Modeling and Simulation of MEMS Energy Harvester

Vinod Rajendran[R], PraveenkumarSukumar[F], Dr.L.Sujatha[P]
Research Associate[R], Assistant Professor[F], Professor[P]
Saveetha Engineering College[R,F], Rajalakshmi Engineering College[P]
Chennai, Tamilnadu, India [R, F, P]
vinod.rajendran@hotmail.com, praveenkumarsunil@gmail.com, sujathaln@rediffmail.com

Abstract-In future, demand on portable electronic devices will create the requirements of enduring recharged sources of power. A non-environmental friendly conventional battery with limited lifetimes has no longer feasible option. This work elucidate the design and simulation of MEMS based piezoelectric device which is capable of converting plenteous waste energy such as vibration asserted on the surface of various type of engines into electrical power. We at hand worked with theoretical modelling, Simulation and fabricating micro machined EHD. This novel design of energy harvester is capable of conserving energy from all kind of engines that we use in day to day life.

Note- the mechanical FEA was conducted using COMSOL and Intellisuite.

Keywords- EHD, PZT, COMSOL, Intellisuite, Engines, Micro machine, Simulation.

I. INTRODUCTION

Due to the fast depletion of non-renewable resources the concept in developing environmental energy harvesting Systems have attracted lot of attention among the researchers to concentrate on the generation of renewable energy sources.

From Newton's law of energy conservation, energy can neither be created nor be destroyed; it is converted to other forms of energy. From the above principle it is evident that the energy provided to a system can be utilised in many ways which must include efficient utilisation and promote conservation.

The idea of EHD is to detain the waste energy coming out from any systems and convert it to usable source of energy. Energy can be harvested from the environment using electrostatic, electromagnetic and piezoelectric transduction technique. Of the three mechanisms, piezoelectric transducer has been reported to hold the maximum output power.

We propose a novel idea to fabricate energy harvester in this work, which will also be suited for multi–environmental conditions like short duration vibrations and it can be designed according to the required application.

II. APPLICATION OVERVIEW

The intended application for the EHD is to scavenge energy from the low level vibration exerted from engines. Vibration spectrum indicates that automotive engines resonance frequency is between 100-200 Hz. The piezoelectric energy harvester has therefore been designed to work initially for this application although the principle of operation can be applied to variety of novel application.

III. THEORY OF PIEZOELECTRIC DEVICE

A. Basic Design parameters:

Piezoelectric material deforms in the presence of electric Field and vice-versa, it produces electrical charge when mechanically deformed.

B. Equations are defined as follows:

$$\delta = \sigma / Y + dE \tag{1}$$

$$D = \varepsilon E + d\sigma \tag{2}$$

Where,

δ = Mechanical strain (µm/µm)

σ = Mechanical stress (µN/µm2)

Y = Modulus of elasticity (Young Modulus) (µm2/µN)

d = Piezoelectric strain coefficient

E = Electric field

D = Electrical displacement (charge density)

$d\sigma$ = Dielectric constant

Piezoelectric material selection is based on coupling Coefficient (k) which indicates the material's ability to convert mechanical energy to electrical energy or vice versa.

$$k = \sqrt{\frac{Y}{\varepsilon}}\, d \tag{3}$$

Materials which have larger coupling coefficients have Higher energy conversion efficiency .The modulus of Elasticity (Y) affects the stiffness of the bender. While, a high dielectric constant (ε) lowers the source impedance and is preferable for energy harvesters.

IV. DEVICE STRUCTURE WITH TIP MASS

The cantilever structure with tip mass at the end, Identified as the best suitable structure for maximum energy conversion design .The natural frequency of spring mass system, ωn .

$$\omega_n = \sqrt{\frac{K}{M}} \tag{4}$$

The model of the power output of the system at resonance is where m is the seismic mass, Y is the amplitude vibration(w) is the system resonance frequency and ζ is the relative damping ratio.

$$P_{max} = \frac{m\omega^3 Y^2}{4\tau} \qquad (5)$$

The output power is directly proportional to mass which means that the converter size directly impacts the power output produced. Power is inversely proportional to the damping ratio, which is directly related to selection of Materials and design. Output power of the system will be optimized if the piezoelectric system is operating at the resonance frequency.

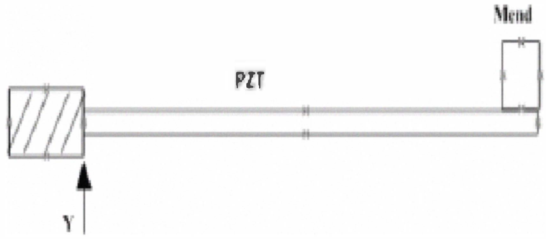


Figure 1.PZT cantilever structure

V. OPERATING MODE OF PZT BEAM

Two frequent modes that are applied for energy harvesting devices are d_{33} mod (longitudinal effect) and d_{31} mode (transversal effect)(see Fig 2). Ind_{31} mode, the stress is applied in axial direction but the voltages obtained in perpendicular direction. In contrast, for d_{33}mode, the applied stress has the same direction as the generated voltage. The d_{31} mode has separate top and bottom electrodes while the d_{33} mode employs only the interdigitated top electrode.

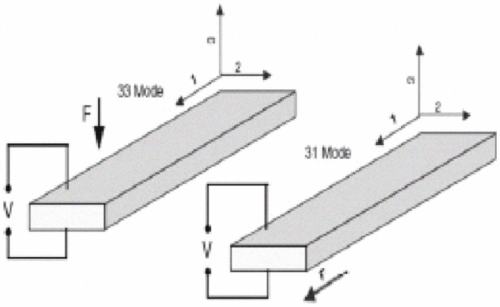


Figure 2.peizoelectric operating modes

VI. DESIGN STRATEGIES

A variety of modelling approaches have been used to analyse the power outputs of the EHD. According to several researches, it was concluded that, the harvested power depends on the input vibration characteristics (frequency and acceleration), the mass of the generator, the electrical load resistor, the natural frequency, the mechanical damping ratio, and the electromechanical coupling coefficient of the system.

Hence based on the above study, we can understand how the cantilever based piezoelectric EHD affect the electrical outputs of voltage, current, and power and also the displacement amplitude and resonant frequency shift. With this understanding, design strategies are drawn for each geometric parameter.

Designing a model with the aim of generating more power, the following strategies can be used:

1. For the beam a shorter length, larger width, and lower ratio of piezoelectric layer thickness to total beam thickness are preferred in the case of a fixed mass.
2. For the mass, a shortened mass length and higher mass height are preferred in the case of vibration in the mass length and the mass height with mass width and mass value remain fixed, and a wider width and small mass height are preferred in the case of vibration in mass width and height (mass length and value remain fixed).
3. For the case of fixed total length, a shorter beam length is preferred. It can be seen that with such design strategies, the output power of the devices can reach around 1 to 2 mW/cm^3.

VII. PROPOSED WORK

The proposed work consists of two parts(see fig.3), Design of low level vibration energy harvester using Intellisuite and hardware implementation of existing model available in the market and validates the prominence of our model presented in this paper.

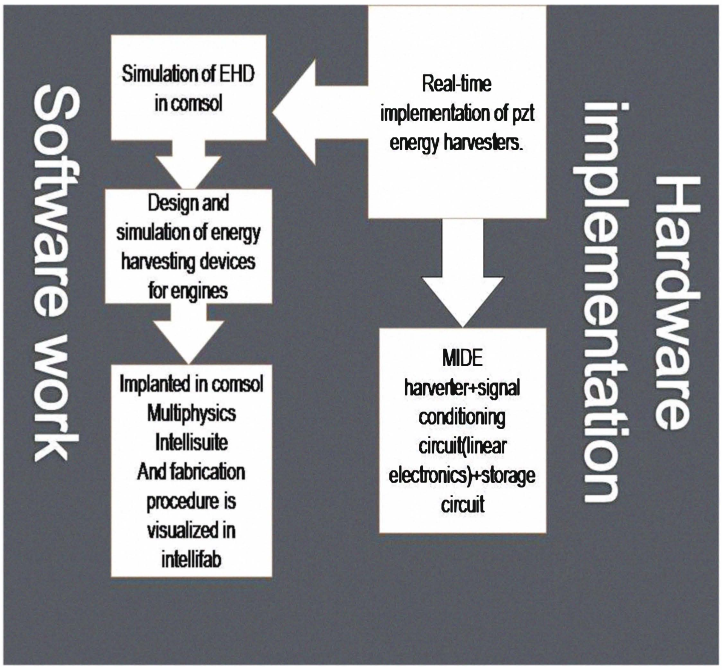


Figure3. Show the overall flow of our work

VIII. SYSTEM LEVEL MODELLING

The PZT cantilever structure consists of five layers namely Si, Sio2, PZT, Cu, Tungsten (proof mass) (see Fig.4). The substrate is chosen as Si 110 symmetry bulk standard, flowered by a layer of insulating sio2 and piezoelectric material is PZT. The electrodes are deposited on top of the PZT, proof mass or tip mass is made up of tungsten where the mass is varied to vary the natural frequency of the structure. Additional power is produced while changing the dimension of the proof mass to suite the environment.

The above device is modelled and analysed using finite element simulator, Intellisuite which has the capability of modelling 3d structure using Intelli-3d builder and Tem module to analyze the structure.

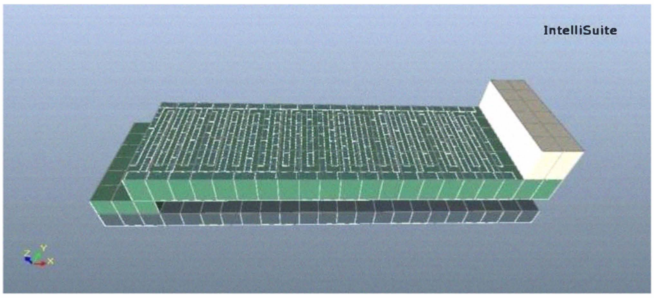


Figure4. Side view of the PZT EHD structure

The aim of the simulation analysis is to simulate the structure which capable of producing the maximum output power at a resonance frequency of 200 Hz. A mechanical finite element simulation was conducted using Intellisuite.

IX. DEVICE GEOMETRY AND BOUNDARY CONDITION FOR FEM SIMULATION

The structure goes with five different layers with the device with the dimensions as follows

TABLE I. MICRO MACHINE GEOMETRY

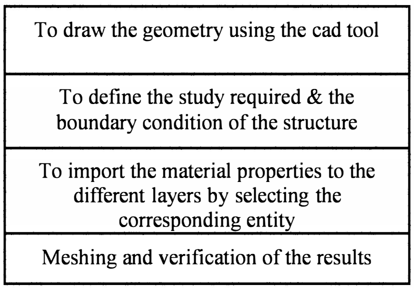
Material	**Length (um)**	**Width (um)**	**Thickness (um)**
Silicon	230	60	10
Sio2	50	60	30
PZT			
Layer 1	216	60	10
Layer 2	30	60	10
Copper			
Horizontal	3	45	1
vertical	185	5	1
Tungsten	20	60	10

Above table shows the device dimension and the model was then exported to Intelli-TEM to analysis the device characteristic under external acceleration.

The boundary conditions were initialized in the first stage of simulation using FEM solver. The boundary conditions were,

- All the faces of silicon is fixed (i.e. substrate is fixed to the base)
- One end of the silicon dioxide and PZT were fixed (i.e. to achieve the cantilever prototype).
- The bottom face of the PZT was made free, which is the vibrating portion of the device.

The overall steps involved in FEM simulation is as follows (refer Figure.5)



To draw the geometry using the cad tool

To define the study required & the boundary condition of the structure

To import the material properties to the different layers by selecting the corresponding entity

Meshing and verification of the results

Figure 5. Block shows the process flow in FEM

The piezoelectric constant was defined in d33 mode because of the following reasons, the d33 piezoelectric mode is more eligible for the energy harvesting of low-level vibration, because the d33 mode can generate a larger voltage than the d31 mode with less displacement

of the cantilever, due to the following structural and material property issues. The output voltage of d33 mode is more sensitive to the induced vibration than d31 mode. The other properties to be noted is the mass of the tungsten since the proof mass adds to the resonance frequency and the output voltage. The density was taken as 17000(Kg/m3), silicon is taken as bulk standard and the Sio2 is chosen with high resistivity because it provides the electric insulation between the positively polarized PZT and the Si ground.

TABLE II. MATERIAL PARAMETERS FOR FEM SIMULATION

Material parameter	**Values**
Substrate material(Si)	
Young's modulus(Gpa)	110
Poisson ratio	0.23
Density (Kg/m3)	2330
Insulating layer sio2	
Resistivity(ohms)	210
Piezoelectric material	
Young's modulus(Gpa)	
E11	62
E33	50
Elastic constant(Gpa)	
C11	110.8
C12	49.8
C13	49.8
C33	110.8
C44	30.5
Density(Kg/m3)	7800
Piezoelectric constant	
D33(x10-12m/volts)	650
Coupling coefficient	
K33	0.75
Tungsten(tip mass)	
Young 's modulus	400
Poisson ratio	0.28

X. MECHANICAL MODEL ANALYSIS SIMULATIONS

Mechanical model analysis or stress and displacement analysis was done by placing 1000pa pressure at the end of the cantilever beam. The results show that the highest displacement occurs in z direction as shown in the figure6.

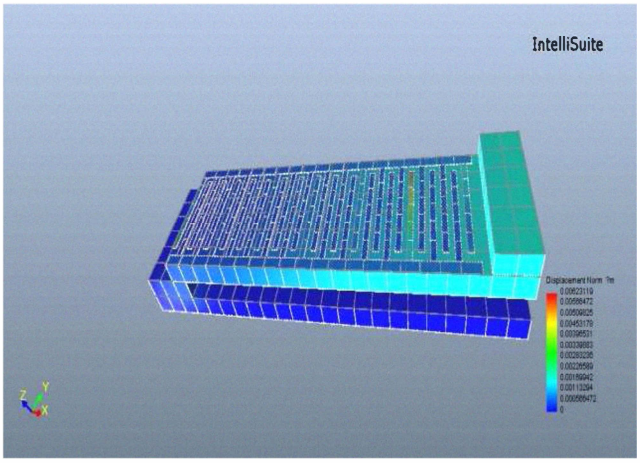


Figure 6. 3D view of Displacement of the cantilever beam

Further moving on to the potential plot the modal developed a voltage of 14v which was measured at open circuited condition for 1000pa of pressure(see fig.7). The 100ohms resistor was connected to the electrodes and the power was measured to be around 10mw in range.

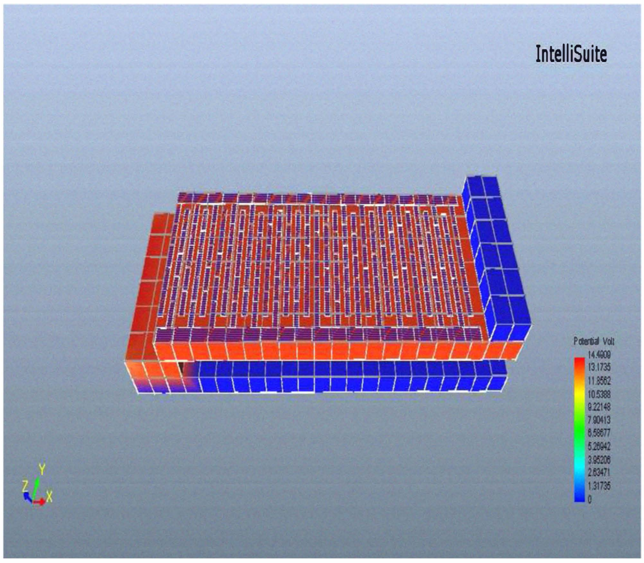


Figure 7. Shows the potential distribution for the applied pressure (with the peak voltage of 16v).

XI. NATURAL FREQUENCY DEVICE ANALYSIS

The Eigen frequency analysis were computed for the structure, Results prevail the frequency range of the device were about 200hz. The harmonic analysis computes a displacement solution based on a user range of input frequency to find the best resonance frequency which has the maximum displacement. The graph shows the displacements Vs resonance frequency of the device.

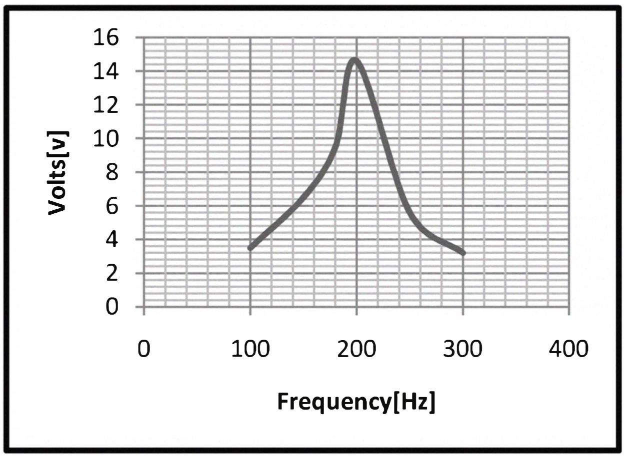
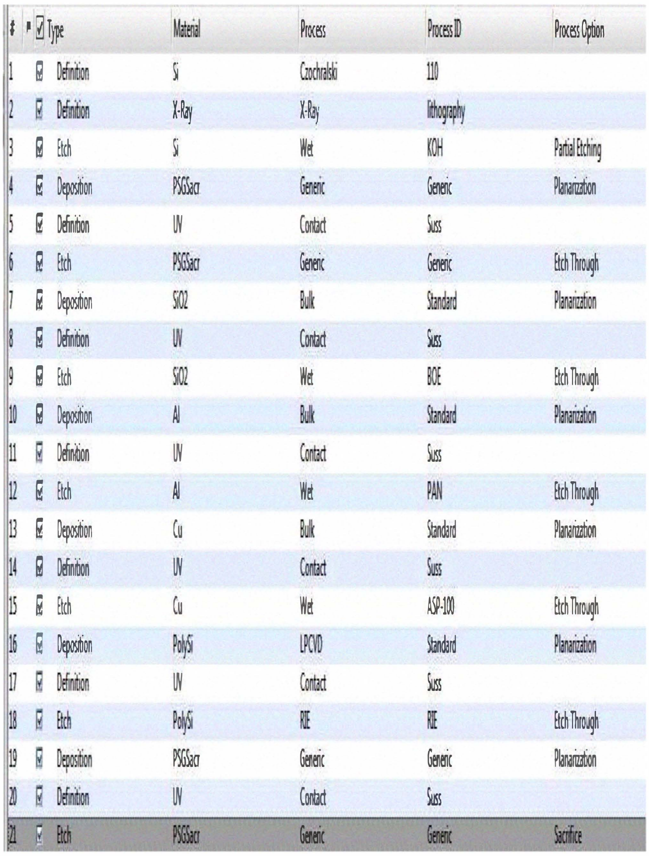


Figure8. Displacement vs Frequency of Piezoelectric Device

XII. FABRICATION STEPS OF PIEZOELECTRIC ENERGY HARVESTER

The virtual fabrication was done with the help of Intelli-Fab tool, were the mask layers were drawn using intelli mask. The fabrication outline includes Deposition, Definition of mask, Etching with surface is cleaned after every deposition. In this we adopted bulk micromachining procedure and deposition type was planarization to increase the flatness of the surface in order to achieve the cantilever structure.



#	☑	Type	Material	Process	Process ID	Process Option
1	☑	Definition	Si	Czochralski	110	
2	☑	Definition	X-Ray	X-Ray	lithography	
3	☑	Etch	Si	Wet	KOH	Partial Etching
4	☑	Deposition	PSGSacr	Generic	Generic	Planarization
5	☑	Definition	UV	Contact	Suss	
6	☑	Etch	PSGSacr	Generic	Generic	Etch Through
7	☑	Deposition	SiO2	Bulk	Standard	Planarization
8	☑	Definition	UV	Contact	Suss	
9	☑	Etch	SiO2	Wet	BOE	Etch Through
10	☑	Deposition	Al	Bulk	Standard	Planarization
11	☑	Definition	UV	Contact	Suss	
12	☑	Etch	Al	Wet	PAN	Etch Through
13	☑	Deposition	Cu	Bulk	Standard	Planarization
14	☑	Definition	UV	Contact	Suss	
15	☑	Etch	Cu	Wet	ASP-100	Etch Through
16	☑	Deposition	PolySi	LPCVD	Standard	Planarization
17	☑	Definition	UV	Contact	Suss	
18	☑	Etch	PolySi	RIE	RIE	Etch Through
19	☑	Deposition	PSGSacr	Generic	Generic	Planarization
20	☑	Definition	UV	Contact	Suss	
21	☑	Etch	PSGSacr	Generic	Generic	Sacrifice

Figure9. Shows the fabrication procedure in intelli-fab

The below fig shows the fabricated cantilever model with fabrication output yielding the same results.

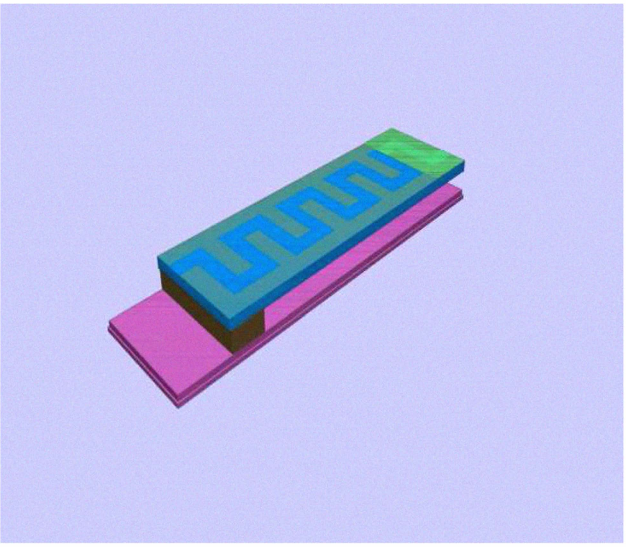


Figure10. Shows the 3d view of the fabrication model in Intelli-fab

XIII. HARDWARE IMPLEMENTATION

The basic idea of the paper is not only to model piezoelectric EHD but also to provide a model which suites the real time application. Towards that the modelling work were done to suite in the car engines, i.e. to utilize the free vibration from car engines and convert it into useful energy. The main parameter which was considered towards the design is the resonant frequency which as to be optimized to the frequency of vibration in car engines. The experimental verification shows that about 100-230 Hz is vibrating frequency of engines and our above proposed work is designed to a frequency of 200 Hz, thus delivering the maximum output.

The next step of our work is to tell between its greatness from the existing model available in the market. The V21b from MIDE was used for the statistical study(seefig.10), in which the signal conditioning circuit was designed to filter and the harmonics flowered by dc to dc convertor and the buck boost converter to provide ma output.

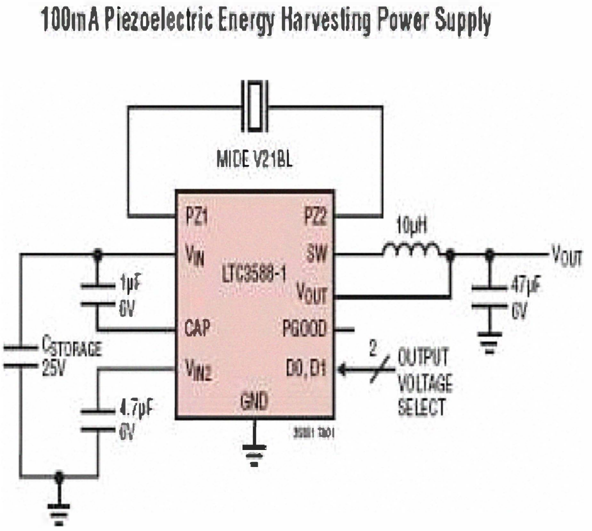


Figure 11. Signal condition circuit of PZT energy harvester.

The MIDE PZT was encapsulated in a thermal insulator cover in order to avoid the high temperature of engine affecting the MEMS energy harvester, It was mounted on to a car engine where the speed was maintained in 100km/s. The output power of that will be 2-3uwatts.

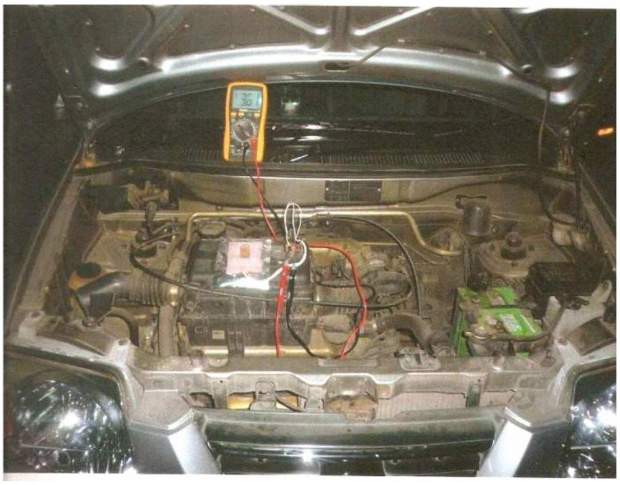


Figure12. PZT EHD mounted on the surface of the car engine

XIV. LITERATURE SURVEY ON PREVIOUSLY REPORTED MEMS PIEZOELECTRIC ENERGY HARVESTING DEVICE

TABLE III. ESTIMATED DATA FROM REFERENCES

Ref paper No	**Dimension of cantilever structure**	**Resonance Frequency**	**Power**	**Amplitude**	**Acceleration**
[1]	1000x800x10 (um3)	525-530 (Hz)	0.4 (uw)	1.2(v)	0.4 (g)
[2]	-----	90-13998(Hz)	300 (uw)	-----	7.2 (g)
[5]	71x23(um)	34.4 (KHz)	---	2.7(v)	---
[6]	6x3.1x0.278 (mm)	160(Hz)	372 (uw)	16.1 (v)	----
[8]	Mm scale	57(Hz)	2.7 (mw)	----	----
[9]	0.566X4.0 (mm)	500(Hz)	15 (uw)	4 (v)	17.11 (mg)
[12]	2.00x1.50x0.003 (mm)	53.8(Hz)	13.0 (mw)	30.57(v) (30 k ohms)	----

XV. FUTURE WORKS ON MEMS PIEZOELECTRIC ENERGY HARVESTING DEVICE.

To Fabricate the modelled Energy Harvester, to analysis the structure at real-time conditions and proceeding our model for final stage packaging to get a complete product to prevail in the market . The next stage of our research work is to work on with coupling the different energy generation physics on to a single membrane, such as a device be capable of producing energy out of both vibration and heat.

XVI. CONCLUSION

The mechanical finite element simulation of a novel MEMS Piezoelectric Energy Harvesting device was effectively modelled and the statistical comparative study of the novel EHD with existing design available in the market to scavenge energy from low vibration. The distinguishing features of our design is

- Maximum power output.
- Low Frequency optimization to suite the application.
- Easy to fabricate procedure easy availability of resource.

In order to optimize the design for low level vibration energy, multilayered cantilever structure with tungsten proof mass in order to adjust the resonant frequency. In order to achieve the large output the zigzag electrode was employed for d33 mode operation, with the dynamic modelling and results presented. The virtually fabricated model was subjected to various excited frequencies, low level vibration.

ACKNOWLEDGEMENTS

We would like to thank Mr.N.vijayram, Mr.S.srinivasan, Mr.M.vijaykumar of Department of Electronics and Communication at Saveetha Engineering College for their generous assistance and laudable works contributed.

REFERENCE

[1]. Jong cheol park, Jae yeong park and yoon pyo lee“ Modeling and characterization of piezoelectric d33 mode energy harvester” journal of micro electromechanical systems, vol19, no5, October 2010.

[2]. D.blazevic,S.Zelenika and G.gregow ”mechanical analysis of piezoelectric vibration energy harvesting devices” mipro 2010,may 24-28,2010,optatijia,Croatia.

[3]. Sh.priya and D.j inman (ed.),energy harvesting technologies, springer,newyork, 2009.

[4]. www.mide.com/products/volture/volture_catalog.php

[5]. Aliza aini md ralib.Anis Nurashikin Nordin,hanim salleh “Simulation of am mems piezoelectric energy harvester “ dtp 5-7 may 2010, Seville, spain.

[6]. Meiling zhu,emma Worthington and ashutosh tiwari “Design study of piezoelectric energy harvesting devices for generation of higher electrical power using a coupled piezoelectric circuit finite element method” ieee transcation on ultasonics,ferroelectric and frequency control , vol 57,no2 ,February 2010.

[7]. S.roundy ,P.K.wright and J.rabaey, ”A study of low level vibrations as a power source of wireless sensor nodes”, comput.commun.,vol 26,no11,pp.1131-1144,2004.

[8]. Mykola pereyma “Overview of the modern state of the vibration energy harvesting devices”

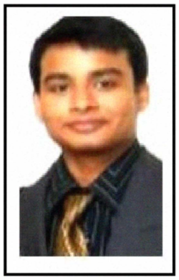
[9]. Lars-curil julin blystad, einar halvorsen,svein husa“Piezoelectric mems energy harvesting systems driven by harmonic and random vibration” ieee transcation on ultasonics,ferroelectric and frequency control ,vol 57,no4 ,February 2010.

[10]. R.N.torah,M.Jtudor,K.patel,I.N.garcia,S.P.beeby“Autonomous low power microsystem powersd by vibration energy harvesting “

[11]. http://www.linear.com/product/LTC3588-1

[12]. Geffrey k.oyyman,health F.hofmann,archin c.bhatt and George A.lesieutre ”adaptive piezoelectric energy harvesting circuit for wireless remote power supply”

BIOGRAPHY ABOUT THE AUTHOR



Mr. R. Vinod, is a Research Associate at Saveetha Engineering College, Chennai in the Department of Electronics and communication Engineering. He has 1 Year of Research Experience. He has presented his work in 1 International conference. His area includes MEMS Device modelling He is more Specialised in MEMS Energy Harvesters.

Mr. S. Praveenkumar, working as Assistant Professor, ECE at Saveetha Engineering College, Chennai. He has 6 years of Teaching Experience. He has presented his work in 5 International conferences. He has 1 publication in international journal. He got the Best Teacher award for the last consecutive years. His research area includes MEMS, VLSI.

Dr. L. Sujatha, Professor & Head in the Department of Electronics & Communication Engineering, Rajalakshmi Engineering College has fourteen years of teaching and five years of research experience. She has done her Ph.D. research in the field of Micro Electro Mechanical Systems (MEMS) at Indian Institute of Technology Madras and graduated in 2008.She Established a National MEMS Design centre at her institute and claimed a project worth 10 Lakh Funded by AICTE. She has 4 publications in refereed international journals. Also, she has presented her work in 10 International Conferences. She has attended the SPIE conference at USA twice and presented her research work in the conference. She has received a “Best Poster Award” for her research work presented at IWPSD, IIT Bombay and a “Best Woman Engineer” from Pondicherry Engineering College. Her research interests are fabrication of chemical and bio sensors.