

VIBRATION ENERGY HARVESTING FROM AIRFLOW USING PIEZOELECTRIC MATERIAL

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by

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Based on research carried out

under the guidance of

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I, *Subrat Kumar Behera (113ME0352)*, hereby declare that this dissertation entitled *Vibration Energy Harvesting from Airflow using Piezoelectric Material* presents my original work carried out as an undergraduate student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections “Reference”. I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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Any errors are my own and should not tarnish the reputations of my esteemed professor and individuals who helped me.

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Abstract

In this era of modern technology huge research is going on to develop a better power source for the growing energy need of micro-electronic devices and this has led to the production of energy harvesters. Energy harvesters can convert the ambient energy into electrical energy. Ambient and aeroelastic vibrations can be converted into electrical energy by the use of piezoelectric, electrostatic, electromagnetic, or magnetostrictive transducer. Piezoelectric materials are most preferably used as it can be used harvest energy over a wide range of frequencies.

This paper deals with the optimization of a piezoelectric energy harvester of cantilever beam type using an aerofoil and storage of the energy produced. PZT is used as the piezoelectric material. The most important requirement to use such energy harvesting systems is the efficiency of conversion of energy and its storage. In this paper we used softwares like Solid works, Ansys and MATLAB to find out the best possible for a cantilever vibration energy harvester.

Keywords: *Energy harvester, aeroelastic vibrations, piezoelectric, aerofoil, PZT*

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Chapter 1

Introduction

Our energy needs are growing exponentially but conventional energy sources are unable to fulfill this need so we need some device which can convert ambient energy from our surrounding into usable form. This has led to tremendous increase in research in the field of Energy Harvesting. Energy harvesting is a process of tapping energy which can be obtained from the surrounding and storing this energy so that it can be further used up in future for applications with less power or high power. It usually produces very small power which can be used to run the low power consuming electronics.

Some common sources which can be used for energy harvesting are:

- Light energy- solar energy in the form of light or heat
- Thermal – Unutilized energy from heating system
- Mechanical Energy – Vibrational sources, mechanical stress or strain
- Human - energy generated through human actions or from bio- organism and their action
- Natural Energy- wind, flowing water, ocean currents, geothermal energy
- Other energy- from chemical or biological sources

A typical energy harvester system generally contains

- An energy conversion device such as piezoelectric element
- An energy harvester module that captures, stores and manages power for the device which consist of :
 - A rectifier to convert AC into DC.
 - An Energy Storage circuit that uses a storage capacitor for storing the tapped energy efficiently
 - Depending on the type we could include a booster that could maximize our output or a dc buck converter that could store energy and when sufficiently charged could convert it.
- An end application such as wireless sensor network or control and monitoring device

1.1 Vibration Energy Harvesting (VEH)

The continuous improvement of semiconductor manufacturing technologies has led to tremendous technological advancements in small electronic devices, such as portable electronics, sensors, and transmitters in the last three decades. Functionality has been largely broadened and energy efficiency has been greatly enhanced, all while reducing size by orders of magnitude. According to Moore's law the no. of transistors are doubling in every two years.

In addition, as the energy density of batteries continues to improve, many of these devices are able to operate for long periods of time solely on battery power. In some applications, such as sensors deployed in remote locations or inside the human the continuous improvement of semiconductor manufacturing technologies has led to tremendous technological advancements in small electronic devices, such as portable electronics, sensors, and transmitters in the last three decades. Functionality has been largely broadened and energy efficiency has been greatly enhanced, all while reducing size by orders of magnitude but batteries power and lifespan are limited. So batteries always need to be recharged or replaced.

So we need an alternative source of energy which can eliminate the drawbacks of batteries and can be a more dependable source of energy.

1.2 Advantages of VEH

There are various advantages of Vibration Energy Harvesting like

- There are no risk of chemical hazard related to VEH
- These have very long life
- Can be operated where no charging points available
- Very less or no maintenance
- Cheap and dependable
- Sustainable
- Quite Safe
- Can be used in inaccessible sites

1.3 Basic operating principles of VEH

There are two basic operating principles of VEH

1. **Direct force**- In this force is directly applied to the transducer. The energy produced is integral of the product of force and distance. This type of setup is dominated by the driving force, when the force is large the damping is made as big as possible.
2. **Inertial force** – In this the whole set up is put inside a box and the force does not directly to the transducer. When the force acts on the box the box moves as a result it produces relative motion between box and the mass. Here damping couldn't be made very large as it would limit the mass movement. These type of VEH are only attached to only one point to a moving structure hence are much more flexible. These can be made at very small size

1.4 Types of VEH

Based on transduction mechanism mainly there are four types of VEH

1. Electromagnetic
2. Magnetostrictive
3. Electrostatic capacitive
4. Piezoelectric

Table 1 Comparison of different transduction mechanism

Type	Advantages	Disadvantages
Electromagnetic	• no need of smart material • no external voltage source	• bulky size: magnets and pick-up coil • difficult to integrate with MEMS • max voltage of 0.1V
Electrostatic	• no need of smart material • compatible with MEMS • voltages of 2~10V	• external voltage (or charge) source • mechanical constraints needed • capacitive
Piezoelectric	• no external voltage source • high voltages of 2~10V • compact configuration • compatible with MEMS • high coupling in single crystals	• depolarization • brittleness in PZT • poor coupling in piezo-film (PVDF) • charge leakage • high output impedance
Magnetostrictive	• ultra-high coupling coefficient >0.9 • no depolarization problem • high flexibility • suited to high frequency vibration	• non-linear effect • pick-up coil • may need bias magnets • difficult to integrate with MEMS

1.5 VEH using piezoelectric material

Vibration energy harvesting using piezoelectric material is such a type of method in which energy can be harvested by using a piezoelectric material that could supply with an electric charge when there is a stress induced on the material from vibration and this electrical energy can be stored for later or used for mini application levels then. Piezoelectricity is a type of an electric charge that is produced as pressure electricity which is the main feature of certain crystalline structures like quartz and Rochelle salt etc. that develop some electric charge when a pressure is applied.

Among all of the transduction methods piezoelectric energy harvesting has got significant attention as it can be used harvest energy over a wide range of frequencies. Piezoelectric materials can directly transform mechanical vibrations from different source to usable electrical energy.

1.6 Energy storage and circuit

Energy demand and Energy supply are two cars chasing each other on an unending race track of lives of billions of people of the world. Energy demand has already surpassed supply by many miles, and it is getting more and more challenging and unendurable for supply driver to cope up. As a solution Energy supply manufacturers have come up with the idea of storing energy for future application.

Charging circuit plays a key role in charging. Optimization of charging circuit elements is the propelling source to this project. Extensive use of MATLAB SIMULINK has been employed to find out the results and corresponding optimal output also registered. Basics of elements used and different circuits housed in the circuit is also discussed. Li-ion battery and supercapacitors are employed as a modern advancement of storage system. Finally a right set of values of the circuit parameters are chosen which will result in maximum power output in minimum possible time.

Power accumulated can be used in micro power applications, which substantially lacks the need of self-powered batteries, as replacing batteries used in recent micro-electronics need tedious effort for replacement. Also this application can be employed in space sciences where power is of vital concern and without worrying about the shortage of it.

The circuit of a VEH storage module generally consist of

Full wave bridge rectifier

A full wave rectifier uses 4 diodes arranged in such a manner that they are connected to form a closed loop bridge configuration to give a desirable output. The main feedback of this type of circuit is that they do not require a special center tapped transformer which reduces its cost and also the size. The load is connected to the other end of the diode bridge.

Positive Half cycle

During the positive half cycle of a full wave bridge rectifier , diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through as shown in figure1

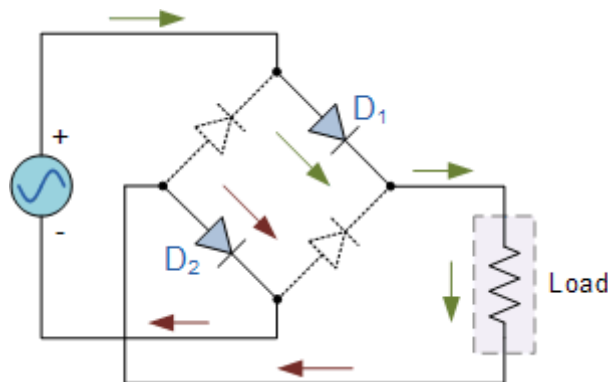


Figure 1 Positive half cycle[1]

Negative half cycle

During the negative half cycle the diodes D3 and D4 conduct in series and the Diodes D1 and D2 will be switched off as shown in figure2 and will be reverse biased.

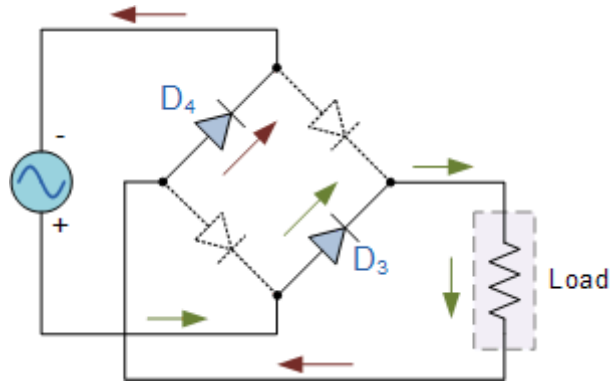


Figure 2 Negative half cycle[1]

The output current or I_{dc} is the value of the DC current that is flowing through the load and I_m is the peak value of AC current.

Equation 1 Formula for output dc Current

$$I_{dc} = \frac{1}{\pi \int_0^\pi I_m \sin(\omega t)} = \frac{2I_m}{\pi}$$

The DC output voltage can be calculated as per the formula

Equation 2 Formula for output dc voltage

$$V_{dc} = I_{dc} R$$

From the above two formulas output dc current and voltage could be find out using the mean AC current

Advantages of a full wave bridge rectifier

- 1) Highly efficient than half wave rectifier since there is double rectification in one cycle(Positive and negative)
- 2) High frequency and ripple voltage is low in full wave bridge rectifier hence simple filtering circuits only required.
- 3) No center tapped transformer required hence smaller size and cost.

Boost converter

A boost converter is used as a step up power stage. It is used as a matter of fact in order to increase the output than the input voltage. The current supplied must be continuous or non-pulsating as the diode connected at the output only conducts during a portion of the switching cycle. The capacitor set up on the outside supplies the load for the rest of the switching cycle.

There is an inductor (L) and capacitor(C) that filters the output. The ESR or equivalent series resistance and LC (leakage current) of the capacitor are taken into consideration and an ideal capacitor should have less LC and low ESR

In a power stage it can operate in both continuous and discontinuous inductor current mode what happens in continuous conduction process is that current keeps flowing continuously in the inductor during the entire switching cycle and in the discontinuous process it start at zero and later reaches to its peak value and then goes on decreasing to 0. It's better off to keep the working of the power stage in either continuous or discontinuous mode because the frequency response of the two changes distinctively

Supercapacitors

Batteries work time to time and keeps the devices working that is batteries have high energy density stored, but once this energy is run out it takes a lot more time to recharge these batteries, here we can inculcate the use of super capacitors. Supercapacitor gadgets, otherwise called electrical two fold layer capacitors (EDLCs), store charge by adsorption of electrolyte particles onto the surface of anode materials. No redox

responses are required, so the reaction to change in potential without dissemination

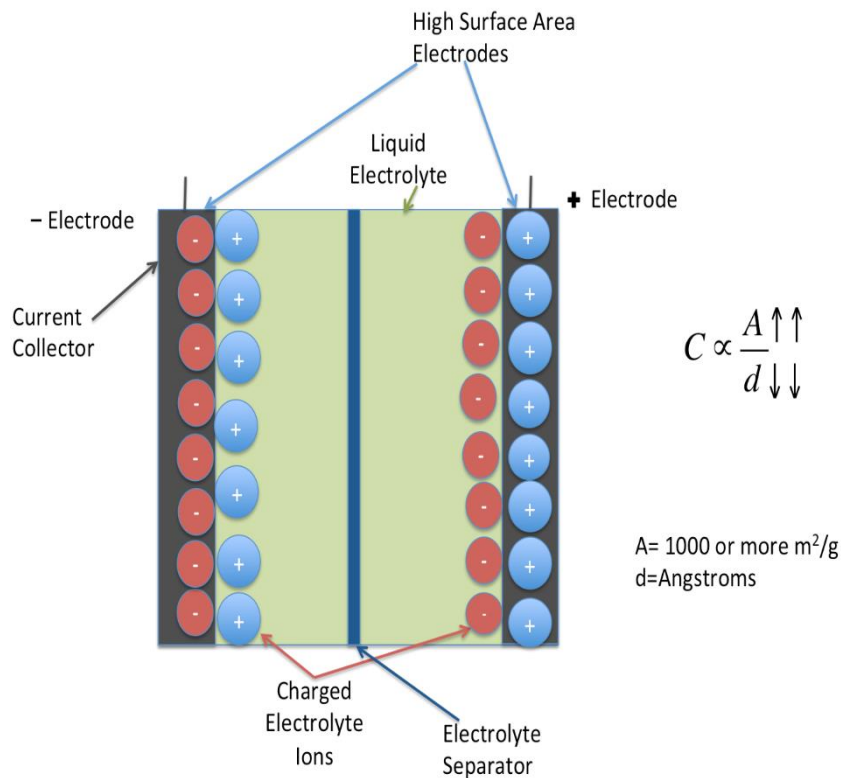


Figure 3 figure showing separation of charge in a supercapacitor [15]

Basically a supercapacitor has two plates that are separated as shown in figure 3. The plates are made with metals that are coated with porous substance such as powdered activated charcoal, this porous surface gives it a larger surface area to store the charge. Hence more space more energy can be withheld and the perfect equipment to be inculcated into our system.

Usually the separator that is used in between the plates is a thick dielectric medium that helps in arranging the ions in the medium in such a fashion that they are aligned opposite to the differently polarized plates when the capacitor is charged creating an electric field between the two plates, this means the plates can store more charge at a given voltage well where as in the case of supercapacitors there is no dielectric used as such, there are metal plates that are soaked in some electrolyte and is differentiated by a thin insulation material. On the plates becoming fully charged, an opposite charge shall develop on any side of the separator that would create an electric double layer. Hence they can also be called as electric double layer capacitors

The capacitance of a capacitor starts to increase with increasing surface area of the plates and decreasing distance between them plates. Basically, supercapacitors get their considerably greater capacitance from a blend of plates with a greater, powerful surface

territory (on account of their actuated charcoal development) and less separation between them (in light of the extremely viable twofold layer).

When the positive electrode is given a voltage ions tend to attach to the electrode and when the negative ions are given a voltage they tend to capture ions and hence this process decreases the distance between them and increases capacitance.

The standard formula to calculate the capacitance of electric double layer capacitor is given as

$$C = \epsilon \frac{A}{d}$$

Where, A – Area of plates

ϵ - permittivity

D-distance between two plates

In order to store a sensible measure of vitality for a moderately brief time frame and there is excessive vitality to store in a capacitor and there is no inspired time to charge a battery, a supercapacitor might be exactly what is required. Supercapacitors have been broadly utilized as the electrical reciprocals of flywheels in machines—"vitality stores" that smooth out power supplies to electrical and electronic gear. Supercapacitors can likewise be associated with batteries to manage the power they supply.

Batteries and supercapacitors

Batteries are higher energy dense (they store more vitality per unit mass) however supercapacitors are more power dense (they can discharge vitality all the more rapidly). That makes supercapacitors especially appropriate for putting away and discharging a lot of energy moderately and rapidly, yet batteries are better off for saving a lot of vitality over long stretches of time. Although supercapacitors work at generally low voltages (possibly 2–3 volts), they can be associated in arrangements with batteries to deliver greater voltages for use in more intense mechanisms.

Batteries depend on redox reactions and there is electrolyte and metal interaction to form electrons. These electrons are collected on the negative terminal and there is a

connection between the negative and positive terminal and there must be always flow of electrons from negative to positive to keep the reaction set in motion.

Synchronous rectifier

Synchronous rectifiers or active rectifiers are those in which diodes in a rectifier circuit are replaced with active electrical elements such as switches like MOSFET or transistors that can be switched on and off at required time interval for the rectification to occur. A Synchronous rectifier helps in improving the efficiency of the circuit by replacing them with such switched since the diodes would always possess a min voltage drop of 0.7-1v except for the schottky diode that has a min of .3v voltage. By replacing the diodes with active elements such as the switches we get a drop in mΩ or lesser. Since the switching of these elements occur synchronously with the incoming waveform they can be termed as synchronous rectifiers.

The drawback to synchronous or active rectifiers is that they require controlled hardware to guarantee the gadgets turn on synchronously. Hardware required for the control of the synchronous rectifier regularly incorporates voltage level locators and drive circuitry for the dynamic devices. One key issue for the control hardware is to guarantee that two gadgets that are connected opposing each other don't turn on together generally because then a short circuit would be exhibited. The turning on and putting off the gadgets are regularly controlled to guarantee that even at the point where one turns on and another off, there is a short time period that both gadgets aren't on together. Active correction or synchronous circuit is frequently utilized in AC/DC converters where productivity is a key issue. Utilizing a synchronous rectifier empowers control misfortunes to be limited and proficiency levels to be enhanced, in spite of the fact that to the detriment of extra multifaceted nature.

Tantalum capacitors

Tantalum capacitor is a type of electrolytic capacitor that is a polarized capacitor with an electrode made of tantalum which is the anode and it has a thin insulating metal oxide formed which acts as a dielectric for the capacitor, a solid or semisolid electrolyte which covers the primary acts as the cathode .Tantalum capacitors are said to have high capacitance per volume and low weight due to its very thin and relatively high permittivity dielectric layer.

They are commonly available as surface mount pieces with solid polymer electrolyte. The importance of solid polymer electrolyte is that it ensures low equivalent resistance and its characteristic traits don't change over temperature. The high storage capacity of tantalum capacitors makes it best for the use of passing or by passing low frequency signals up and to store energy for some highly integrated circuits. The design and weightlessness makes it actively inclusive in small prototypes or mechanisms but however the capacitors are highly expensive because tantalum ore is very expensive and also the tantalum capacitor can work only in some specified restrictions as it cannot handle reverse voltage or ripple currents.

1.7 Objective

The main aim of this project is to design a vibration energy harvester with higher efficiency, the basic objective of this project is shown below

- Design a Vibration Energy Harvester which uses Piezoelectric material as transducer
- Find optimum values of different parameters for best efficiency possible.
- Make a storage module which can store the energy produced by VEH
- Find optimum values of circuit elements for optimal power storage.

Chapter 2

Literature Review

Sodano et al. [2] investigated three types of piezo electric devices namely bimorph Quick Pack (QP), piezo-ceramic material lead zirconate titanate (PZT) and the macro-fiber composite (MFC) in order to test their capacity to convert ambient vibration to electrical energy efficiently and store it in to a discharged battery. These energy harvesting systems are used to charge batteries of different capacity. Authors estimated the time required to charge the batteries in order to determine the efficiency of the systems.

Kahrobaee and Vuran [3] studied the feasibility of an energy harvester below the level of ground to be used for wireless sensory networks using vibrational source above the level of ground by. They studied the power developed at various depths to find out the maximum power which can be generated and stored analytically. For experimental results agriculture field was used and the output power for different case was found.

With the advancement of technology more and more sensors are installed in vehicles to monitor wide range of parameters. But with increase in no. of sensors a lot of complexity arises like the increase in no. of wire connections, power usage. **Zhu et al** [4] investigated the possibility of use of energy harvesters using the ambient energy of vehicles. It was found the vibrating source or the ambient energy of vehicle have sufficient potential to power WSNs. It was also established that the efficiency can be significantly increased with the modification of the design.

Xiong and Oyadiji [5] exploited broadband power output by constructing two layered convergent and divergent piezoelectric vibration energy harvester with a cantilevered design, provided with proof masses at the ends, out of which one serves as a support. Changing the position of the masses different modes with resonant frequency achieved with optimum power output. Finite element analysis handed over the modal parameters. The design involved optimizing the system structure to achieve close resonant

frequency, equipped with close mass ratio. Deriving the power density and Electro-mechanical-coupling-coefficient was the aim.

Chao Lu et al. [6] established a system for battery less application in micro power system by using piezoelectric materials driven through maximum power point (MPP) tracking and time-multiplexing mechanism alternately. Proposed system poses the capacity of self-starting without the help of energy buffer. Optimal voltage output was the sought after result. Entire process was designed in very small CMOS process. Experimental results and measurements showed that efficiency of electrical circuit through this system is 90%.

Chen et al. [7] performed three different analyse to establish the effect of piezoelectric geometry on power output. Taking three different shapes, viz. rectangular, trapezoidal, triangular, and subjecting each one of them to three different analyses namely analytic analyses, based on mathematical and mechanics formulae; Finite Element analyses through ANSYS; and at last through physical experimentation. Finally it was firmly established with redundancy of each test over each other that triangular shape has the best voltage output and strain distribution followed by trapezoidal and then rectangular shape.

Guoliang Ye et al. [8] scavenged for optimum output power from the piezoelectric cantilever beam using genetic algorithm and numerical methods. This algorithm was so constituted that to take into account the real world vibration rather than just usual sinusoidal ones. Vehicle excited man-hole cover was employed to demonstrate successfully the algorithm in selection of right frequency and optimization of damper and resistive load, eventually optimize the power generated.

Mukherjee, Datta [9] brought down the relation between piezoelectric material properties that are mostly useful in power output and vibration energy harvesters in a cantilevered fashion. Authors also compared various material properties to search for best set of properties that might produce optimal result. Mathematical model is employed for calculation purposes of cantilevered beam.

Wang et al. [10] executed the test of vibration energy scavenging from piezoelectric materials using circular diaphragm array subjected to mechanical vibration. Array housed four discs in a parallel manner. Vibration acceleration of 9.8 m/s^2 with 150 Hz frequency and with optimal resistive load of 11k ohms power output was found out to be 27mW. Inference was made that use of parallel circular diaphragm array is more efficient than single plate.

Son-mao Chen et al. [11] went in a unconventional way to use beams of piezoelectric materials with non-uniform thickness excited to vibration and energy extracted and compared the output to the regular uniform thickness piezo-materials. Non-uniformity was achieved by equally spacing rectangular grooves of equal size and equipping the beam with rectangular patches. Under acceleration of 1g and 15.1 Hz maximum power output was found to be 48.5 μ W. Comparison with uniform piezo-electric it was concluded that non-uniform beam gives more power than former.[7]

Trimble et al. [12] innovated a device that traps the rotational vibration energy. Deviced equipment was a spring-damper-mass system with torsional bar as spring element, excited through normal sinusoidal vibration and real life vibration. Electromagnetic circuit was appointed as the energy harvester. The device was essentially a resonant type harvester. Maximum output power obtained was 250mW.

Chapter 3

Design of cantilever VEH

3.1 Cantilever Design

Cantilever geometry is one of the most commonly used structures for energy harvesting using piezoelectric material, as the construction of piezoelectric cantilevers is quite simple further large mechanical strain could be produced in the piezoelectric material by the mechanical vibrations. The cantilever which is made by only one piezoelectric layer is called unimorph, a cantilever can also be made by bonding two piezoelectric material layer this is called a bimorph. Bimorph almost doubles the energy output without increasing the volume significantly, hence it is most commonly used in piezoelectric energy harvesting.

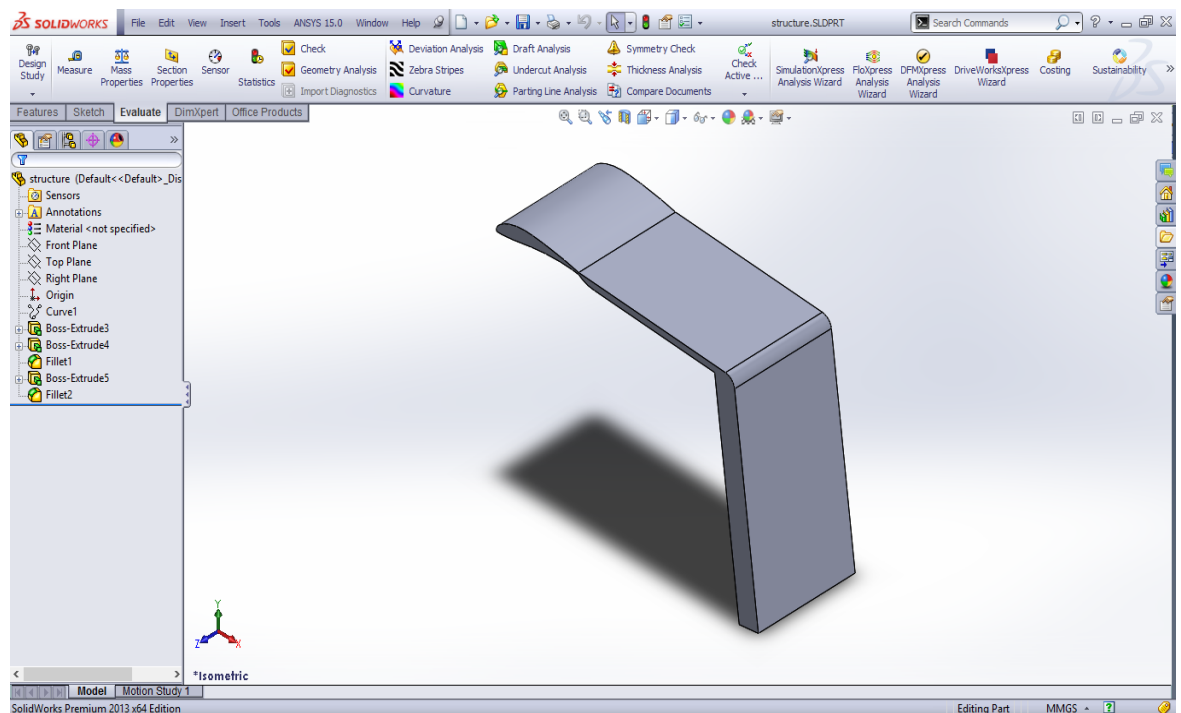


Figure 4 Figure showing the cantilever beam design

In this project piezoelectric energy harvester of a cantilever geometry is used as shown in figure 4, a thin layer of piezoelectric material is built in the form of cantilever and then it is bonded to the non-piezoelectric layer. Apart from the force applied on cantilever, a proof mass is attached to the end of cantilever which also determines the mechanical strain. Roundy discovered that the power output is proportional to the proof mass.

3.2 Airfoil

An airfoil is specialized body which when interacts with fluid flow produces an aerodynamic force. This aerodynamic force has two components the component perpendicular to the direction of motion is called lift, the component parallel to the direction of motion is called drag.

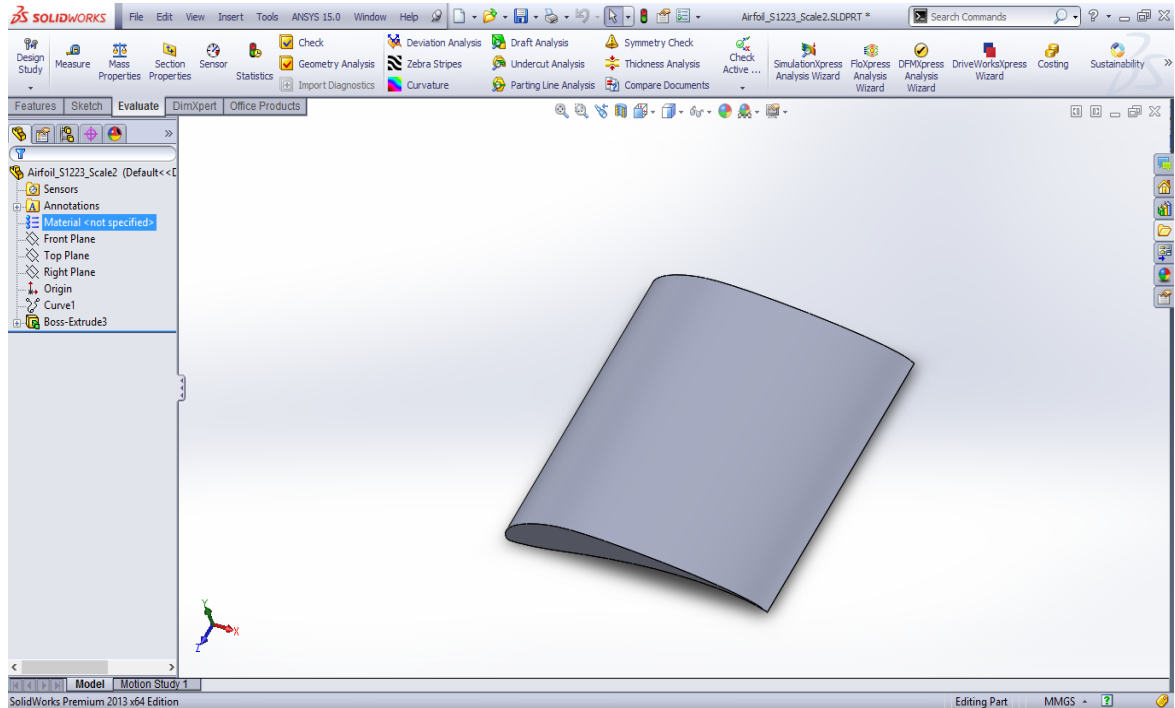


Figure 5 Solid model of S1223 airfoil

The airfoil used shown in figure 5 is S1223 (s1223-il). It generates very high value of lift at low speed, and also this high lift is generated at very low angle of attacks. The data for the above airfoil is taken from the department of Aerospace Engineering, Illinois University [13]

In this project the airfoil serves two purpose first when the fluid flows across the cantilever a lift is generated which helps to initiate the vibration, second it also acts as a proof mass which helps to maintain the vibration due to inertia.

3.3 Material Used

3.3.1 Material for structure

The material used for whole structure is aluminum. Here Aluminum is preferred over the generally used structural steel as:

1. Aluminum does not corrode/rust- It forms an oxide layer which resist type of corrosion. Hence it can be used in moist and corrosive environments.
2. Aluminum is lightweight- This property makes it friendly to be used in cantilever VEH as the amount of lift required to lift would be quite low
3. Aluminum is more elastic and malleable than steel- This property allows the use of thin plates for the experiment.

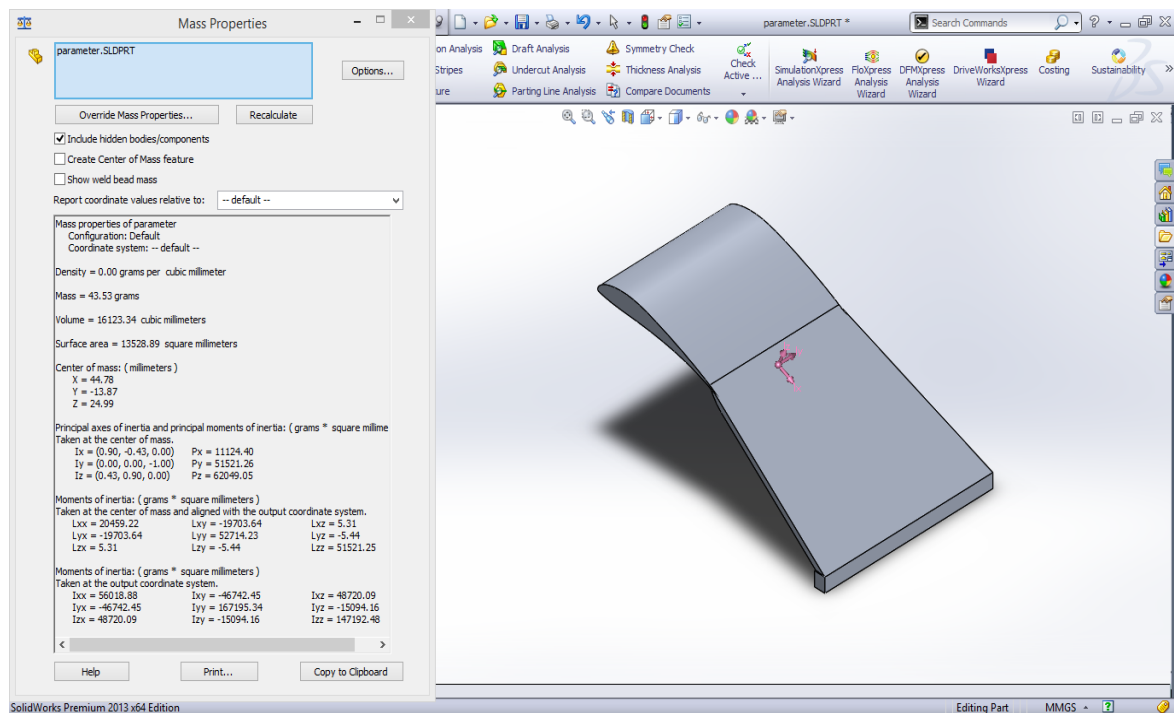


Figure 6 Mass properties of cantilever structure

The above figure 6 shows the mass properties of the cantilever structure. It shows the mass is as low as 43 gm which is low enough to be lifted by natural airflow.

3.3.2 Piezoelectric Material

The energy that can be harvested from piezoelectric material is double or triple times the energy that can be tapped electrostatically or electromagnetically. Piezoelectric

material delivers higher energy density and more flexibility as compared to other energy harvesting alternatives. So these can be easily included in a Energy harvesting system.

Generally piezoelectric material are classified in four types

- Piezo-ceramics
- Single crystals
- Polymers
- Composites

The piezo ceramics are rigid but brittle and produces strong polarization. In this project we used PZT 5h as the piezoelectric material which is also a type of piezo-ceramics.

Chapter 4

Numerical Analysis

4.1 Fluent Analysis

It is the analysis which deals with the behavior of different bodies due to the influence of a flow of fluid. It is used to produce the flow virtually and then analyze the affect due to interaction. In this project Fluent is used to find the force of lift due to change in parameters like attacking angle, and velocity of flow. The process used is explained below

4.1.1 Creation of Geometry

The first step in CFD fluid analysis is creation of computational geometry of the cantilever structure. For creation of geometry we used solid works 2013 where the model is made. This part is then imported to Design module of Ansys 15.

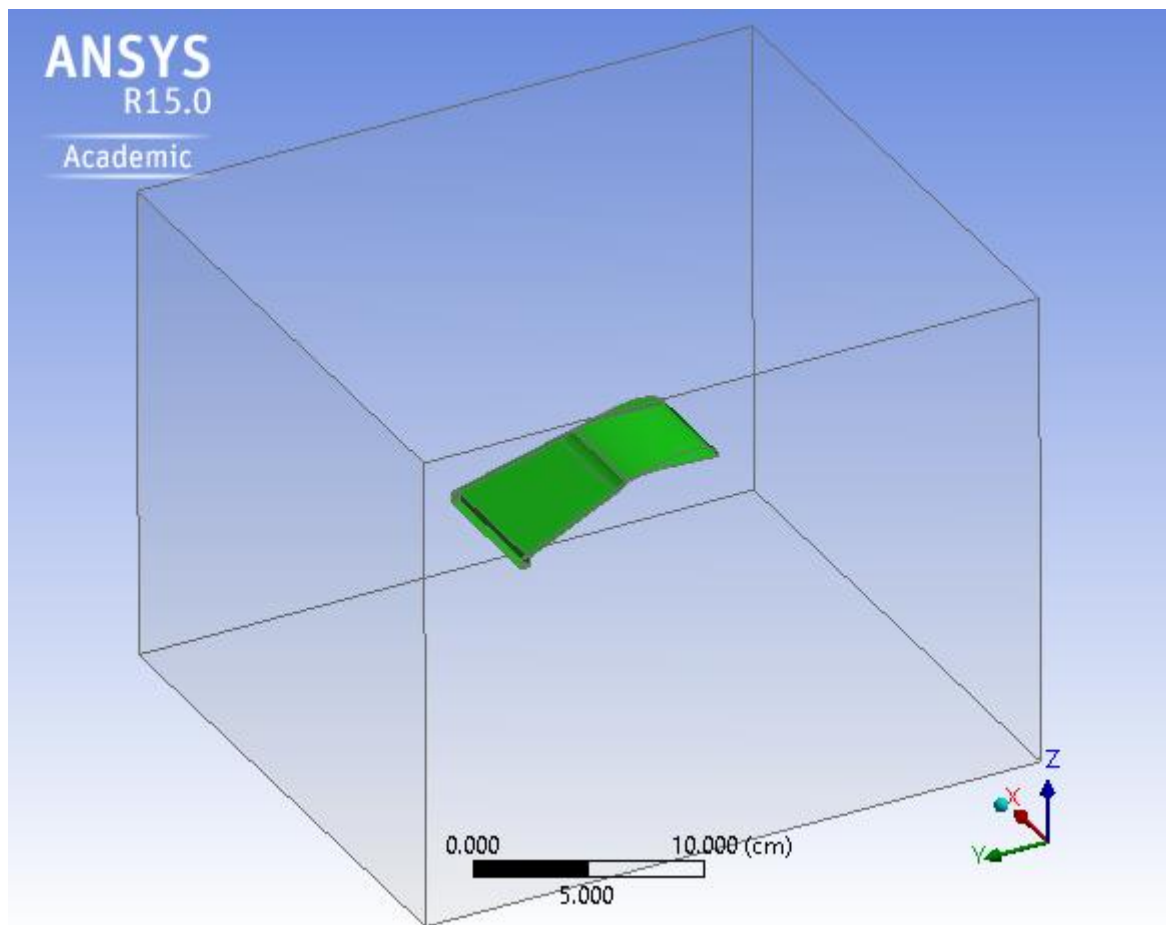


Figure 7 Cantilever structure with enclosure in design modular

Here first an enclosure is made as shown in figure 7 which is used to represent the boundary of air surrounding the set up. The values like attacking angle and dimensions are converted into parameters so as to make it easy to change the values and get the output.

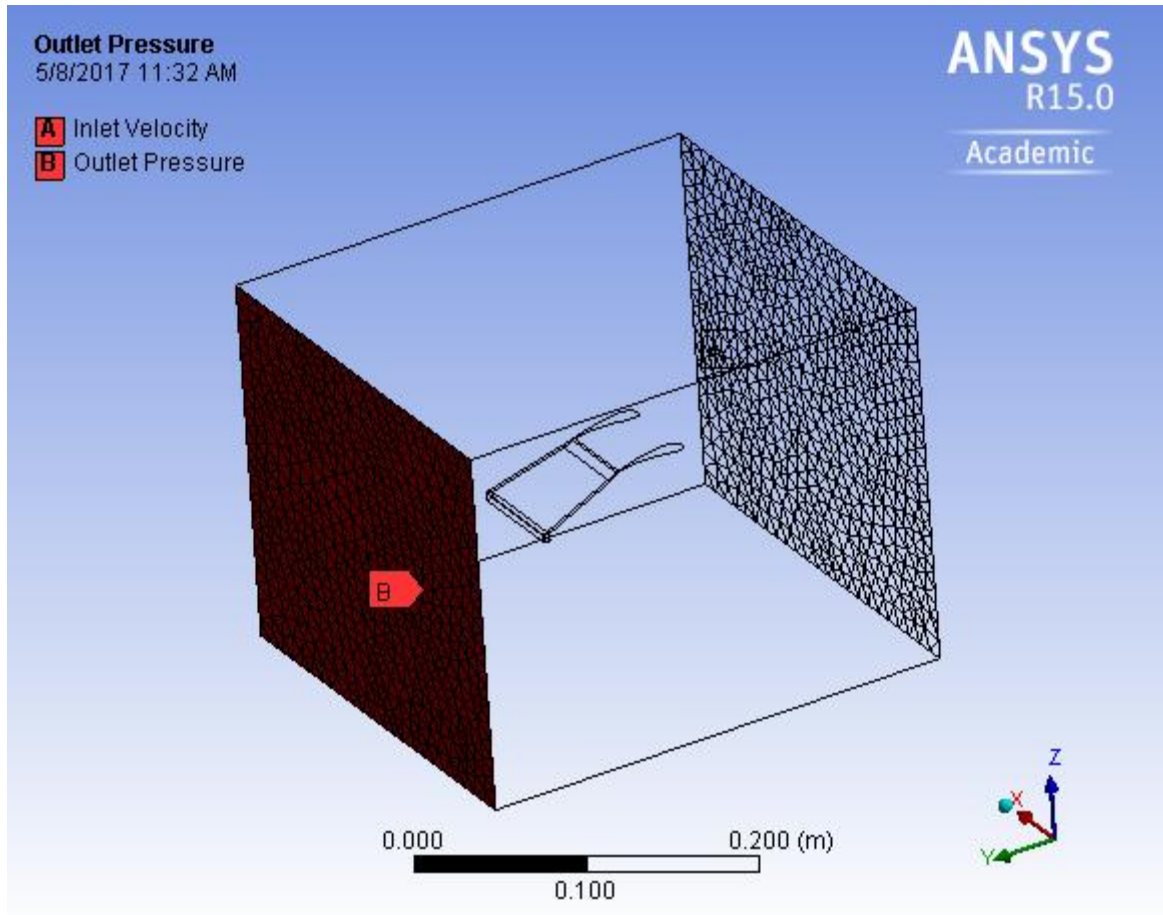


Figure 8 inlet and outlet for the airflow

The above figure 8 shows the direction of flow for the analysis, the face of enclosure on the side of airfoil acts as the inlet for the airflow and the side just opposite to it acts as the outlet

4.1.2 Meshing

Meshing is done to define the type of elements by the aggregation of which the body is made. In this project triangular surface mesh is selected, and the program controlled option is used so that the algorithm is determined the program automatically. For better accuracy the relevance center of sizing is changed to fine.

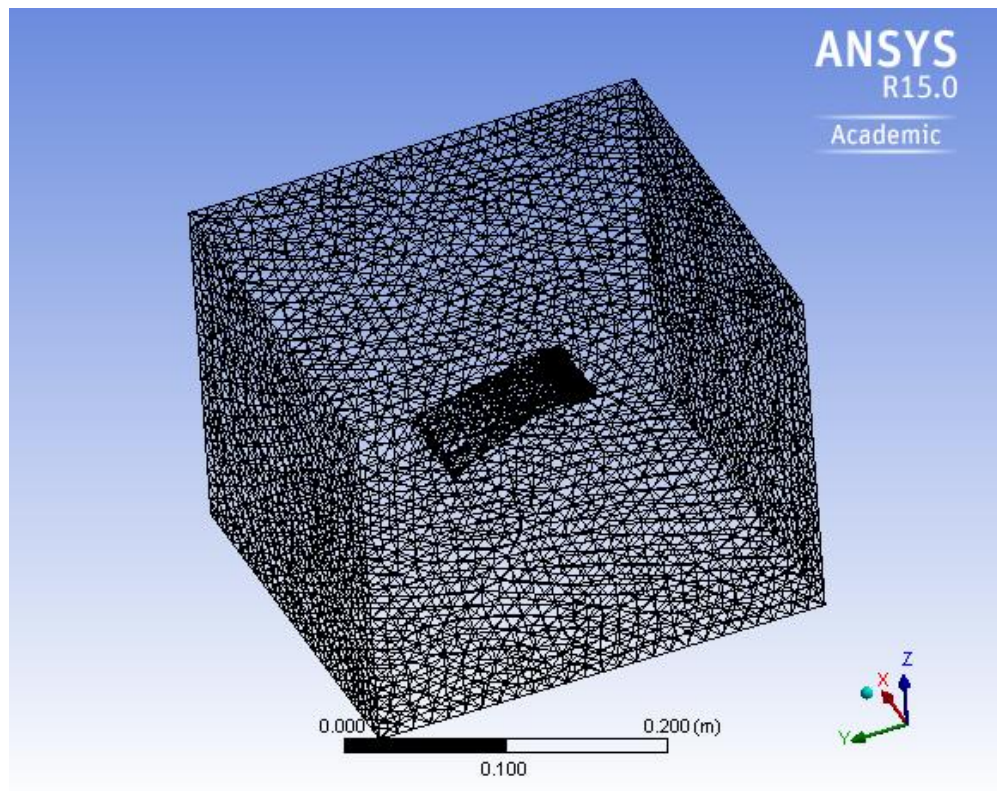


Figure 9 Meshed cantilever structure

The figure 9 shows the schematic view of the mesh grid used in the numerical model. The no. of nodes in this mesh are 85215 and no. of elements are 466695.

4.1.3 Solution

After the meshing is done the CFD analysis is set up at first the viscous model is changed to k epsilon (2 eqn). In the boundary condition the zone and their types are checked also the value of velocity of flow from the inlet velocity is provided. In the solution methods changed the values to Second order upwind. Then calculation is run which gave the following contours of pressure.

The figure 10 shows the pressure due to flow is higher at the edge of airfoil where the flow first strikes the cantilever beam.

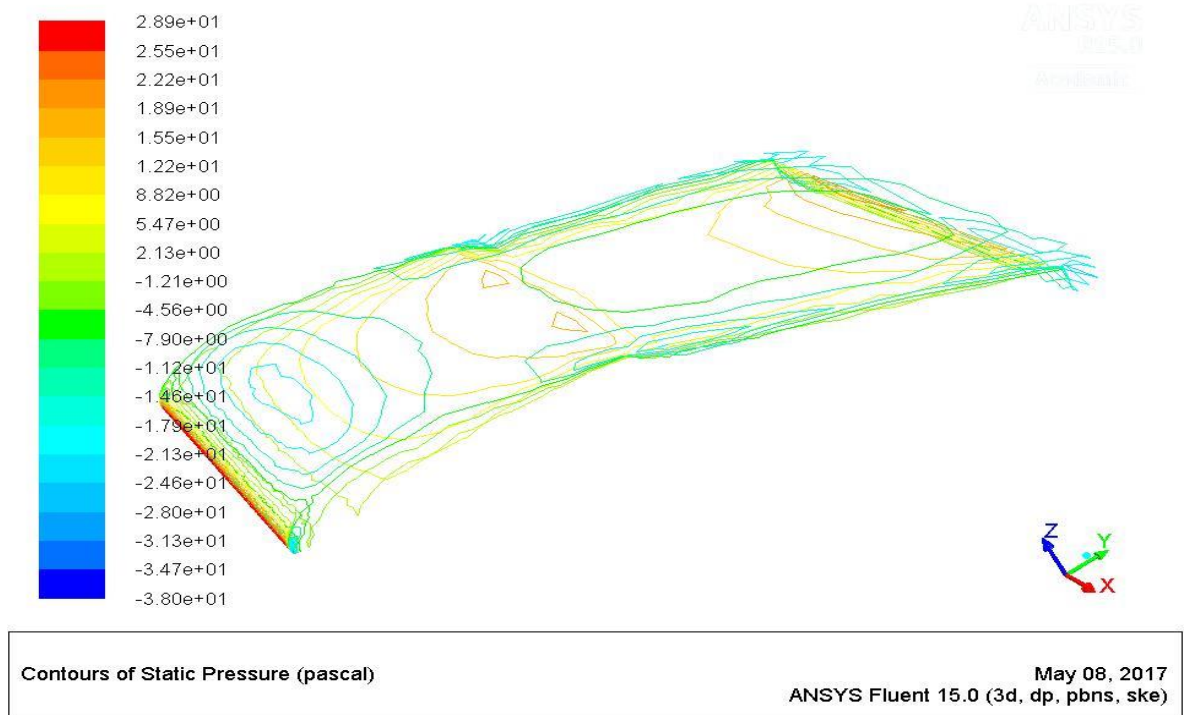


Figure 10 contour of static pressure on the wall of cantilever structure

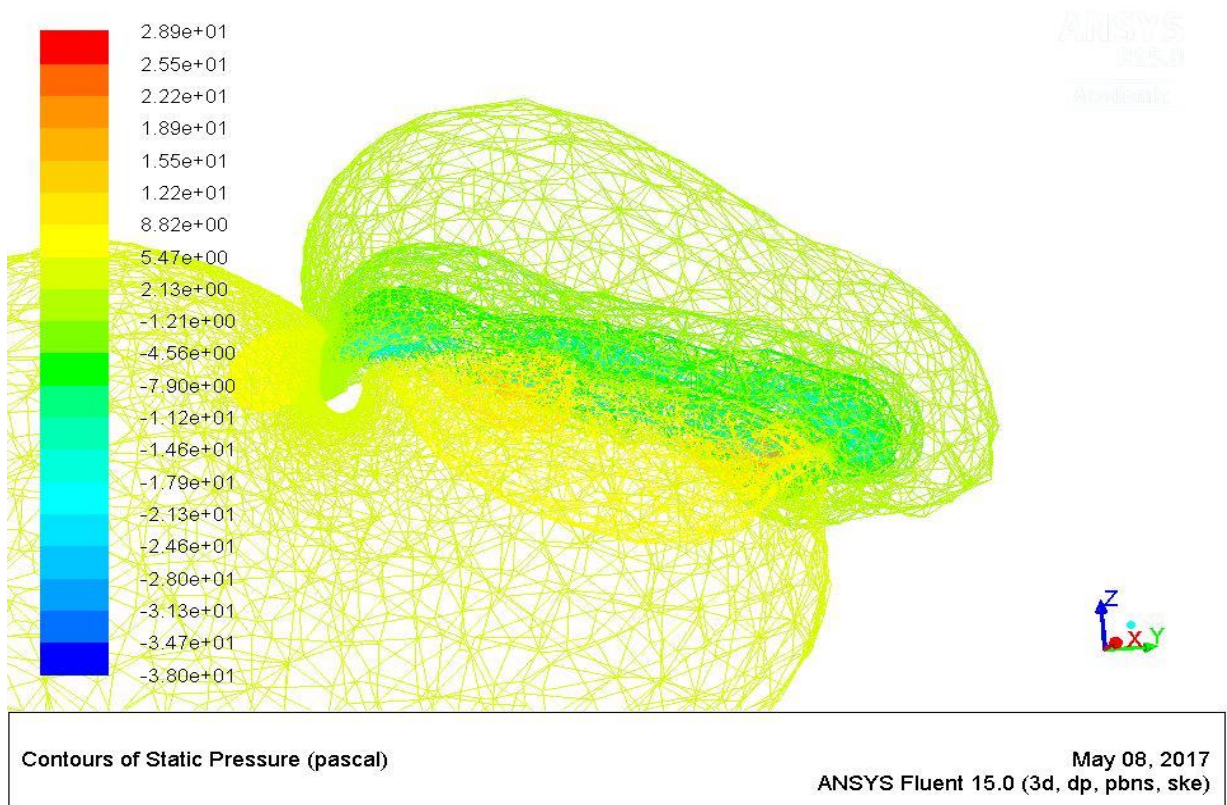


Figure 11 Contour of static pressure in the surrounding of cantilever structure

The figure 11 shows the how the flow is affected by the interaction with cantilever structure. It clearly shows the pressure below the structure is more than the pressure above and it will result in positive lift.

4.2 Modal Analysis

Modal analysis is the analysis of different properties of a body under some excitation. It is generally used to determine mode shapes and natural frequencies of a body. In this project Modal analysis was done to get the different mode shapes.

Table 2 Mode and frequency output:

Mode	Frequency [Hz]
1	862.59
2	2975.8
3	4641
4	8441.4
5	10490
6	11596

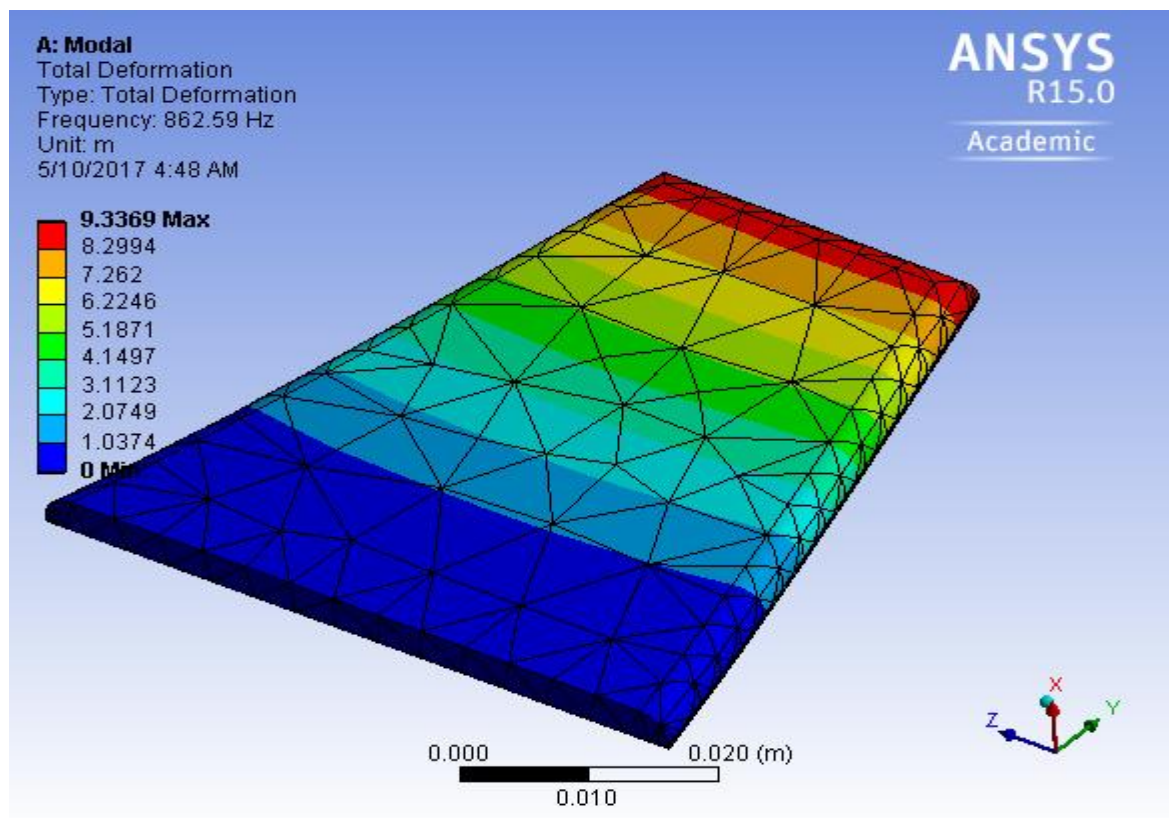


Figure 12 figure showing total deformation at 862.59 Hz during modal analysis

The figure 12 represents the one of the mode shape of the cantilever beam of the modal analysis

4.3 Harmonic Analysis

It is the analysis which is used to find out the response of a structure due to a harmonically varying force. It is used to find out the graph between the frequency and a different quantity.

In this project it is used to find out the graph between deformation vs frequency and stress induced on cantilever beam vs frequency.

Table 3 Frequency response of displacement

Frequency [Hz]	Amplitude [m]	Phase Angle [°]
1950	4.44E-09	180
3400	1.20E-09	180
4850	9.87E-10	180
6300	4.04E-10	180
7750	2.65E-10	180
9200	1.99E-10	180
10650	2.02E-10	180
12100	5.98E-10	0
13550	8.84E-11	180
15000	6.44E-11	180

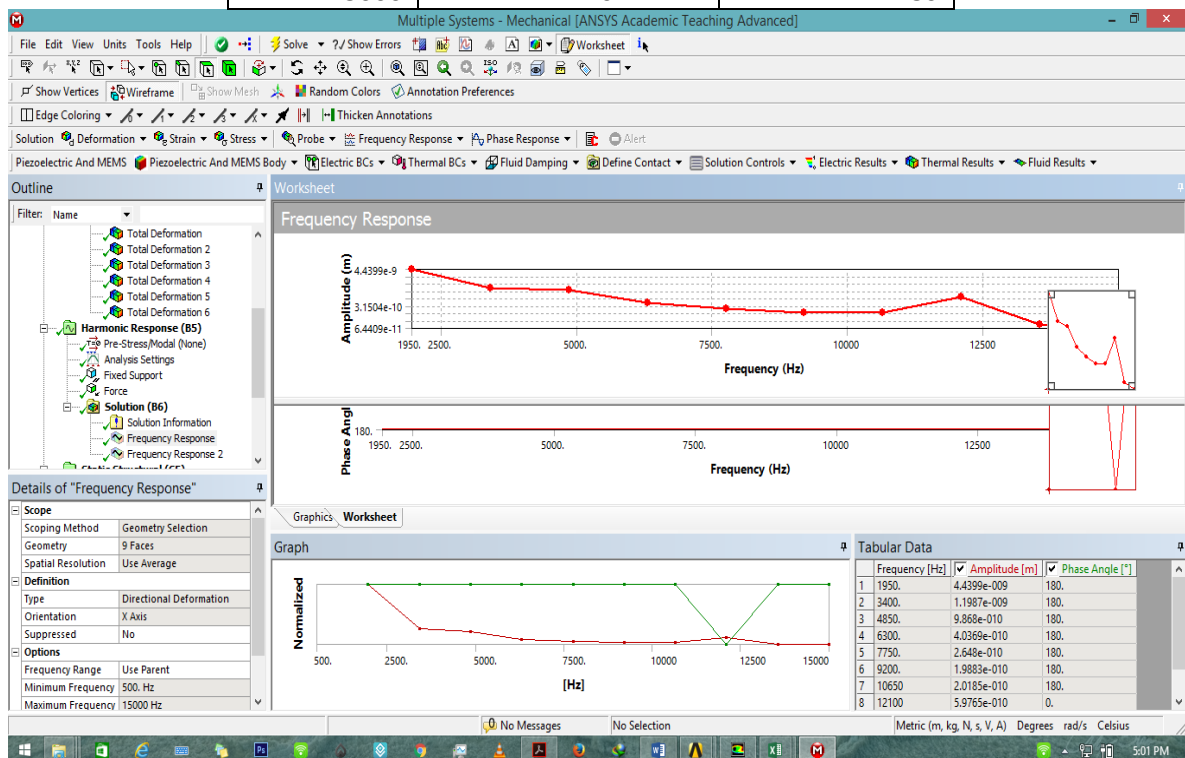


Figure 13 frequency response of deformation

Table 4 Frequency response of stress

Frequency [Hz]	Amplitude [Pa]	Phase Angle [°]
1950	0.88124	0
3400	14.443	0
4850	73.678	180
6300	6.2065	180
7750	1.1727	180
9200	1.3613	0
10650	4.7538	0
12100	42.777	0
13550	5.5665	180
15000	2.0023	180

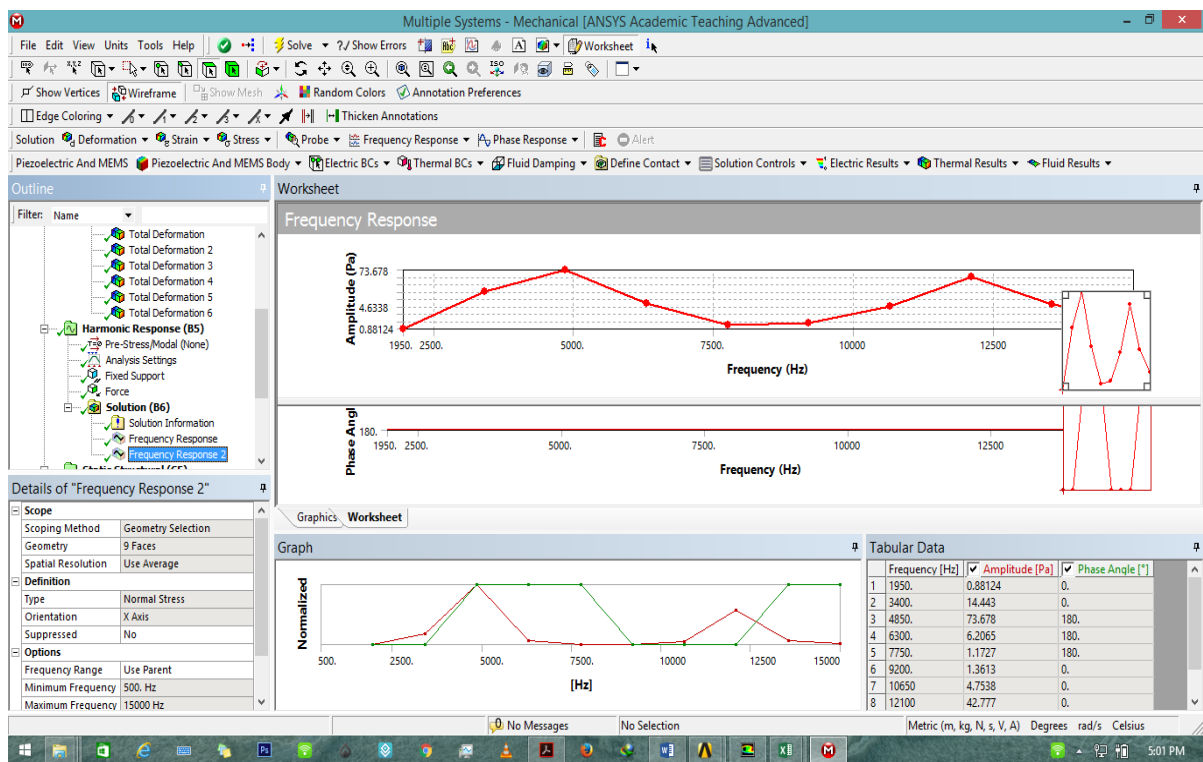


Figure 14 frequency response of stress

4.4 Static structural analysis

After the modal and Harmonic analysis this analysis is used to find out the potential difference in the PZT material generated. First the PZT body is defined then the fixed force is applied on it. The PZT material used is PZT 5h. Solving it gave the values of maximum and minimum voltage.

Chapter 5

Storage System

After taking a look at the circuit components and different circuits used in storage system, detailed arrangement of circuit, it's working in briefs are presented here. With the results obtained from each alteration done with variable parameters and circuitry, tables are formed indicating each outcome from MATLAB SIMULINK

5.1 Complete Circuit

The circuit starts with an AC voltage supply which is symbolic for the output voltage obtained from piezoelectric terminals through ANSYS software. The AC supply is connected to a full wave rectifier circuit. The output from full wave rectifier circuit is connected to a voltage regulator circuit. Finally voltage regulator circuit ends in storage elements; viz. supercapacitor and battery. Here Supercapacitor is used as secondary storage device when battery is the primary storage device.

Here AC voltage used is 0.3 Volt as obtained from ANSYS. Diode resistances were varied and each variation is tabulated. Also varying regulating circuits are used and their results are tabulated too.

The complete circuit is shown in fig 15, which is a model extracted from MATLAB SIMULINK, hence shows MATLAB library elements like display, scope, product etc.

5.1.1 Working of Circuit

Voltage supply is a sinusoidal wave form with peak voltage 0.3V. Although this model is not quite the replica of the obtained voltage outputs of the ANSYS analysis, but it approximates the outputs for better understanding and better result. This AC voltage source is connected to full wave rectifier.

Full wave rectifier consists of four diodes arranged in a specified manner as discussed earlier in Chapter I. This rectifier rectifies the AC input voltage to DC output voltage. The rectification may not be cent percent perfect but for micro power application deviation is acceptable. Full wave rectifier circuit than is connected to voltage regulators.

Voltage regulators may be of step up type or step down type as discussed in Chapter I. Hence boost converter for step up and buck converter for step down has been used.

These converters consist of resistors, inductor and capacitors arranged in a specified manner for each setup, resulting in either stepping up or stepping down the voltage as discussed in Chapter I.

The output terminals of the converters are connected to supercapacitor and battery terminals to store the charge as a future use. Here battery is Li-ion rechargeable battery with very long life period also supercapacitor is of specified type with high ($\sim 10^6$) life time, which means the discharging of supercapacitor is very low.

Using MATLAB SIMULINK operations power output, voltage and current measurement at different output terminals are calculated and shown.

5.2 Varying Parameters

Varying different controllable parameters different results were obtained. These parameters include diode resistance, voltage source value, full wave rectifier circuit configuration etc. For micro power applications the resistances were taken as small as possible and a few experiments were done to calculate the optimum one. The system is designed with buck converter (step down) voltage regulator.

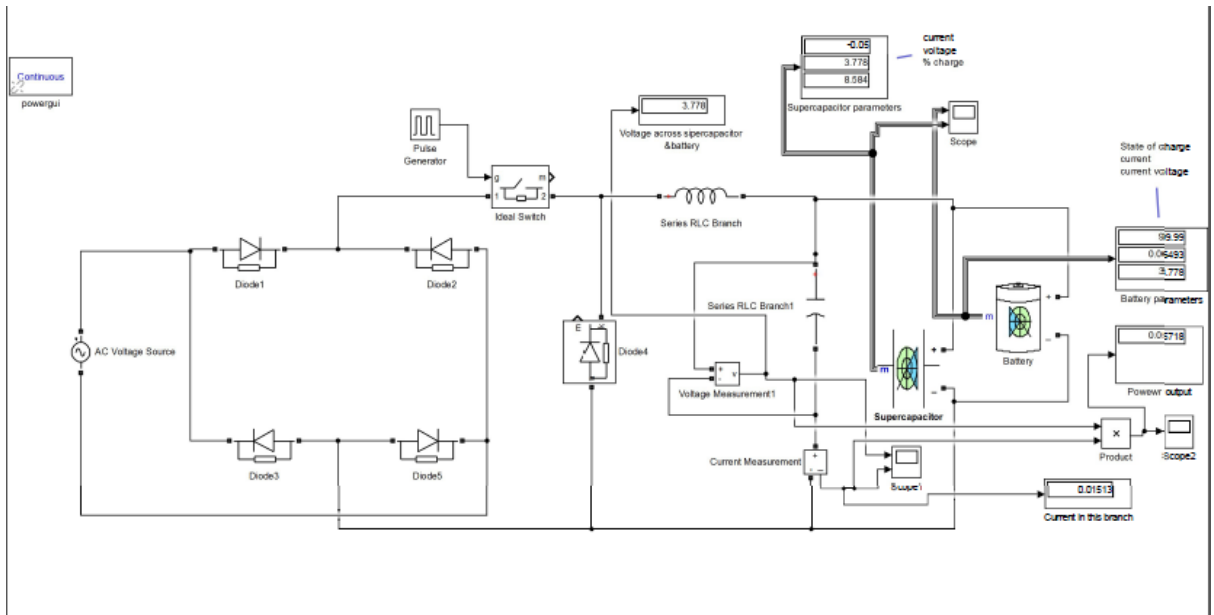


Figure 15 MATLAB SIMULINK model using diode rectifier and buck converter

5.3 Using Boost Converter

Instead of buck converter, this circuit appoints boost converter which steps up the DC voltage output from the rectifier terminals. Hence changing the parameters that can be

regulated with this system has been presented below in accordance with their effect on power output.

Details of Boost converter can be found in Chapter I.

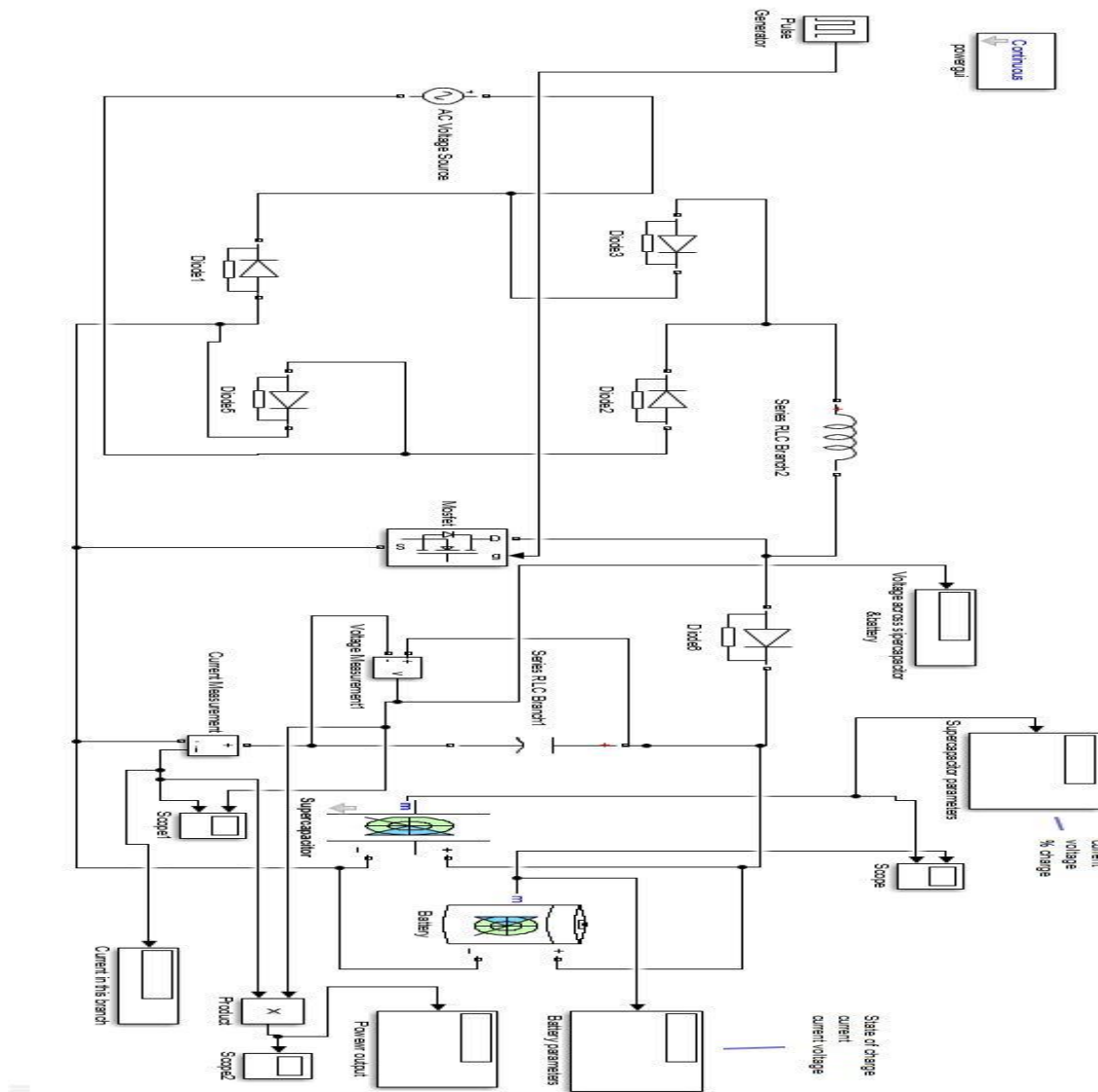


Figure 16 Use of Boost Converter in Circuit

5.3 Use of Synchronous Rectifier instead of Diode Rectifiers

Recent development suggest that synchronous rectifier has lower resistance and higher efficiency in converting AC to DC. This is examined through MATLAB Simulink with. Synchronous rectifier uses MOSFET instead of diodes. For better picture of the synchronous rectifier circuit Chapter I may be referred.

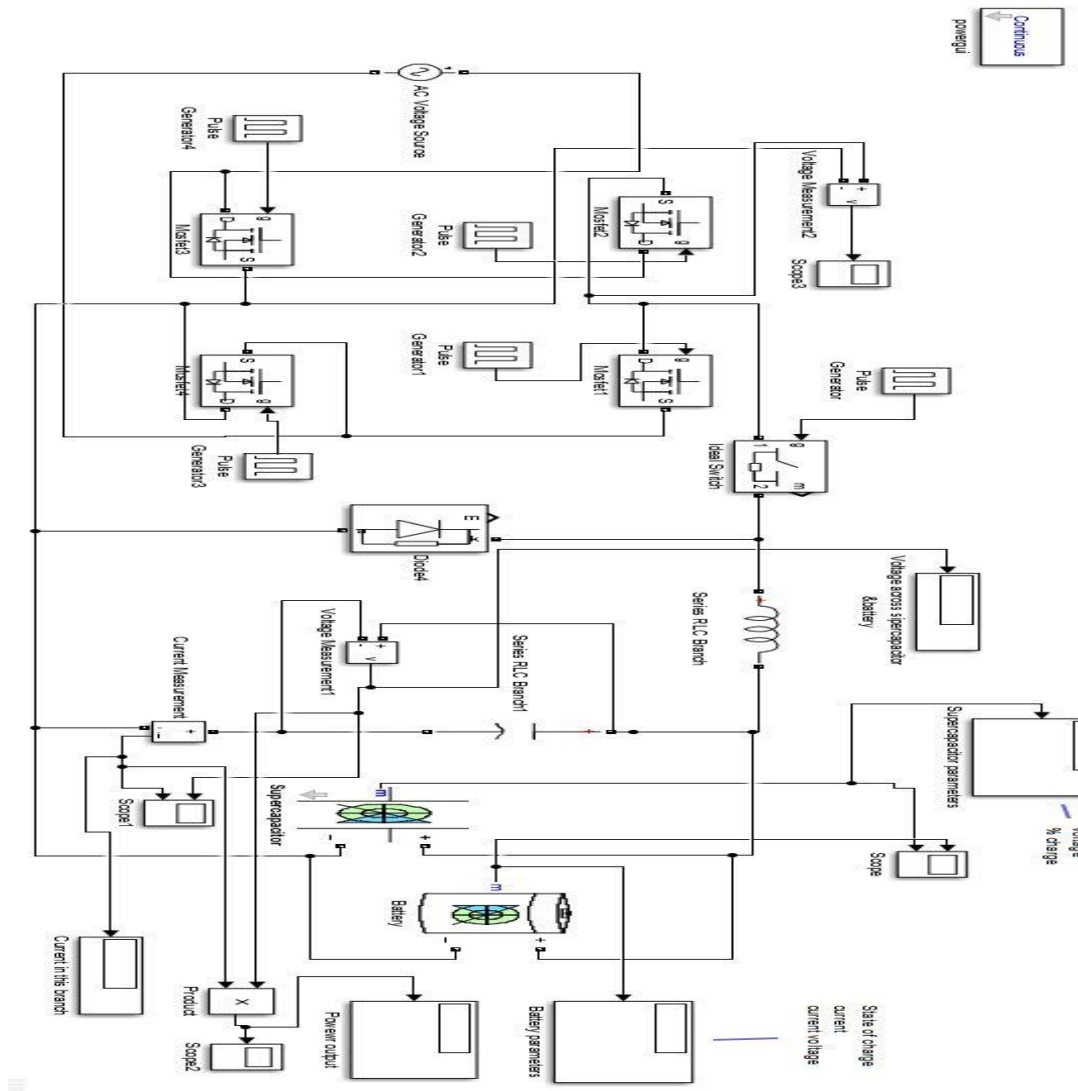


Figure 17 MATLAB SIMULINK model using Synchronous rectifier

Fig 17 shows a MATLAB SIMULINK model of synchronous rectifier circuit applied in the desired storage circuit. Scope, Display are MATLAB functions.

For selecting the optimal case of the synchronous rectifier parameters different values of resistance of the MOSFET is chosen and then experimented. The best output is compared with the diode mode rectifier to calculate the percentage efficiency of this system over the previous one.

The changing values of power with the changing FET resistances of MOSFET is tabulated.

Chapter 6

Results and Discussion

6.1 Lift

6.1.1 Variation of lift with velocity of air

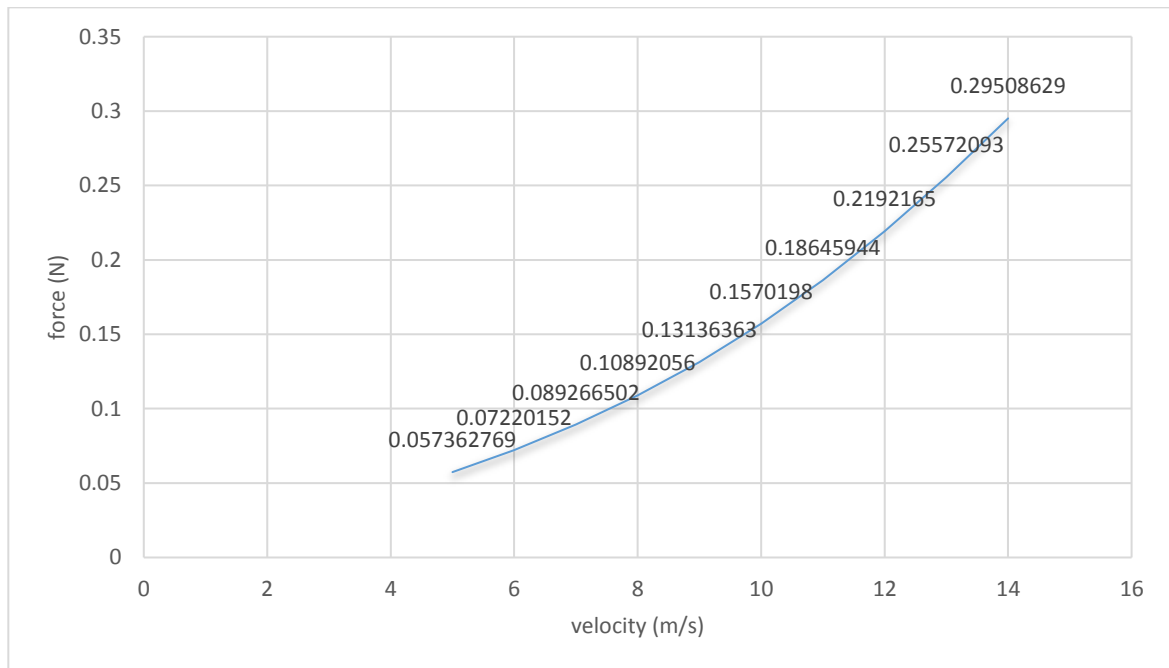


Figure 18 Figure showing variation of lift with velocity

Lift is generated when there is change in direction of a flow due to any solid body or simply due to turning action [14]. As the amount of air molecules turned by the airfoil increases with the increase in velocity of air hence the lift also increases which corresponds to the graph which is generated by the fluent analysis of cantilever structure

6.1.2 Variation of lift with attacking angle airfoil

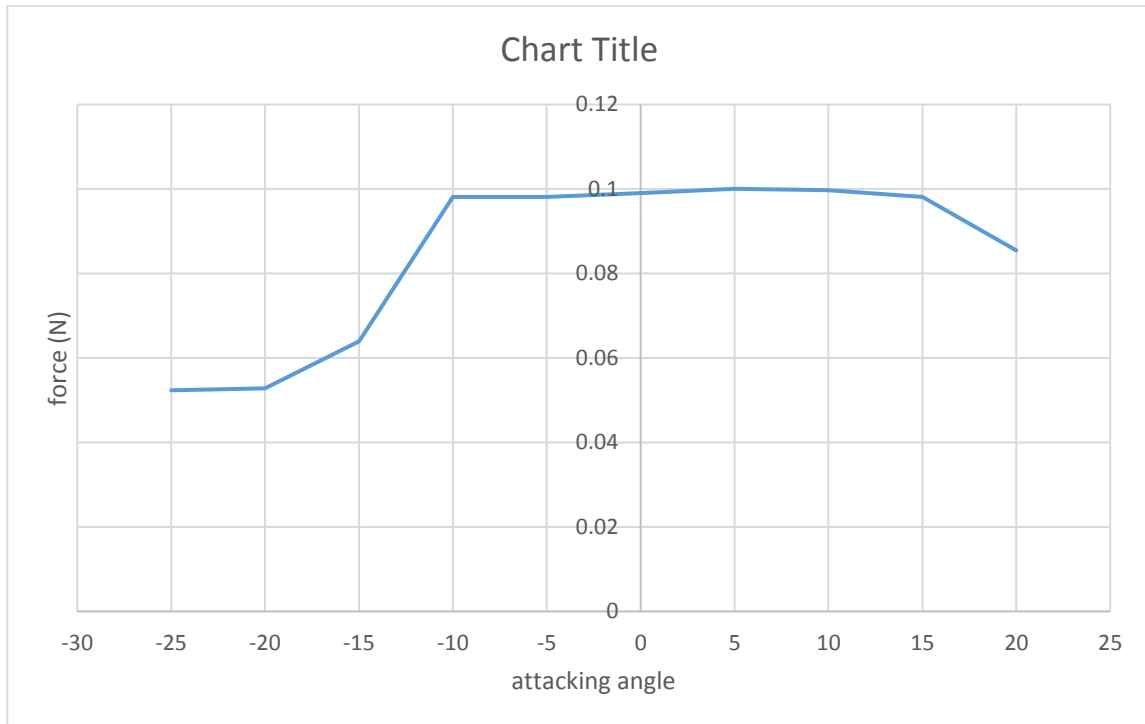


Figure 19 Figure showing variation of lift with attacking angle

The figure 19 shows that maximum lift is generated at attacking angle 5 degree with force of 0.1 N at 6m/s velocity of flow.

6.2 Potential Difference

6.2.1 Variation of potential Difference with length of big side

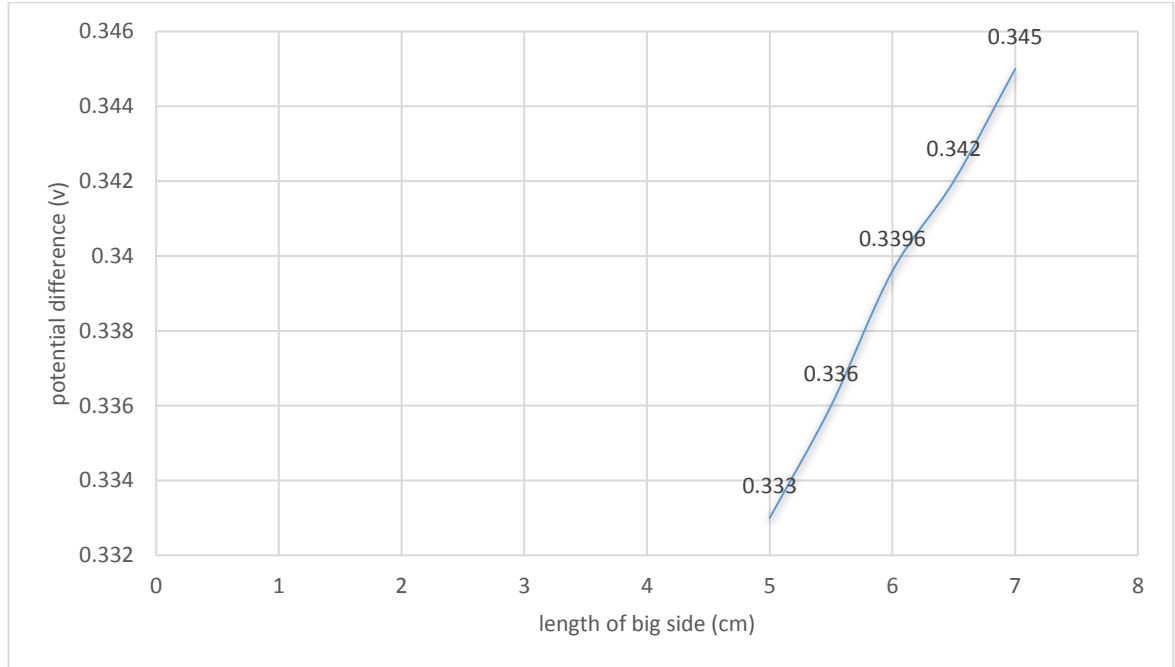


Figure 20 figure showing variation of potential difference with length of big side

When a cantilever beam vibrates the maximum stress is induced near the edge which is attached to the base structure so more compression and expansion occurs near the big side edge. So the trapezoidal Structure for cantilever is selected for the cantilever structure. The graph clearly shows that with increase in the length of big side the potential difference increases.

6.2.2 Variation of potential Difference with change in lift

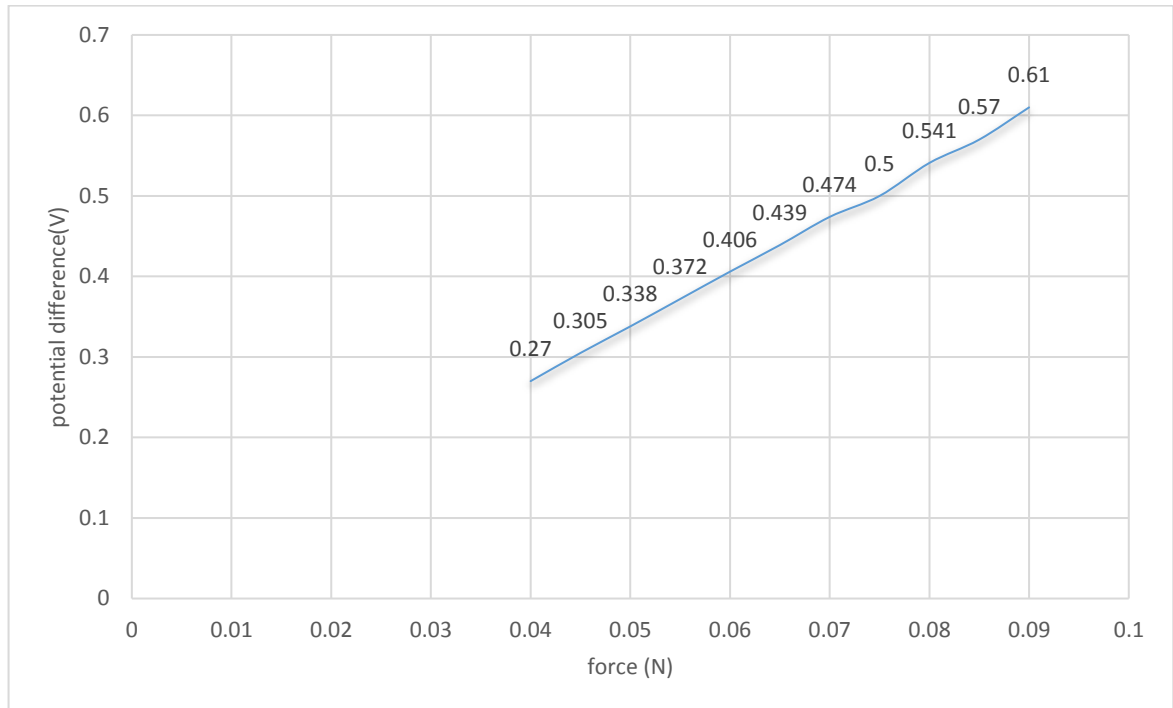


Figure 21 figure showing variation of potential difference with change in lift.

As with increase in lift the generated stress in PZT layer also increases so the potential difference also increases. It is clearly represented in the graph.

6.3 Power

Analysis of power is made through MATLAB SIMULINK with varying parameters of different circuit parameters and configuration. Each of them is presented below with tables and graphs showing the variation and at the end conclusion is drawn for each section.

6.3.1 Varying Resistance of Diode

Diode resistance is varied from 0.001 ohms to 10000 ohms and power measurements were calculated keeping other variables constant. This power is measured at the end terminals of the voltage regulator which subtends to storage systems.

Table 5 Effect of varying rectifier diode resistance on power output

Resistance of Diode (Ohm)	Simulation Time (s)	Peak Power Output (W)
0.001	0.1	0.6828
0.01	0.1	0.683
1	0.1	0.6827
10	0.1	0.6828
100	0.1	0.6823
1000	0.1	0.682
10000	0.1	0.6823

Result:

From the above table it is observed that the power output remains same by changing the value of rectifier diode resistance. Hence any suitable resistance can be connected to the circuit.

Power output graph is same for each case and looks like as shown in fig 21. Battery and supercapacitor parameters remain same for each case and is shown table 5. The graph in fig 21. shows abrupt changes till 0.01 micro seconds in power and then power maintains periodic shape.

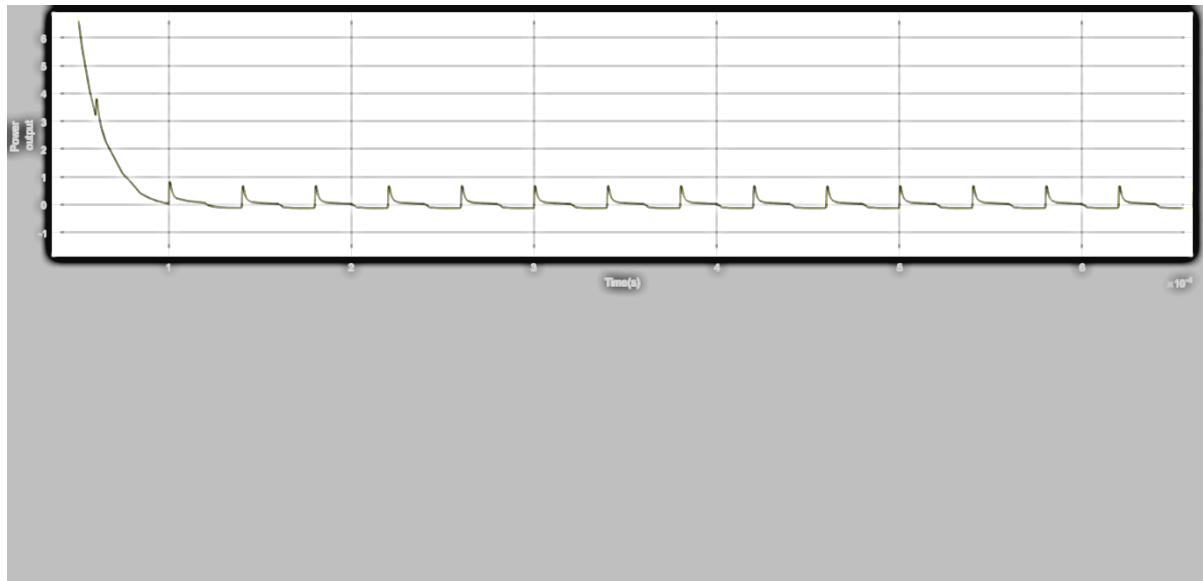


Figure 22 Graph between time and power output for varying rectifier diode resistance

Table 6 Battery and supercapacitor parameters for rectifier diode resistance variation

Parameters	Battery	Supercapacitor
State of Charge	100%	8.587
Current	0.06493	-0.05
Voltage	3.779	3.779

6.3.2 Varying Buck Converter Capacitance

Buck converter is step down voltage regulator. The effect of converter's capacitance value is affected by power. Which is shown in table 7 within a few range, i.e. 220 micro Faraday to 10 Faraday while other parameters of the circuit remains same.

Table 7 Effect of varying buck converter capacitance on power output:

Capacitance (F)	Simulation time(s)	Power output(W)
220 μ F	0.1	0.6828
300 μ F	0.1	0.7222
400 μ F	0.1	0.7225
500 μ F	0.1	0.7105
600 μ F	0.1	0.7001
800 μ F	0.1	0.6998
1mF	0.1	0.6948
100mF	0.1	0.4178

Inference:

Here the value of capacitance is varied from 220 μ F to 100mF. Above which the simulation of MATLAB shows abrupt result and due to multiple zero crossing at the same time simulation stops.

Result:

From the table it is evident that with increasing Capacitance value first power output increases and then decreases. Optimum power output is obtained at 400 μ F value of capacitor. The variation is given in a graphical form in fig 22. Battery and Supercapacitor parameters are shown below:

Table 8 Battery and supercapacitor values for varying buck converter capacitance

Parameters	Battery	Supercapacitor
State of Charge	100%	8.587
Current	0.07634	-0.03474
Voltage	3.779	3.779

These parameters remain almost same.

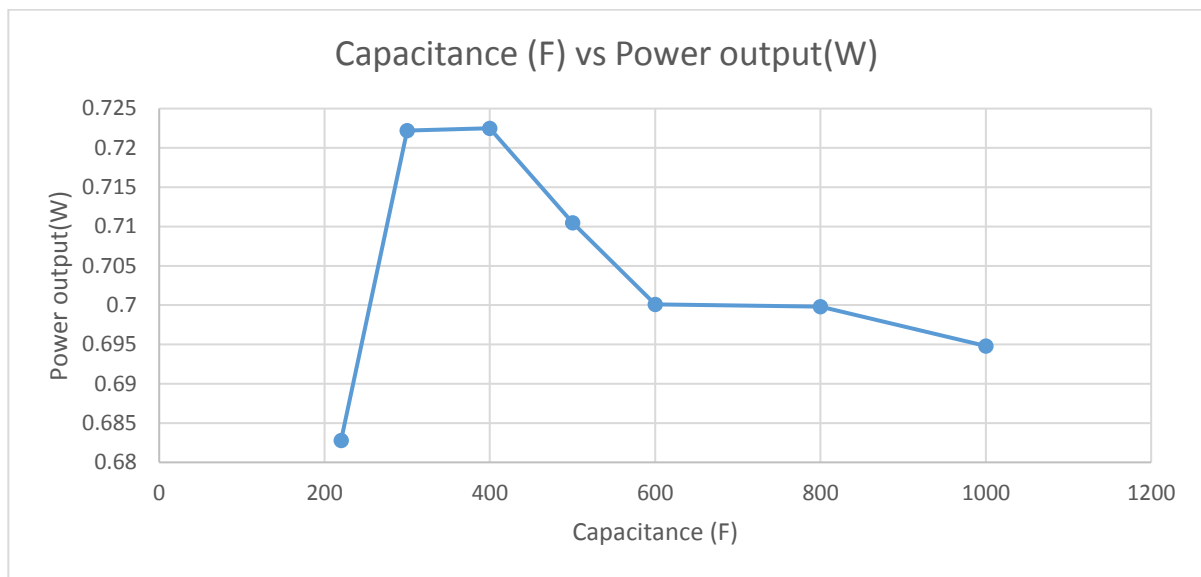


Figure 23 Variation of power at different capacitance value of buck converter

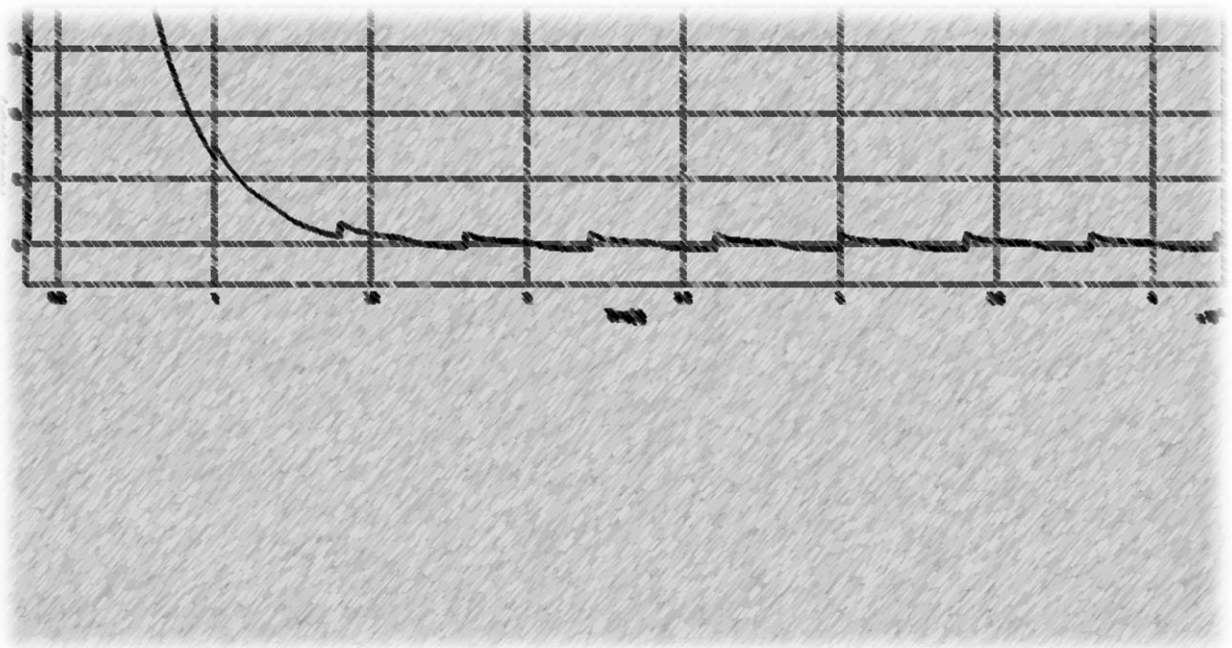


Figure 24 Power output vs simulation time

Here the periodic part is same as before, just the closeness of the shapes have been varied.

6.3.3 Varying Buck Inductance

The inductance is changed from its original value 150 micro Henry to various other values and the change is measured. Optimum value than calculated from graph or table. The value of inductance is changed from 150 Micro henry to 100 mili Henry and variation is tabulated in table 9.

While varying the inductance all other parameters of the circuit was kept constant in addition with the previous simulation time of MATLAB SIMULINK, i.e. 0.1 second. The power vs time spent graph extracted from software clearly shows the variation output. While tabulating the power output only the peak value is considered. However taking the average would be more reasonable, but calculation of average is more complicated at the initial as random variation is seen.

Table 9 Effect of variation of inductance of buck converter on power output:

Inductance (H)	Simulation time(s)	Power output(W)
0.1 μ H	0.1	1.915
1 μ F	0.1	1.905
10 μ H	0.1	1.8995
100 μ H	0.1	1.0085
150 μ H	0.1	0.7225
300 μ F	0.1	0.3515
400 μ H	0.1	0.2522
500 μ H	0.1	0.1912
600 μ H	0.1	0.1496

Constructing graph we see that:

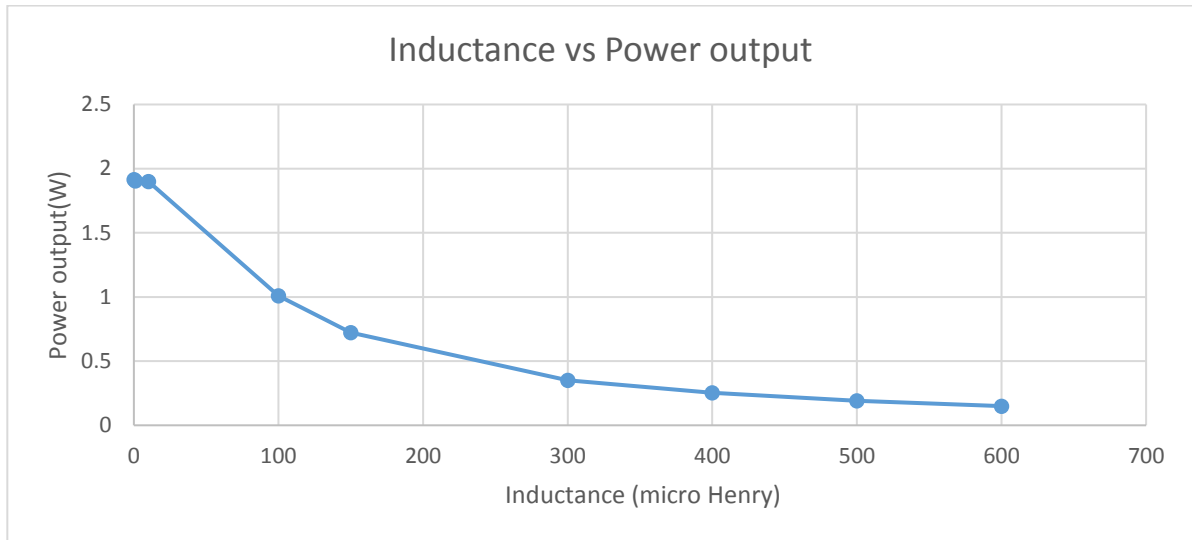


Figure 25 Variation of Power with inductance of Buck converter

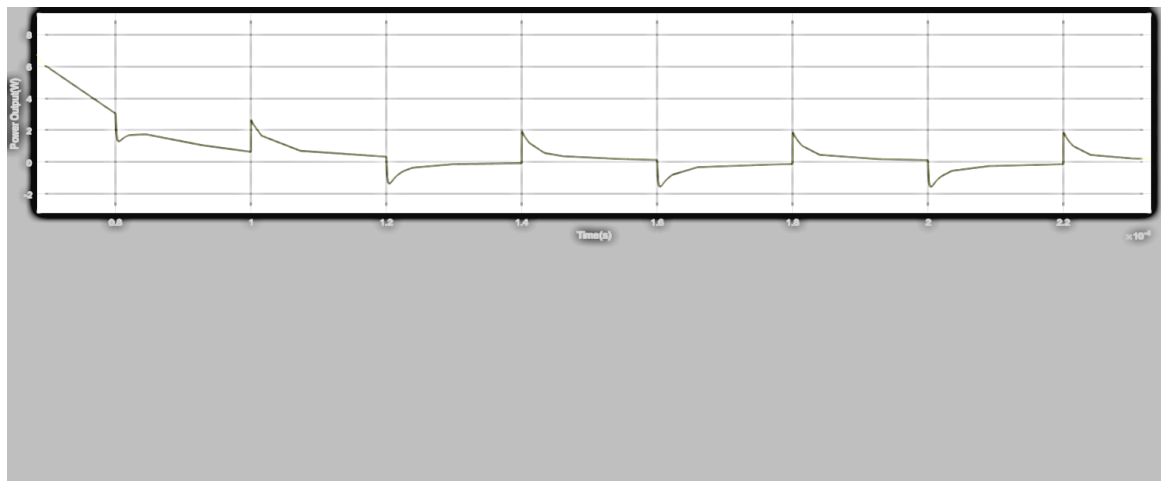


Figure 26 Power output of MATLAB SIMULINK

Result:

From the above graphs and tables it is clear that with increasing the value of inductance of buck converter the power output decreases. The optimum power output is obtained under the value of inductance as $0.1\mu\text{H}$ or below, for which power output remain constant.

Also here the value of inductance is varied from $0.1\mu\text{H}$ to $600\mu\text{H}$. above which the simulation of MATLAB shows abrupt result and due to multiple zero crossing at the same time simulation stops.

Battery and Supercapacitor parameters remained almost unchanged, except the current flowing through them and they are tabulated below.

Table 10 Battery and supercapacitor parameters for buck converter inductance variation

Parameters	Battery	Supercapacitor
State of Charge	100%	8.579
Current	0.2212	-0.1365
Voltage	3.777	3.777

6.4 Power (Boost Converter)

6.4.1 Changing Inductance

With the circuit consisting of boost converter as given in Fig 16, the inductance of inductor can be varied and the result can be inferred to get an optimal output. Keeping other values constant the inductance is varied from 0.1 μ H to 500 μ H and result is tabulated in table 15.

Table 11 Effect of variation of inductance of boost converter on power output:

Inductance (H)	Simulation time(s)	Power output(W)
0.1 μ H	0.1	0.00001
1 μ F	0.1	0.000002
10 μ H	0.1	~0
100 μ H	0.1	~0
150 μ H	0.1	~0
300 μ F	0.1	~0
400 μ H	0.1	~0
500 μ H	0.1	~0

Hence from the above table it is observed that changing the inductance does not change the power output and also power output almost equal to zero in each case.

6.4.2 Changing MOSFET resistance

Changing the MOSFET FET resistance also has little effect on power output, which is consistent on almost zero value. As output is almost zero there is no need of finding the optimal one through tables and graphs

6.4.3 Changing Capacitance

Boost converter although steps up the voltage but changing its parameters does not affect very much the power output. Power output remains constant and shows almost zero value. From these experiments it can be concluded that boost converter should not be used in this circuit.

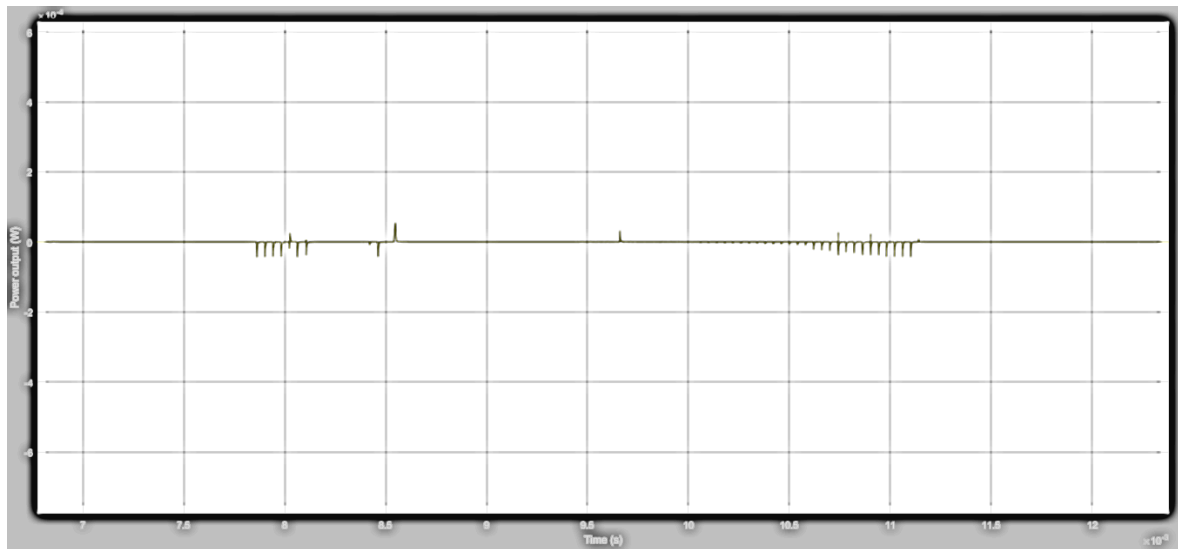


Figure 27 Power output from employing boost converter in the circuit which shows almost zero value

6.5 Power Output (Synchronous Rectifier)

6.5.1 Changing MOSFET resistance

FET resistance of MOSFET used in Synchronous rectifier is changed from 0.001ohms to 1000 ohms with steps of 10, the corresponding output power change is tabulated below. Inference is taken out from the table and compared with diode rectifier circuit. While changing the value of FET resistance, other parameters of circuit remained constant.

Table 12 Effect of varying rectifier diode resistance on power output

FET Resistance (Ohm)	Simulation Time (s)	Peak Power Output (W)
0.001	0.1	6.615
0.01	0.1	6.585
0.1	0.1	6.588
1	0.1	6.586
10	0.1	6.587
100	0.1	6.586
1000	0.1	6.586

From the above table it is evident that with increase in MOSFET FET resistance the power output remains unchanged. Hence any suitable value can be used.

Also the power output is much higher than diode rectifier. If efficiency is be calculated than:

Efficiency of Synchronous Rectifier to diode rectifier

$$= \frac{\text{Difference in power output}}{\text{Power output from Diode Rectifier}} = \frac{6.587 - 0.6828}{0.6828} = 8.64$$

Hence it is seen that efficiency of Synchronous rectifier over diode rectifier is 864%, as stated in reference [2].

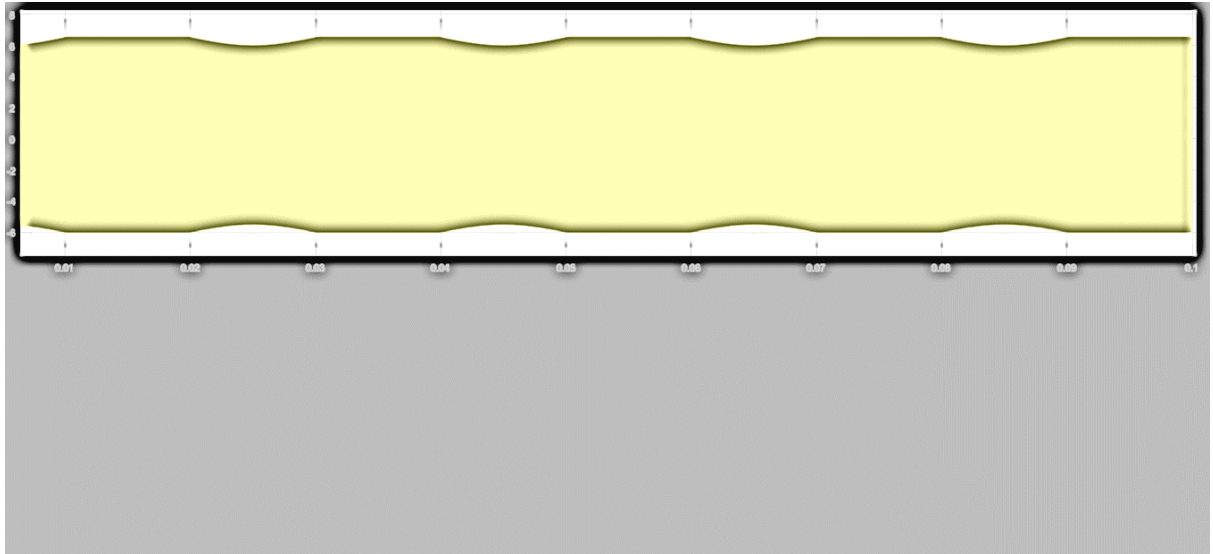


Figure 28 Power output from Synchronous rectifier Circuit

From above experimentation it is concluded that for optimal power supply to storage device the following systems and components must be employed:

- Synchronous Rectifier for AC-DC rectification with any MOSFET FET resistance
- Buck converter for voltage regulation
- Capacitance used in buck converter should be between 350-400 μ F.
- Inductance of value 0.1 μ H or less should be employed in buck converter

6.5.2 Battery Charging time calculation:

The Li-ion battery employed for storage has the maximum capacity of 2.3Ah. The current flowing through this at the upper given condition is 1.598 A, which is the peak value.

Hence the battery charging time for 100% charge will be:

$$\begin{aligned} \text{Charging Time } (t) &= \frac{\text{Rated Capacity}}{\text{Current flowing through it}} = \frac{2.3}{1.598} = 1.44H \\ &= 1\text{Hour and } 26\text{ minutes} \end{aligned}$$

6.5.3 Supercapacitor charging time calculation:

Model used in MATLAB SIMULINK uses Electric Double Layer Supercapacitors. It has the capacitance of 400 μ F. The current and voltage across this is calculated from MATLAB which shows current to be 0.51 A peak and voltage to be 3.776 V, which is acquired by employing the optimal charging circuit parameters.

From electrical knowledge the time to charge 100% will be:

$$\text{Charging time} = \frac{\text{Capacitance} \times \text{Voltage}}{\text{Current}} = \frac{400 \times 10^{-6} \times 3.776}{0.51} = 0.00296 \text{ s} \\ \approx 3 \text{ millisecond}$$

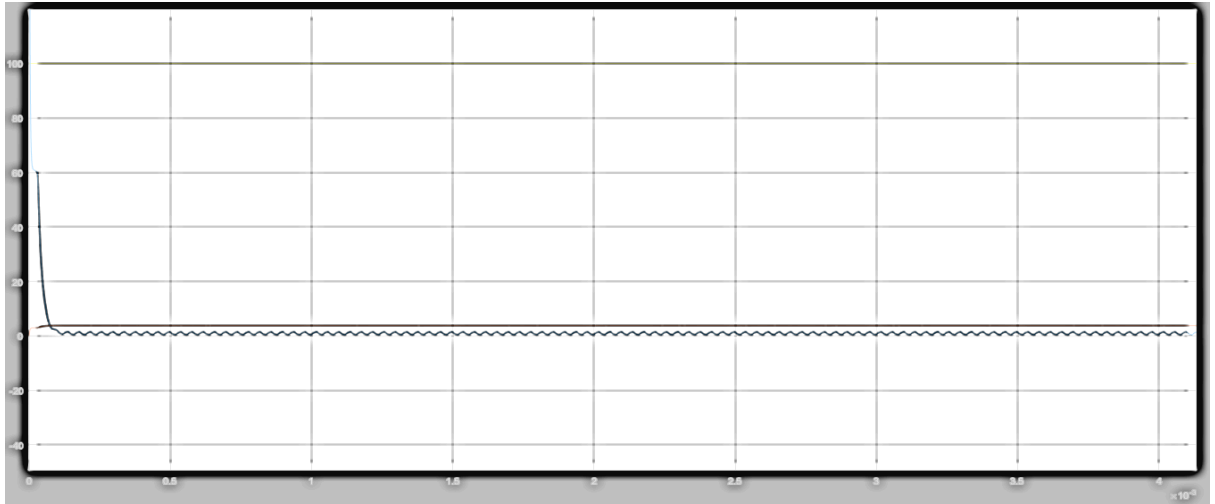


Figure 29 Battery Parameter Graph

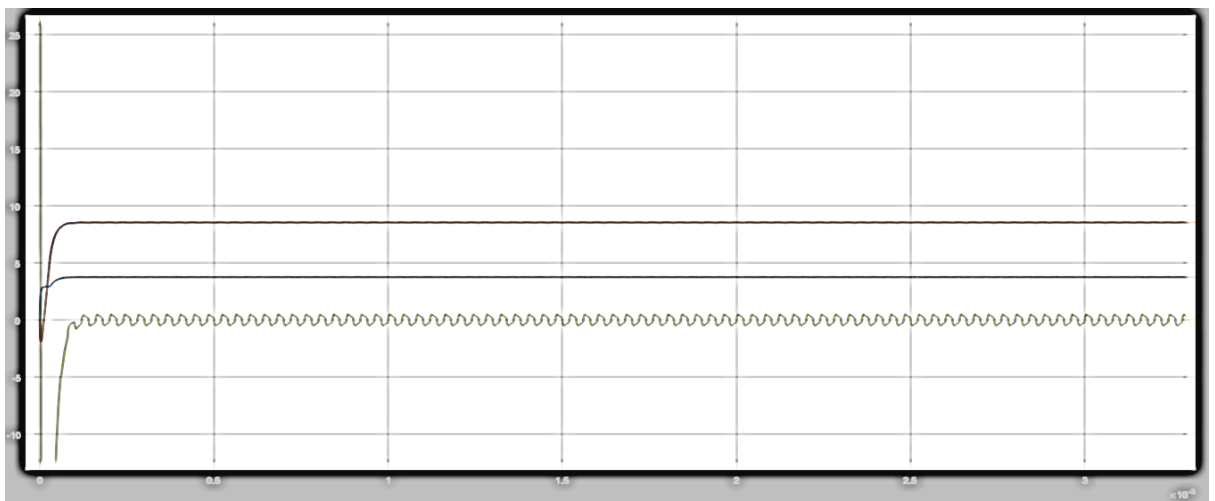


Figure 30 Supercapacitor Parameters Variation Graph

Chapter 7

Conclusion

With advancing time and technology and deescalating non-renewable energy sources, this human race is suffocating out of scarcity of power. Macro to micro every system built in this world needs power. Coming down to the micro application, power supply through conventional way has become obsolete and undesirable. Leaping towards renovations and alternatives, Vibration energy harvesting has been proved to be authentic and reliable for its omnipresence nature. This project focused on optimization of technique to extract the power from vibration.

Out of four choices for converting vibration to electrical energy, piezoelectric method is chosen. Out of Piezoelectric materials PZT 5h came out with flying colours. Taking a step towards modification Tapered or triangular shaped piezoelectric is used in bimorph form in a cantilever fashion. Equipping this structure with proof mass shaped like an optimal chosen air foil S1223 at the free end of cantilever to facilitate vibration from ambient air flow and to maximize power output. Also an angle to the cantilever provided at the fixed end to make it more susceptible to vibration. This angle was also optimized to make the lift higher at $5-10^0$. Voltage and frequency response were measured by using ANSYS software.

Taking the voltage from above storage system is built with utter optimization. Changing different parameters of the circuit, it is concluded to go with synchronous rectifier for AC to DC rectification purpose; Buck converter is used with inductance $400\mu\text{H}$ and capacitance $0.1\mu\text{F}$ as a voltage regulator. The output of which is connected to Li-ion battery and Electric double layered Supercapacitor for storage purposes. Using MATLAB SIMULINK power output was obtained as 6.587W at 0.3V input voltage with 50Hz frequency. Battery charging time was calculated to be 1 hour and 26 minutes. Furthermore battery is used as the primary storage device and supercapacitor is used as the secondary one.

Future Scope and Research

Further study may be granted upon by doing real time fluid interaction of piezo-electrics with air. Developing the structure for its commercial use will be next scope or research. Also Charging circuit optimization can be further escalated with the use of real time monitoring systems. This is very vast area to research on, if started there is a long way to go and still it will not enough.

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