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Model and Performance Analysis of Piezoelectric Energy Harvester System for Different Harvester Beam Configurations

T. Ramachandran
Research Scholar
Electrical and Electronics Enginnering
Faculty of Engineering and Technology
Subharti Institute of Technology and Engineering
Swami Vivekanad Subharti University, Meerut, India
Email: ramspowerthangamugam@gmail.com

Aruna Bansal
Supervisor
Faculty of Engineering and Technology
Subharti Institute of Technology and Engineering
Swami Vivekanad Subharti University, Meerut, India
Email: arunabansal75@gmail.com

Abstract— Electricity is one of the main energy resources will be used to operate many devices and appliance for making human life as comfortable. In many of the applications the small electronics equipments or devices are used which requires power in milli Watts, micro Watts, nano Watts. This small power requirement devices are gets power form battery which is nowadays replaced by the PEH energy technology. There are many configurations are used and modeled to improve the power performance of the PEH. This paper is focus on the improvements of the PEH through the continuous beam, segmented beam with tip mass and clamped – clamped continuous beam harvester. The performances of the harvesters are analyzed with the factor like voltage generation, power generation, strain stress imposed on the harvester like that. The major difficulty in the use of PEH harvester to obtain electrical energy from the vibrations or motion energy is that the output power is very less; efficiency is very poor during the low frequency periods. The vibration frequency is not at all same for all duration of vibration. So, the vibrations in the frequency reduce the output of PEH particularly at low frequency situations. So, finding and designing a suitable PEH to produce high output power in any field of vibration energy source available.

Keywords— Piezoelectric energy conversion, PE harvester modeling, cantilever beam, clamped – clamped beam, Results and discussion, PEH performance comparisons

I. Introduction

In the automation field the electronics devices and equipments are very important because, the control circuit, measuring circuit, sensing circuits will be of electronic circuits. These circuits normally need of very low power supply to energize the elements which are present in the circuit. This low power elements and or equipments can get power from decentralised small sand small power producing units such as from PEH souse. The PEH generates th4e electrical energy from the vibration based energy source of any moving body. Many electronics devices are wearable which can also be get power input for their sensing units from low power generator device like PEH module. Wearable electronics devices electronics watches, smart watches, digital watches [1-3], smart glass contactless headsets should be avoided having the battery as energy recourse. Because the use of battery as energy recourse for a device makes it such devices more bulk in size. So in this kind of electronics device applications the power supply mechanism will from the piezoelectric harvesting technique is more prefer nowadays. So, best choice for energy supply to mobile electrics devices and sensing device would be is vibration energy source enable power supply module.

There are various piezoelectric harvester beam configurations are in the process of research in order to improve the harvesters performance and increase the voltage generation and power out puts.. At different frequencies the power can be generated from the PEH which is feed input from the vibration energy source. Two factors in particular decide the performance of PEH such as piezoelectric materials properties in electromechanical coupling, geometry of the device in converting the electrical energy efficiently from the mechanical energy. In the field of IoT applications, automatic device control and other electronics applications, the low power electronic device and sensing devices are used.

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The recent technological development shows that the providing self power to the low power electronics device will be the better and best for the different mechanism but among them the piezoelectric conversion technique is best suitable for low power generation form the vibration sources.

Energy in the form of vibration is present in house appliances, industrial machines, motion systems. These energy are freely and feed to the electric devices. Among the three technological approaches the concept of piezoelectric is more reliable and best suitable approach for vibration based energy harvesting system for low power electronics devices.

Piezoelectric materials play important role in improving the energy conversion efficiency without need of any additional power. The piezoelectric materials show that they can be easily fabricated at any level of scale such as macro, micro, and nano etc. The maximum power is harvested by the piezoelectric energy harvesting system when the resonant frequency matches with vibration frequency of excitation system. At this situation, the system ensures that the maximum vibration energy is converted in to electrical energy from the vibration source. Any deviation from the resonance will cause decrease the output electrical energy comes out from the harvester. Charge cancellation is one of the main factors which also reduce the voltage generation of the harvester. For this effect the segmented Beam harvesters are used. But still uniform strain and stress is not imported on the harvester. So, the clamped –clamped configurations with top side force applied to the harvester beam proofs the uniform strain stress imposed on the harvester. The uniform strain stress ensures the life of the harvester and maximum optimum use of the piezoelectric materials. So, different harvester beam configurations are analysed with various parameters like voltage generation, materials need, output power, performance improvements on the efficiency of the system has been analysed and results were compared. The results shows that the uniform strain stress is achieved in clamped –clamped harvester configurations than that of the continuous harvester beam configurations.

II. PIEZOELECTRIC ENERGY HARVESTER (PEH)

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There are many and several research publications discussed about the different configurations of piezoelectricity harvesting technique and various beam configurations and segmented harvester beam with continuous beam configurations with tip mass configurations, clamped –clamped beam harvester configurations [4]. In all different cases the basic principle is the conversion of the vibration based energy of mechanical vibration in to electrical energy. The basic block diagram of the piezoelectric energy harvesting technology is remaining same.

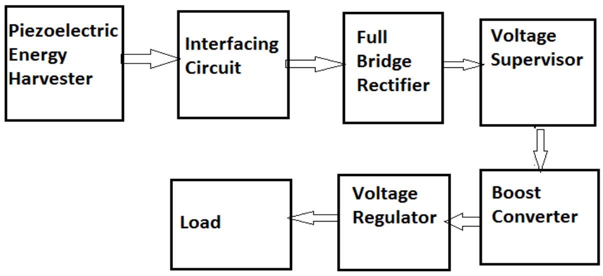

Fig.1 schematic diagram for piezoelectricity generation

The fig, 1 shows the basic schematic diagram represent the piezoelectricity generation system. The external force and /or acceleration from the vibration source is applied to the piezoelectric layer. Then this applied mechanical energy is converted in to electrical energy by the piezoelectric material. The interface circuit is used to collect the output from the piezoelectric harvester. After that the full bridge rectifier ensures the pure DC. This DC also go through the voltage supervisor and boost converter [5]. At last the load gets the electrical energy from the voltage stabilizer and or the voltage regulator. Factors that are limiting the energy transfer to the load are input energy available from the vibration source, efficiency of piezoelectric material, and the efficacy of the power transfer circuit and different types of configurations of the harvester beam.

III. MODELING OF HARVESTER BEAM

The power generated through the piezoelectric energy harvester system is very small in rating of the power. The powers needed to give the supply to the sensing power electric devices are also in the range of milli, micro and nano watts. Continuous harvester beam, segmented harvester beam and different shape configurated beam harvesters are also in the research as part of the requirements of the improvements of the power output of the energy harvester. This section discusses the modelling of piezoelectric energy harvester with different configuration.

Most of the cases the PEH have the cantilever boundary conditions as common configurations [6-7]. In this cantilever arrangement one end is fixed whereas the other end is free configuration conditions provide non uniform stress and high stress near the clamped line. Because of this two conditions the harvester provide low power for the low stress area, and structure failure may occur for the high stress region, due to this two reasons the cantilever configuration with one end fixed and others one is free from fixing is not best suitable configuration in the piezoelectric energy harvesting technology. In this paper the cantilever beam boundary conditions numerical results on COMSOL is also compared with the new proposed PE harvester configurations. Both of the PE harvester boundary conditions are analyzed with a applied static force with the consideration of electromechanical coupling effect. The figure 3.1 shows a PEH cantilever with applied static force with tip mass on it, indicates the non uniform distribution of stress over the length

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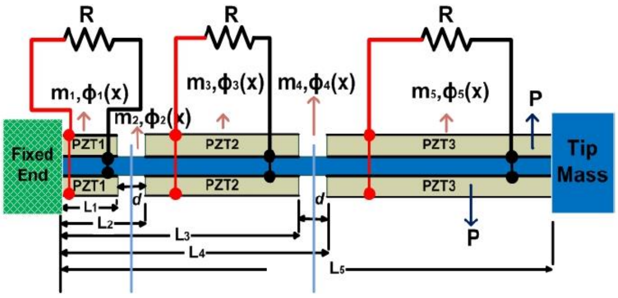

Fig. 3.1 segmented harvester beam cantilever with tip mass

The segmented harvester beam with tip mass configuration is used for the improvement of the harvester performance and to reduce the charge cancellations effects of the harvester. In comparisons with the performance of the continuous configurations and segmented configurations the performance has been improved and the effects of the charge cancellations are also improved in the segmented harvester beam configurations.

The continuous piezoelectric beam of the harvester is segmented to improve the harvester performance and reduce the effect of the charge cancellations occurs in the harvester due to the sign polarity changes of the strain. Further to reduce the effect of charge cancellations in the higher vibration modes the harvester beam segmented at the position of strain node for the cantilever structure. The electrical response of the harvester can be collected in individually from each segment of the harvester beam or can be collected as total response from the segmented beam to improve the efficiency of the harvester on the higher modes of vibrations [7-9]. The full length of the harvester beam divided in to three discrete layer of the harvester beam. It has been show in the fig. 3.2a and b

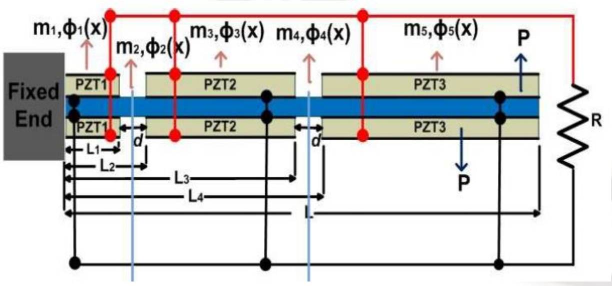

Fig3.2a Electrical response collected as total with R

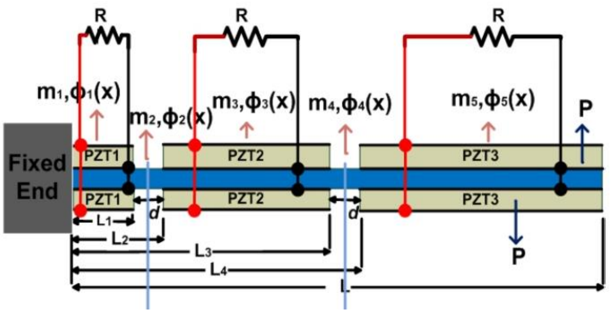

Fig3.2a Electrical response collected as individually with separate R

The electrical response equations are as below [9]

$$-r_\rho b\int_0^{L_1}\frac{\partial^3 w(x,t)}{\partial t\partial x^2}-\frac{e_{33}b(L_1)}{h_p}\frac{dv_1(t)}{dt}=\frac{v_1(t)}{R_l};$$

$$-r_\rho b\int_{L_2}^{L_3}\frac{\partial^3 w(x,t)}{\partial t\partial x^2}-\frac{e_{33}b(L_3-L_2)}{h_p}\frac{dv_2(t)}{dt}=\frac{v_2(t)}{R_l};$$

$$-r_\rho b\int_{L_4}^{L}\frac{\partial^3 w(x,t)}{\partial t\partial x^2}-\frac{e_{33}b(L-L_4)}{h_p}\frac{dv_3(t)}{dt}=\frac{v_3(t)}{R_l};$$

With the cantilever continuous beam harvester or segmented beam harvester of discrete segmented beam harvester the improvements are there as far as charge cancellations are concern and efficiency of the harvesters are concern but the strain stress distributions are not uniform in the harvester but it is higher on the tip mass end where as its low at fixed end. This non uniform strain stress imposed on the harvester does not allow the proper use of the materials and life of the harvester also reduced. So, to overcome this drawback of the cantilever with tip mass continuous, segmented configurations the clamped –clamped configurations with top clamped the force is applied [10-11].

The force is applied to the top clamp which is transfer the force stress in to the harvester beam. The harvester beam is not directly getting the applied force. The harvester beam is presented in between the two clamps as shown in the fig.3.3a and b

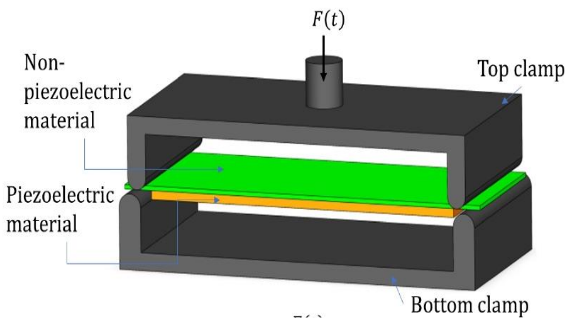

Fig.3.3a Two clamped harveser beam

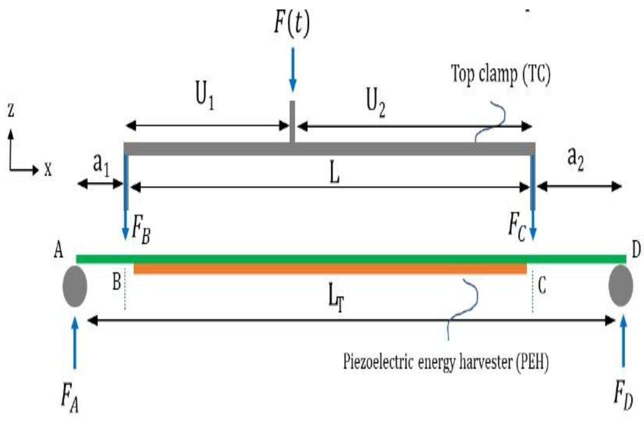

Fig.3.3b Two clamped harveser beam configuration

In the clamped – clamped configirations the motion's differential equation write as below

$$YI\frac{\partial^4 w(x,t)}{\partial x^4} + C_a\frac{\partial w(x,t)}{\partial t} + m^*\frac{\partial^2 w(x,t)}{\partial x^2} +$$

$$\mathcal{P}V_R(t)\left(\frac{d\delta(x-x_i)}{dx} - \frac{d\delta(x-x_f)}{dx}\right) = Q(x,t)$$

The coupling coeefficit of the force is given as below

$$\sigma_n = -\left(\left(1-\frac{U_1}{L}\right).\phi_n|_{x=a_1} + \frac{U_1}{L}.\phi_n|_{x=L_T-a_2}\right)$$

The electrical equation of the two clamped harvester is given as below

$$C_P\frac{dV_R(t)}{dt} + \frac{V_R(t)}{R_L} = I_p(t)$$

With the configuration of the two clamped beam piezoelectric energy harvester the conversion efficiency and performance of the harvester has been improved. In addition to that the materials used are saved and uniform strain stress relations are achieved.

IV. MODEL RESULT ANALYSIS

The model analyses of different piezoelectric harvester beam configurations are done in the previous section. The different configurations are used to improve the performance of the harvester and efficiency of the harvester. In addition to this to reduce the effect of the charge cancellations of the harvester due to the sign changes of the strain is also taken in to the account. In each of the configurations there are some improvements in voltages, power and strain stress distributions are reported in the results. Through the segmentations the performance of the harvester at higher mode of the vibrations are improved. The clamped free configurations with tip mass harvester's performance are compared with the continuous cantilever harvester bream configurations.

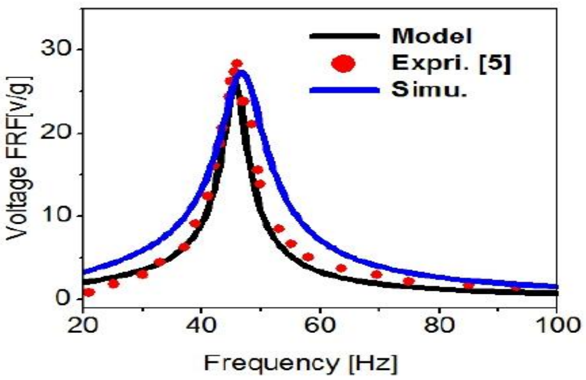

Fig.4.1voltages for 1st mode vibration of segmented harvester

The segmentation of total capacitance in parallel with source is done. Due to this reasons the power is increased by 10mW. Because of the addition of parallel current sources, the charge cancelations are nil in the 1st vibration mode. The way how the power is improved and the same way the band width and power output of the segmented PZT harvester has been increased from 1.12 and 14.46 times from the continuous harvester layer configuration for the 3rd vibration mode

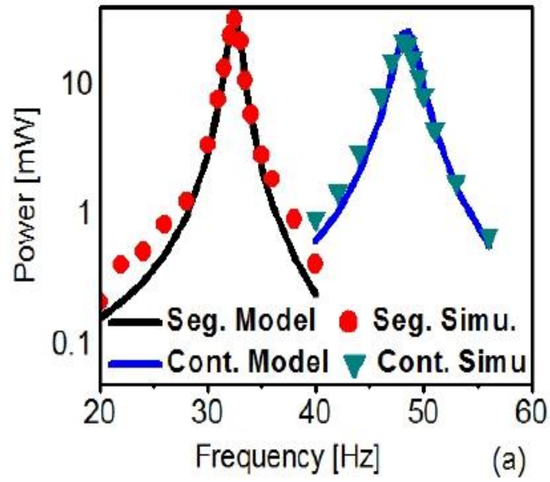

Fig.4.2 power output for 1st mode vibration for optimum load cantilever segmented harvester

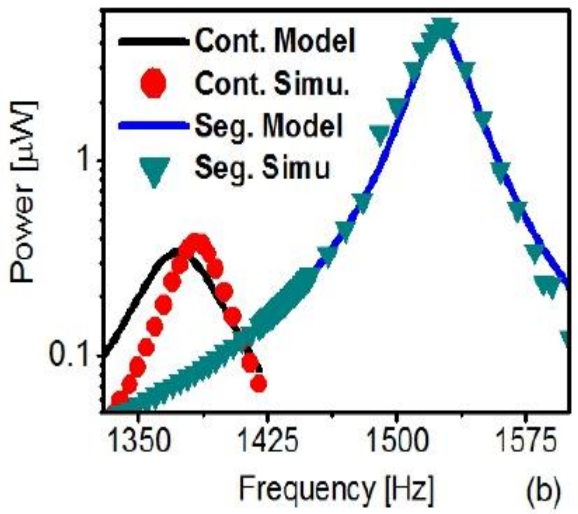

Fig.4.3 power output for 3rd mode vibration for optimum load cantilever segmented harvester

But the 3rd natural frequency of the segmented harvester is higher than cantilever spring effect and hence the motion is opposite to the cantilever spring effect [12]. This results as higher resonance frequency in segmented PZT in comparison with the continuous PZT layer configurations. The strain distribution to the near areas of the 3rd segmented PZT layer is less and hence the coupling factor of the concern 3rd segmented PZT is also small. This is represented and shown in figure 5.4. The 3rd segmented PZT layer produce more power at 3rd vibration mode due to the more strain at 3rd vibration mode in the segmented layer of PZT3. Each segmented PZT layers are

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having lesser and smaller resonance frequency than that of the case of continuous layer PZT harvester configurations. But which is not true for 3rd vibration mode. Because in case of 3rd vibration mode the 3rd natural frequency of the PZT layers of segmented harvesters has greater than the normal cantilever spring effect, which in turn, result the coupled system motion in opposite to the cantilever spring effect[14]

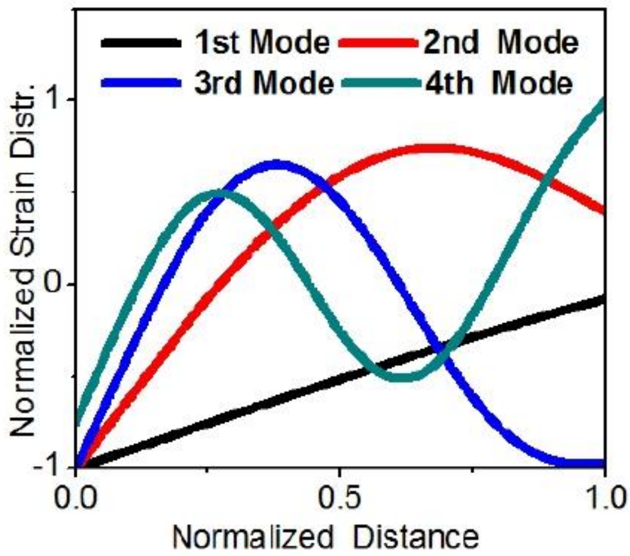

Fig 4.4 distribution of strain for the 1st four lower modes of vibration for cantilever tip mass PZT harvester

PZT layer name	1st mode		2nd mode		3rd mode	
	f_r (Hz)	P_{max} (mW)	f_r (Hz)	P_{max} (µW)	f_r (Hz)	P_{max} (µW)
PZT1	33	33.75	381	179	1566	5.05
PZT2	33	33.68	376	39	1563	3.8
PZT3	33	10.78	381	147	1552	7.07
Continuous PZT	48	24.95	484	36.7	1384	0.383

Table 4.1 power outputs and corresponding resonance frequency of segmented harvested with continuous layer configurations

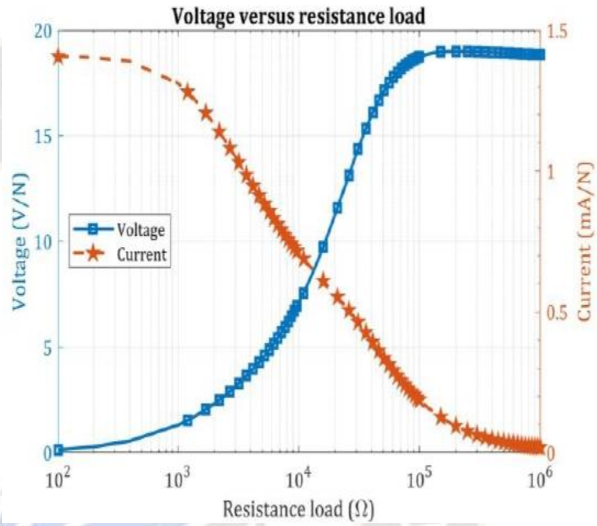

Fig 4.5 Voltage versus R load for two clamped harvester

With the different values of R electrical load connections the voltage and current peak output values are plotted in the figure 4.5 and the relations between voltage and current shows the converse trends. The power generated by the PZT harvester for the varies values of R electrical load has been plotted in figure 4.6. The generation of highest power is obtained for the optimum load condition just like in case of other conventional harvesters. For the optimum load of 29kΩ the maximum power peak value for a unit impact reported as 6.7mW/N^2

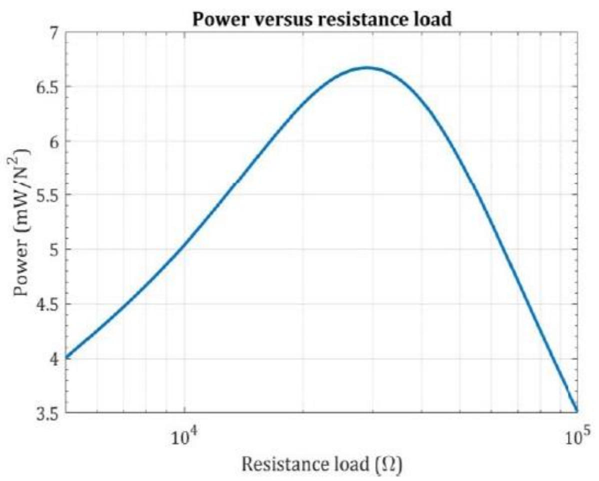

Fig 4.6 power versus R load for two clamped harvester

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The fig.4.7 and 4.8 shows that the reduction in the value of k leads to increase the bending moment and hence the strain as well as increase on the harvester beam. For the unit impact force the strain has been plotted for the dimensionless parameter k=0.44 and k=0.88. For the value of k=0.44 the strain magnitude is greater than for the value of k=0.88 case [10]. The way how the strain effect is change on the beam for the different value of k the similar way the beam deformation also influenced by the dimensionless factor k. maximum deflection of 1.61mm is occurred for the value of k=.44 which in turn 4 times higher than that of the value of for k=0.88 case. Force span variations bring the variations on the strain and deformation of the harvester beam, which is non linear.

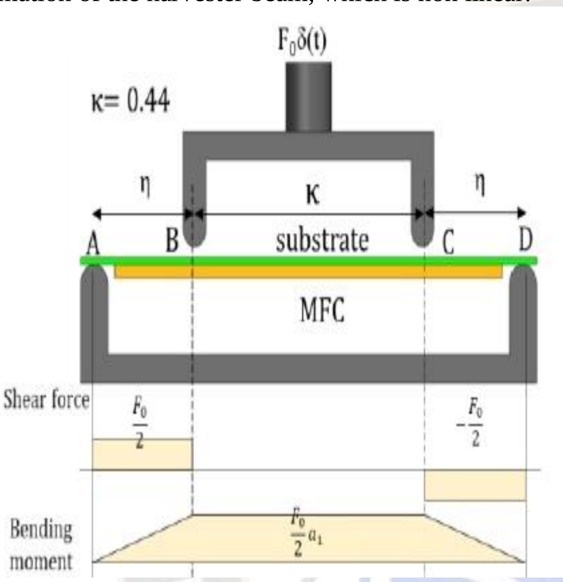

Figure 4.7 Force span L changes

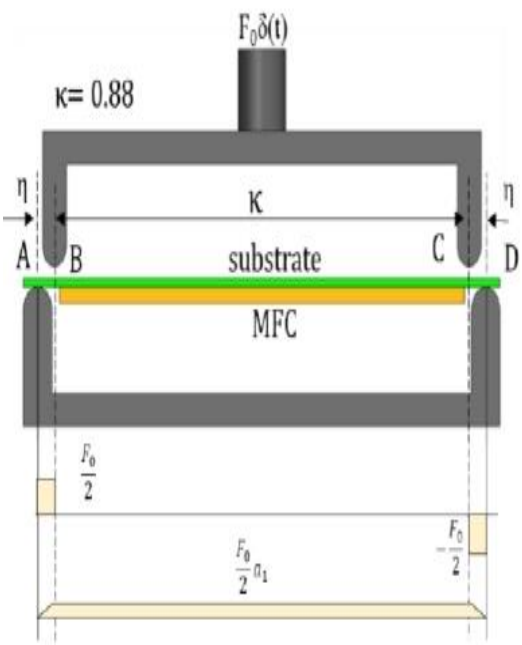

Fig 4.8 Force span L changes

Performance of the harvester for dimensionless factor k=0.44 and k=0.88	Max(W)	Max(E_{xx})	Peak value of voltage V_p	$\lambda = V_p/$ Max(E_{xx})
k=0.44	1.61mm	$1.32x10^{-4}$	57.79 V	$1.34x10^{5}$ V
k=0.88	0.41mm	$1.12x10^{-4}$	18.81 V	$1.68x10^{5}$ V

Table 4.2 performance of the harvester for dimensionless factor k=0.44 and k=0.88

The index λ gives the voltage generation for the per unit strain imposed on the harvester beam. The λ index is higher means that the materials used in best manner or energy conversion. $\lambda_{k=0.88}$ is 25% higher than that of $\lambda_{k=0.44}$ indicate that the performance of the energy conversion in the harvester is best for the higher value of the k even though the voltage peak value of the harvester under this greater k value is small. For the low value of dimensionless factor the voltage generation of the harvester increases where as for the higher value of the k the use of materials s best and performance of the energy conversion of the harvester also best. So, the both the aspects of the parameters should be considered while the design of the harvester is takes place. The figure 4.7 and 4.8 represents the relations between the λ index and the voltage generation per unit strain where the λ index increase up to the value of k =0.83 and beyond this value the λ index slightly decrease. The table 4.2 give the performance of the harvester for the dimensionless factor of k=0.44 and k=0.88

V. COMPARISIONS OF THE HARVESTERS PERFORMANCE

In this section the various harvester configurations results were compared in the aspect of the voltage, power and strain stress imposed on the harvester beam. From the comparisons it is understood that the charge cancellations effects are reduce through the segmented configurations and voltage, power also increased but the requirement of materials and uniform strain stress improvement is achieved in the two clamped configurations with top force applied case. It is evidence from the above section that the structure stiffness of the PEH system play important role in changing the resonant frequency. The structure stiffness can be increased or decreased by applying the magnetic forces in to the PEH system. Thus, the resonant frequency of the system can be changed. There are two magnetic force are present and they are named as attractive and repulsive.

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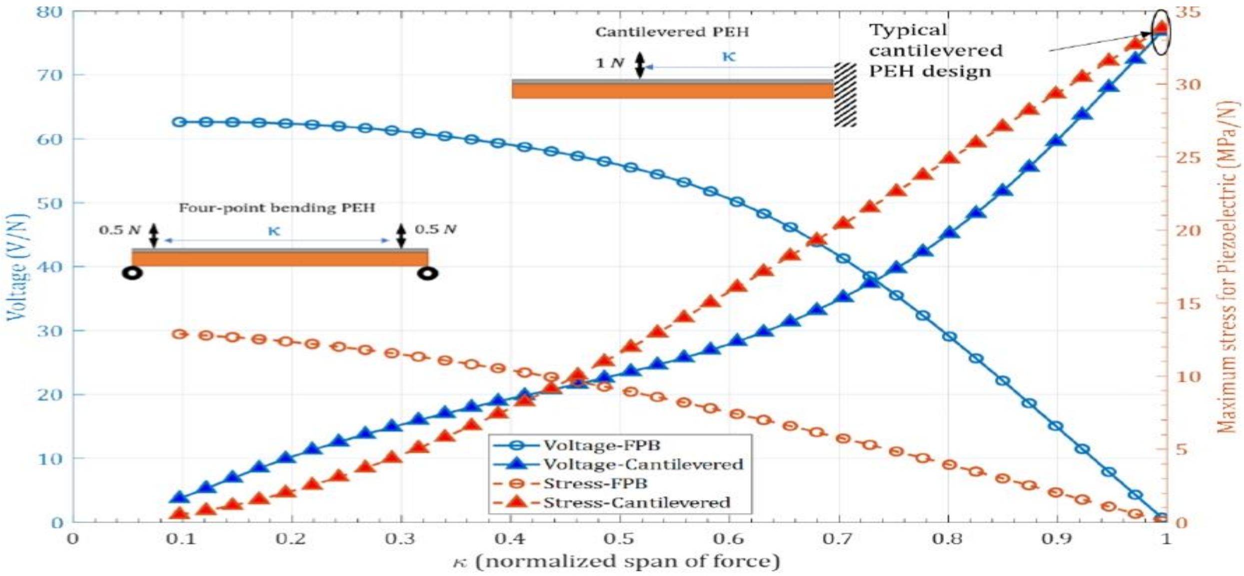

Figure 4.9 voltages versus the force span comparisons

Here the discussion findings of the mechanical stress and the voltage generation of the both the harvester such as clamped-clamped continuous beam harvester configuration and the cantilever continuous beam layer harvester. Then the both the parameters are compared for the both cases. The voltage and corresponding maximum stress imposed on the harvester beam for the clamped and cantilever beam harvester has been shown in figure 4.9. Force span increase brings the reduction in the transformation of force to the harvester and hence the voltage generation is reduced. But it is opposite in the case of cantilever configuration in which the force span increase the stress on the harvester beam and hence the increase in the voltage generation if takes place. The stress imposed on the harvester beam is increased dramatically and the maximum voltage generation by the cantilever beam harvester also approximately 13 % higher than the clamped –clamped configuration. However the power generation performance of the clamped –clamped configuration shows that the substantially stress reduce model

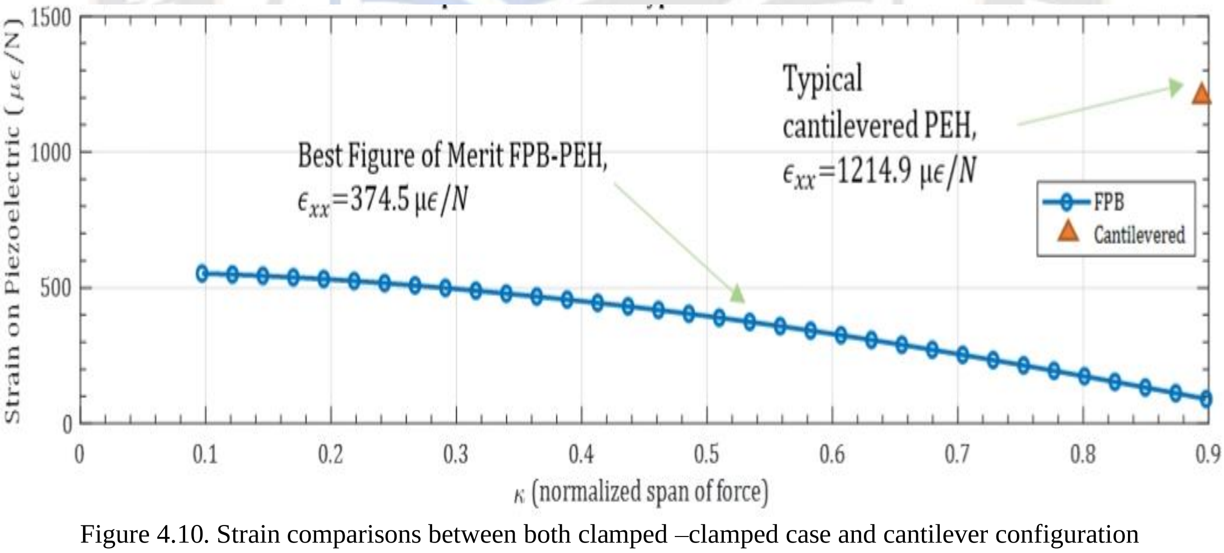

Figure 4.10. Strain comparisons between both clamped –clamped case and cantilever configuration

The electrical energy generation by the piezoelectric harvester takes place due to the mechanical strain applied to the harvester through the vibration energy. The dynamic strains that can be applied on the MFC have the reliable upper limit which is approximately 600με. If the dynamic strain goes beyond the 1000 με then the cracks may be found on the harvester beam [13]. The reduction in the applied stress to the harvester beam about 21% will increase the life of the harvester beam by double [14]. By considering this fact the clamped –clamped configuration will bring the life of the harvester for long period than that of the cantilever configuration. Because in cantilever configurations the more strain is imposed and it's more near to the tip mass end. But in clamped –clamped case the strain imposed is reduced and moreover the uniform strain is imposed on the harvester beam. The strain comparisons for both of the harvester have been shown in figure 4.10.

VI. CONCLUSION

The various configurations and approaches that are applied on piezoelectric energy harvester technology for power generation to supply the small rating power requirements deceives are discussed. The configurations of the harvester beams are changed to improve the energy conversion efficiency of the harvester and the segmentations are done on the harvester beam to improve the charge cancellations effect. The uniform strain stress improved on the harvester beam if the two clamped type configurations model is applied on the energy harvester. The cantilever configurations with tip mass arrangements provide the on uniform strain stress on the harvester beam. But the clamped – clamped configurations with top lamped the force is applied case provide and ensure the uniform strain stress imposed on the piezoelectric energy harvester. The performance of the harvester also improved and the optimum use of piezoelectric materials ensured in the two clamped type harvester beam configurations. The uniform strain stress increase the life of the harvester beam far better than the cantilever configurations with tip mass arrangements. The optimum uses of the MFC reduce the requirements of the materials which in turn reduce the manufacture cost the harvester model.

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