam respectively. \( A \) is the area of the beam’s cross-section. And \( u \) is the displacement of the beam’s elements from their unbuckled state.

For the sake of simplicity, it is assumed that the beam will always maintain its shape as an arc of a circle. Thus, the buckling mode could be considered as mode-1 for every state of deformation. Therefore, \( u \) for each point of the beam could be calculated by the equation of the circle.

Since all geometrical parameters could be related to each other, it is possible to calculate and write potential Energies as a function of the half of distance.
between fixed ends \( (l') \) and distance of the buckled beam’s mid-point from its straight state \( (\delta) \). Regarding that \( \delta_0 \) is dedicated to stable position.

\[
U_{st} = \frac{E}{2} \left( \frac{l'^2 + \delta^2}{\delta} \arcsin \left( \frac{2\delta l'}{l'^2 + \delta^2} \right) - 1 \right) \times AL
\]

\[
U_B = EI \left[ 3\delta \ln \left( - \frac{l' + \frac{l'^2 + \delta^2}{2\delta}}{l' - \frac{l'^2 + \delta^2}{2\delta}} \right) \right] - \frac{3l'^3}{8(l'^2 + \delta^2)} + \frac{5l'(l'^2 + \delta^2)^2}{32\delta^2 \left( \delta - \frac{l'^2 + \delta^2}{2\delta} \right)^4}
\]

Projecting \textbf{Equation-1} in \textbf{Figure-3A} shows that the energy of the system is minimum at two symmetric positions in which the structure is on its stable position. Also this figure shows that there is a finite amount of energy required for the beam to translate from on stable state to another. So, it is evident that the snap-through mechanism is happening and the snap-through energy is measurable.
Writing the equation for total energy of the system when subjected to force would be:

$$\Pi = U - F \times (\delta - \delta_0)$$  \hspace{1cm} (6)

Where $F$ is the force applied to the center of the buckled beam. To determine $F$ as a function of $\delta$, the derivative of the total energy with respect to $\delta$ was calculated and $F$ was determined as:

$$F(\delta) = \frac{dU}{d\delta} - \frac{d\Pi}{d\delta} \quad \quad \frac{d\Pi}{d\delta} = 0 \quad \rightarrow \quad F(\delta) = \frac{dU}{d\delta}$$  \hspace{1cm} (7)

For the sake of simplicity the force function was written as the structure be below:

$$F(\delta) = E \frac{A + B + C + D}{H}$$

In which

$$A = (\delta^{12} + 4l'^2\delta^{10} + 9l'^4\delta^8 + 16l'^6\delta^6 + 19l'^8\delta^4 + 12l'^{10}\delta^2 + 3l'^{12}) \times$$

$$\left(1 - \frac{4l'^2\delta^2}{(\delta^2 + l'^2)^2}\right)^{\frac{3}{2}} \arcsin^2 \left(\frac{2l'\delta}{\delta^2 + l'^2}\right)$$
\[ B = \text{arcsin}\left(\frac{2l'\delta}{\delta^2 + l'^2}\right) \left( r \text{arcsin}\left(\frac{l'}{r}\right) \left(-4l'^2\delta^9 - 16l'^4\delta^7 - 24l'^6\delta^5 - 16l'^8\delta^3 - 4l'^{10}\delta\right) \left(1 - \frac{4l'^2\delta^2}{(\delta^2 + l'^2)^2}\right)^\frac{3}{2} - 4l'\delta^{11} + 16l'^3\delta^9 - 16l'^5\delta^7 - 8l'^7\delta^5 - 20l'^9\delta^3 - 8l'^{11}\delta \right) \]

\[ C = \left(4l'^2\delta^{10} - 8l'^6\delta^6 + 4l'^{10}\delta^2\right) \sqrt{1 - \frac{4l'^2\delta^2}{(\delta^2 + l'^2)^2}} \]

\[ D = r \text{arcsin}\left(\frac{l'}{r}\right) \left(-8l'^3\delta^8 + 24l'^5\delta^6 - 24l'^7\delta^4 + 8l'^9\delta^2\right) \]

\[ H = 2r^2\delta^4(\delta^2 + l'^2)^4 \text{arcsin}^2\left(\frac{l'}{r}\right) \left(1 - \frac{4l'^2\delta^2}{(\delta^2 + l'^2)^2}\right)^\frac{3}{2} \]

The function also pictured in Figure-2B. From this figure it is completely evident that the structure behaves in a bi-stable manner. Looking the energy curve there are two points of the beginning and end of deformation which has zero energy. Looking at the force curve the two subsequently mentioned points it is evident that they are stable points requiring no force to stay on those states.

Looking at the energy curve there is an energy gap reaching its peak at the middle of deformation where the deflection angle is zero or in another word the beam is straight. This gap of energy could be considered as snap through energy it is the amount required to be absorbed by each beam in order to deform to the
second stable state. It could be alleged that each unit cell uses four times of the snap through energy in each change of configuration.

![Diagram](image)

*Figure 4-Deformation theory. A- Schematic of the buckled beam indicating parameters used in theoretical study. B- Energy curve of snap through motion of a buckled beam showing the snap through motion and the energy gap required to be surpassed in different ratios.*

Looking at the force curve there are two peak forces in different directions which could be considered as snap through force. The force which if it is applied to the structure the configuration is subjected to a change.

Regarding the equations. It was measured that the bending part of the deformation plays a less significant role in the whole force and energy of snap through procedure. Most of the required energy comes from compression energy which gets it maximum value at the fully straight state (while the bending energy
is minimum there). Therefore the compressive portion could be used as an approximation of all.

It could be seen from Figure-2B that the snap through happens when the beam receives a displacement more than quarter of whole traveling distance. Thus this kind of deformation is easily achieved and seems suitable for energy harvesting applications.

II.III. Electrical Design

Piezoelectric materials are certain crystals or ceramics or sometimes biological matters that can convert strain to voltage and vice versa. This attribute is the result of temporarily bipolarization inside the material’s unit cell. As the structure elastically deform, the electrical balance inside the unitcell breaks and the consequence of this disturbance of balance is the voltage generated in the unit cell. The piezoelectric materials are synthetically polarized in a manner that by accumulating all voltages generated by unitcells the whole bulk will hand out electrical energy.

Mathematically the piezoelectric element operates under this equation:

\[ S = sT + \delta^t E \]

\[ D = \delta T + \varepsilon E \]
Where \( S, D, T, \) and \( E \) indicate Strain, Electric charge density displacement, Stress, and Electric field strength. \( \delta \) and \( \varepsilon \) also indicate piezoelectric deformation constant and permittivity respectively\([43]\). Taking into account that:

\[
V = LE
\]

Which \( V \) indicates Voltage and \( L \) indicates the length of bulk in the specific direction of strain, Voltage will be a linear outcome of strain.

So in this device the idea was to use bending strain of a thin sheet of PZT material (Lead Zirconate Titanate). PZT is one of the most common piezoelectric materials to be found. It is in expensive and commonly sold in various size and shapes. It is to be said that there are many other piezoelectric materials that could be substutued with PZT in this structure. Also those materials might result in better performances as they could be more flexible in bending (lower \( s \)) or could possess a higher \( \delta \). However, the goal in this research was to focus on the structural design of the energy harvester rather that the materials selection. The material properties of the selected PZT is indicated in Table-1.

<table>
<thead>
<tr>
<th>Electromechanical Coupling Coefficient</th>
<th>Piezoelectric Constant ( \times 10^{-12} ) m/V</th>
<th>Elastic constant ( \times 10^{10} ) N/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p )</td>
<td>( d_{33} )</td>
<td>( Y_{11} )</td>
</tr>
<tr>
<td>( K_t )</td>
<td>( d_{31} )</td>
<td>( Y_{33} )</td>
</tr>
</tbody>
</table>

Table 1 - Selected physical and mechanical properties of PZT-5H used in the experiment.
Providing the structure with the ability to harvest energy requires to add elements which convert the strain and motion energy to electrical energy. Each beam is reinforced with a bimorph PZT harvester that is made in a way that two layers of PZT with the thickness of 0.4mm were polarized in their thickness direction Figure-1D. Then attached to a thin copper plate in a way that copper plate delivers the negative charge. Top faces of PZT plates are wired together and deliver the positive charge. The bimorph is attached to the center of each unit cell beam in order to keep the balance of deflation. Since the PZT elements are hard and brittle the deflection anticipated for the beams are as low as it would guarantee that the PZT elements will not break. In this research only one type of piezoelectric material was used and the design was set to be compatible with the material. Obviously other combinations of material selection and structure implementation could be introduced in the future. In the next section the experiment developed to show the capability and feasibility of the proposed structure will be explained.
Chapter III

Result and discussion
For validation and qualification of the performance in this section the experiment conducted will be described and the results are presented. The goal of this set of experiments are to demonstrate the ability of a unit cell to harvest energy in low and medium frequency of the cyclic force. Also another set of experiments were done in order to evaluate the capability of the structure in supplying an energy conservator. Using the same frequencies, charging capability of the structures were measured and explained. Thus in the first section a comprehensive description of the experiment is presented. In the second section the energy generation was evaluated and results were presented and discussed. In the third section, the effect of impaired structured is described and compared. And in the final section the expandability of the unit cell as a periodic structure is depicted and explained.

III.I. Experimental setup

A setup was designed to evaluate the electrical capability of the structure. It is consisted of a set of components to accomplish the goal. The motion designed to be introduced by linear actuators. Linear solenoid actuators apply the displacement required by the structure to initiate the snap-through mechanism. In order to maintain the consistency of the applied force by the linear actuators, the draw back spring was not used to return the changed configuration of the unit cell to the initial state. To compensate for the returning procedure, another actuator was placed in front of the adjacent side of the already actuated side as it could be seen in Figure-3. Thus two actuators should work beside each other by a complete phase difference. In order to control his system a circuit was designed. This circuit
connected to a microcontroller dissipates the power between two solenoids and generate the required frequency. Each cycle is defined to be two full change in configurations that the initial and finial shape and placement of the beams to be of a same. As the structure is designed in a way that all the beams undergo an equal strain and displacement.
Figure 5- Experimental setup: A- Power source, B- Input power distributor circuit, C- Input power controlling microcontroller, D- Linear Actuator, E- Energy harvesting structure, F- Consuming circuit (Resistor/Capacitor), G- Data recording microcontroller.
The final outcome of all beam are supposed to be equal. However due to the impact effect of the linear actuators on the directly affected beams could introduce a lot of errors to the measurement. Therefore the evaluation was done on one of the non-directly actuated beams. The measurement circuit is a simple circuit designed to provide the second microcontroller (which is in charge of recording the voltage data continuously in time) with the voltage in a readable range.

III.II. Energy Generation Experiment

In this experiment the capability of energy generation of the structure was measured. Using the setup explained formerly the unit cell was subjected to cyclic displacement. The frequency of the deformation is controlled by a microcontroller as explained formerly. By programming the microcontroller the test was conducted in various high and low frequencies. The results of the experiment is shown on Figure-4. looking at figure it could be seen that the electrical response to higher frequencies is an increase in outcome voltage. As the average of the generated voltage for 2Hz deformation is around 1.17V while for 4Hz is 1.52V and for 10Hz is 2.15V. Considering the materials used in the structure and 25KΩ resistor in the structure is able to generate 54.7 \( \mu J \) energy each cycle in low frequency (2Hz). It shows that the structure is capable to work in low frequencies. Even the structure response in lower frequencies also captured but was not provided due to insignificance. In higher frequency (10Hz) the structure is able to scavenge the average of 185.0 \( \mu J \) of energy in each cycle. It could be shown that this structure can operate in higher frequencies as well. Tests was taken up to 25Hz. Higher
voltages could not be tested as the actuator velocity becomes lower than frequency.

Figure 6- Experimental results of the voltage generated by a single beam in a unit-cell in 3 different frequencies. Bottom right: structure’s capability to charge an energy storage (capacitor).
Another set of experiments were done in order to demonstrate the capability of the structure in charging a power supplier. For the sake of simplicity in evaluation a 100 \( \mu \)F capacitor was used to evaluate the structure's capability. In Figure-4D the stored voltage curve was pictured against the number of cycles. It clearly shows that regardless of the frequency the structure maintains its performance level over the time period. The energy stored in the capacitor is around 200 \( \mu J \) in about 80 Cycles.

As there was no intention to investigate this structure with regard to materials used to manufacture it. The voltage and energy values could vary by changing structural and piezoelectric materials used. Size of the beams so the amount of piezoelectric materials put onto them also could change the amount of voltage generated. The span which the structure made by 3D printer material, brass slabs, and PZT bimorph could function properly was up to 20Hz. However using other materials and specifically less stiff piezoelectric layer will be able to function in higher frequencies.

III.III. Effect of Defect

The structure works in a manner that all beams undergo snap-through deformation in the first buckling mode deflection. If any of the hinges could not function properly whether due to friction or any sort of defect that cause malfunction, the adjacent beams follow the Second mode of buckling after the snap-through. In another word, each cycle will be consisting of change from first mode to second mode and back to the first mode. This change in pattern of
deformation will result in different bending and stretching strains. Thus the piezoelectric material will now generate a new amount of electrical energy.

Figure 7- Experimental results of the effect of defect and mode 2 buckling deformation on the scavenged voltage and charging capability.
The experiment was redone this time by fixing one hinge of the unit cell and data was recorded from the beam adjacent to the fixed hinge. The exactly same frequencies as was reported formerly in section III.II was used in this experiment. The result of this experiment is shown on Figure-5. Now the average amount of the generated voltage for 2Hz, 4Hz, and 10Hz is equal to 0.74V, 0.86V, and 0.80V Volts respectively. It could be seen that the voltage generated from the same frequencies fall drastically in comparison with the flawless structure. This happens since the deformation cycle is in a way that some parts of the piezoelectric material are subjected to a little amount of strain. The figures also show that in high frequencies the loss is greater. This could be interpreted as in high frequencies, while the structure stiffens due to the resistance of one hinge, and the load remains the same the structure finds harder to deform properly. When the loading frequency is high the structure has lesser time to undergo the snap-through. When it is so stiff, it is more probable that the structure has to return to its initial state before the first snap through finishes.

The experiment on charging capability was also done by using the same capacitor (100 $\mu$F) used for flawless structure. Figure-5D shows the charging capability of the structure is decreased by still consistent in low, medium, and high frequency. As it is evident in the figure, it takes about 125 cycles of deformation in flawed structure to charge the capacitor with 2 Volts of electricity. Comparing to the flawless system the charging capability drops around 50%. It is expected as the deformation is limited in mode 2. However, it could be seen that the structure is still functional despite malfunctioning of one of its hinges.
I could be said that in a bigger cellular structure where more than one unit cell is excited by external force the effect of this malfunctioning will decrease as other flawless units will contribute to the deformation of adjacent flawed cell. Conceptually the whole cellular structure will be introduced in the upcoming section.

III.IV. Cellular structure

This structure is designed to be expandable to a cellular structure. Each unit cell is capable of being surrounded by four cells with inverse configuration. An example of the cellular structure 2x2 could be seen in Figure-6A. as evident theoretically if one side of a unit cell is excited to snap through a unit cell will change in configuration and this change will transmit to adjacent cells and finally to the whole structure. Practically for the big structure to deform only by exciting one beam, the connecting hinges should have no friction and beams should be as stiff that they tend to snap through easier than buckling in second mode. If the structure should work defectively the worst case will be a hinge that does not operate in accordance with adjacent structural deformation. In this case four beams connected to that hinge will experience the mode 2 of buckling this defect is depicted in Figure-6B.

One of the properties of this cellular structure is that it could be operating by being excited in both or one of the directions parallel to the unbuckled beams. Similar to the experiments were conducted on one unit cell but using a 2D
excitation, this method of excitation is also applicable on a periodic structure (a structure similar to Figure-6A).
Figure 8- A: cellular structure made of energy harvesting unit cell all buckled in mode 1  B: cellular structure made of energy harvesting unit cell some beams buckled in mode 2
One dimensional excitation is possible on a unit cell (and similarly on a periodic structure) if the applied force uses pull-push cycles. For many applications such as energy generating pavements the structure is required to be capable of excitation in 1D with only a pushing force. This feature is also admissible to this structure. Having a periodic structure with at least two unit cells provides such feature. As an example the 1x2 structure can be excited in the direction perpendicular to the side with two beams. Provided in supplementary materials, the Media-1 shows how this feature works. Two adjacent cells are always in different configurations. Therefore one of the adjacent beams always is available to the pushing force in order to snap-through. As the structure changes the configuration, the other beam will be available for the next pushing force. So a trigger similar to the one shown in the video can effectively help structure to operate with each time the trigger is pushed.
Chapter IV
Conclusion and future works
There is always this challenge to supply remote electrical devices with the energy they require to function. Many researches were conducted to use mechanical, and magnetic cyclic forces and vibrations to generate energy. But the question is; are they able to generate energy from the very low frequency ambient? This research was conducted to propose a new way of generating energy from regular movements. The device showed its capability to scavenging energy in various frequencies. Specially being able to work in low frequencies which is more probable in the environment. The geometrical parameters could be attuned to dominant exploit the maximum energy with respect to the force amplitude of a specific environment. The device can be reproduced in a 2D structure, it could be installed as a layer in structures that bear cyclic loads. The structure is easily functional and can generate energy to charge batteries and run structural health monitoring devices like sensors. In this research, also the effect of partial structural malfunction was studied and it was shown that the structure is still functional even if is experiencing some defects. This structure is proposed to be set on platforms bearing cyclic forces or vibrations; railroads, pavements, stairs, bridges, even buttons such as in elevators. The structure could be furtherly developed. More research is required to develop this structure in smaller scales, using alternative materials, probably bio-compatible, in order to utilize it in more delicate applications such as empowering heart implants.
Reference


42. Tol, S., F. Degertekin, and A. Erturk, *Piezoelectric power extraction from bending waves: Electroelastic modeling, experimental validation, and performance enhancement*. Wave Motion, 2016. **60**: p. 20-34.