A Review of Vibration Energy Harvesting using Piezoelectric Materials

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ABSTRACT- Energy harvesting also known as energy scavenging is the process by which energy is derived from external sources; vibration is one such energy source which can be captured and stored.Piezoelectric materials are considered as a media to harvest vibration energy.Piezoelectric materials have received tremendous interest in energy harvesting technology due to its unique ability to capitalize the ambient vibrations to generate electric potential. Their crystalline configuration allows the material to convert mechanical strain energy into electrical potential, and vice versa. This paper reviews key ideas and performances of the reported vibration energy harvesters using piezoelectric materials. Various types of design study of energy harvesters, FEM models are reviewed.

Keywords: *Vibration,Energy Harvesting,Piezoelectric ,FEM*

INTRODUCTION

In the recent years, a surge of research in the area of energy harvesting has attracted the attention of many researchers. The reduced power requirement of small electronic components has motivated the researchers for design of energy harvesting systems. Energy from vibration is free and meets the requirement at the local level without depending on the conventional sources. Recovering even a fraction of this energy would have a significant economic and environmental impact.

[1]The blades of helicopters are heavily loaded and are critical components. Failure of any one blade will lead to loss of the aircraft .The measuring systems used in aircraft blade to calculate the actual loads, fatigue within the blades and end of life of blade need energy for sensing. Piezoelectric materials are considered as a media to harvest vibration energy of helicopter blades. [2] The human heart has a natural pacemaker called the sino-atrial (SA) node, which sends an electrical pulse through nerves around the muscle tissue causing them to contract. However, if this begins to fail an artificial pacemaker is required to provide pacing. Conventional pacemakers require battery power to last the 5 to 10 year life expectancy of the device. With the power densities available, these batteries are too large to suit an implanted intracardiac pacemaker. This problem could be overcome if it is possible to harvest the mechanical energies from the heartbeat using an embedded energy harvester.

Researchers in this area are involved in understanding the mechanics of vibrating structures and the constitutive behaviour of piezoelectric materials. This promising way of powering small electronic components has attracted researchers from different disciplines of engineering, including mechanical, electrical, and civil as well as from the field of material science and medical.

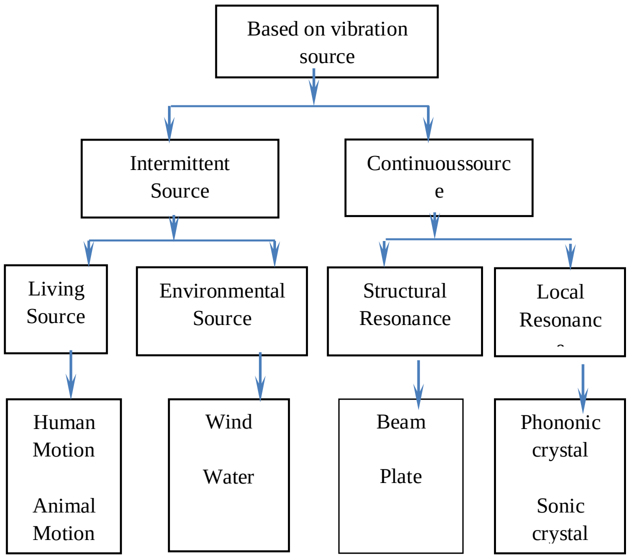

Fig 1: Classification of vibration sources[41]

FUNDAMENTALS OF PIEZOELECTRIC MATERIALS

The mechanical and electrical coupling of a piezoelectric material can be demonstrated in two ways. In a harvesting mode, an applied mechanical pressure produces a proportional voltage response, which is known as the direct piezoelectric effect. Conversely, an applied voltage produces a deformation of the material, which is known as the indirect piezoelectric effect. On a molecular level, this behaviour is due to the polar nature of the material's crystal structure. As the pressure is applied, the crystal structure deforms, causing an ion to shift within each unit cell of the structure, thus producing a net charge displacement. Essentially, this means that each unit cell has an electric dipole which can be re-oriented to certain allowable directions, by imposing a mechanical pressure. For an applied voltage, the ion is pulled away from its original location in the crystal lattice, deforming its structure and thus that of the entire material.

The direct effect and the converse effect may be modelled by the following matrix equations

Direct Piezoelectric Effect:

$$\{D\} = [e]^{T} \{S\} + [\alpha^{S}] \{E\}$$

Converse Piezoelectric Effect:

$$\{T\} = [c^{E}] \{S\} - [e]\{E\}$$

Where {D} is the electric displacement vector, {T} is the stress vector, [e] is the dielectric permittivity matrix, [c^E] is the matrix of elastic coefficients at constant electric field strength, {S} is the strain vector, [α^S] is the dielectric matrix at constant mechanical strain, and {E} is the electric field vector.

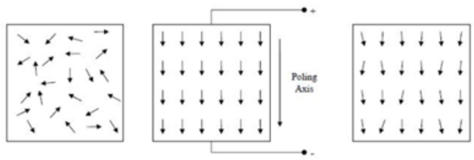

Fig 2: Poling process: (a) Prior to polarization polar domains are oriented randomly; (b) A very large DC electric field is used for polarization; (c) After the DC field is removed.

DESIGN STUDY OF PIEZOELECTRIC ENERGY-HARVESTING

[3] A design study on the geometric parameters of a cantilever-based piezoelectric energy harvesting devices (EHD), is based on the coupled piezoelectric-circuit finite element method (CPCFEM), and concluded that, 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 and for the case of a fixed total length, a shorter beam length and longer mass length are preferred. [4] A non-optimized preliminary design of a low-level MEMS Piezoelectric Vibration Energy Harvester (MPVEH) was performed and the performance was predicted for the next generation MPVEH device, which was built and tested. A power of 0.031 µW from low-level vibrations was predicted, translating into a power density of 28.2 µW/cm3. [5] Designs of experiments and Multiphysics analyses were used to develop a parametric model for a d33-based cantilever. Theanalysis revealed that the most significant parameters influencing the resonant frequency are the supporting layer thickness, piezoelectric layer thickness, and cantilever length. [6] The energy harvesters should be able to sustain under harsh vibrations and shocks. Fatigue and crack of the energy harvesting devices are crucial for real application. Thus, development of flexible and resilient piezoelectric materials is necessary. Since the obtained electrical energy from vibration is small, rectification and energy storing circuits should be able to activate in such a low power condition. For harvesting from vibrations, the cantilever beam with an end mass forms the basis of many harvesting devices. The configuration offers large average strain in the piezoelectric material for a given applied force, and low stiffness of the structure allows low resonant frequencies.[7] when the ratio of the mass of the central metal block to the side metal block masses is large; the PZT actuator attains a higher average velocity.[8] The piezoelectric element's location was determined to be optimal adjacent to the clamped end. The piezoelectric element's length was determined to be optimal at 0.300m on a beam with a length of 0.550m. For the Euler Bernoulli method, the thickness ratio was optimized at 0.525. The transverse forcing function location was determined to be optimal at the free end of a cantilever beam, producing the largest moment arm.[9] The different methods of harvesting from vibration energy was studied and concluded that piezoelectric conversion tends to result in higher power outputs than electromagnetic or electrostatic conversion: typically in the hundreds of µW to a few mW region (e.g. 335µW, 462µW, 900µW, 1.3mW), with voltages reaching high single figures to tens of volts DC or peak (e.g. 8.3Vpk, 13Vpk, 9.8VRMS,20.57VDC).[10] In this study, it is shown that the commonly accepted SDOF harmonic base excitation relation may yield highly inaccurate results for predicting the motion of cantilevered beams and bars.

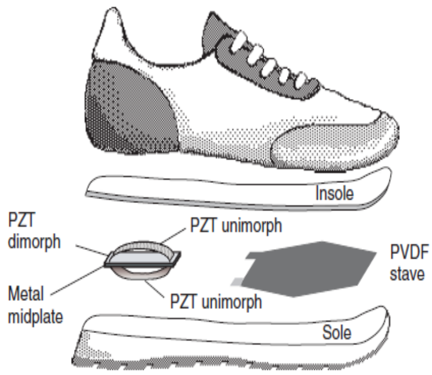

Fig.2: Shoe mounted piezoelectric

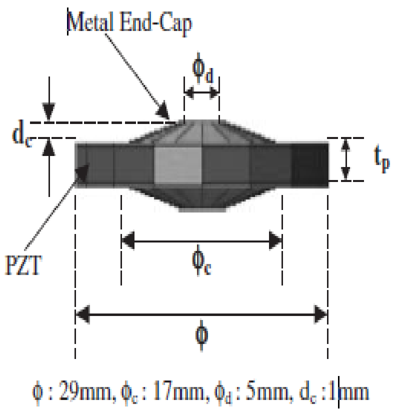

Fig.3 .Cymbal transducer

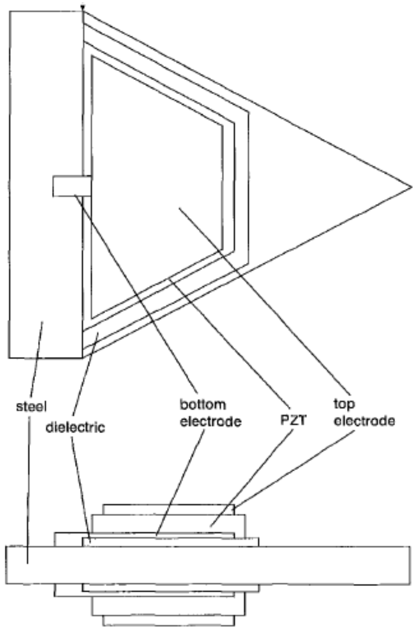

Fig.4 Tapered shape of beam

[34]Fan-folded geometry is used to get the required natural frequency range from heart beat to power leadless pacemakers.The size of the device is $2cm \times 0.5\ cm \times 1cm$

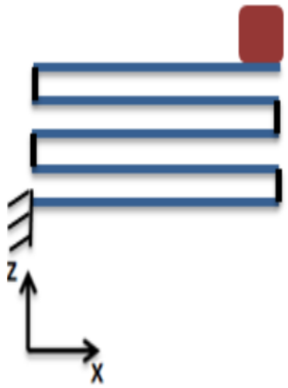

Fig 5(a) Fan-folded energy harvester with five beams and tipsmass [34]

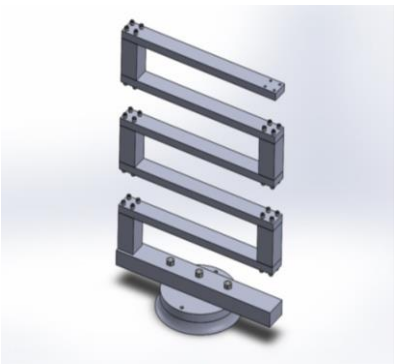

Fig.5 b) 3D model of a five beam fan-folded structure [34]

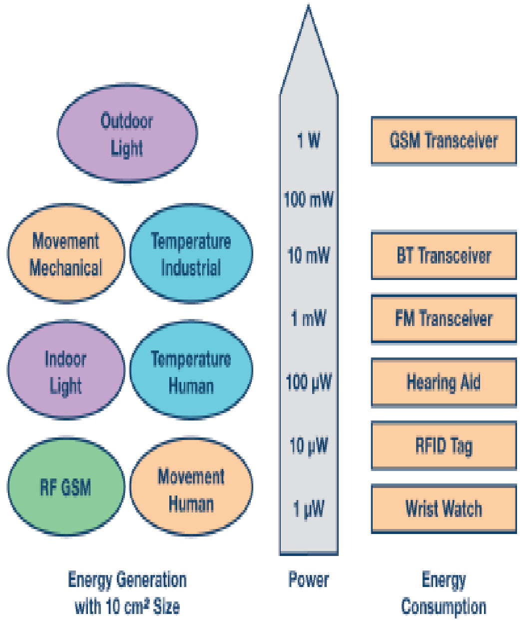

Fig.6. Different sources of energy and the required energy requirements for different applications [38].

[42] Persons with pacemakers powered by lithium batteries require surgery each 8 years for battery replacement.The battery dependence is reduced by using nanogenerators.The nanogenerator is capable to convert the mechanicalenergy of human body motion into electricity through muscles lengthening and even through blood flow. The nanogenerator is built with nanowires of zinc oxide – a material that is piezoelectric and semiconductor.

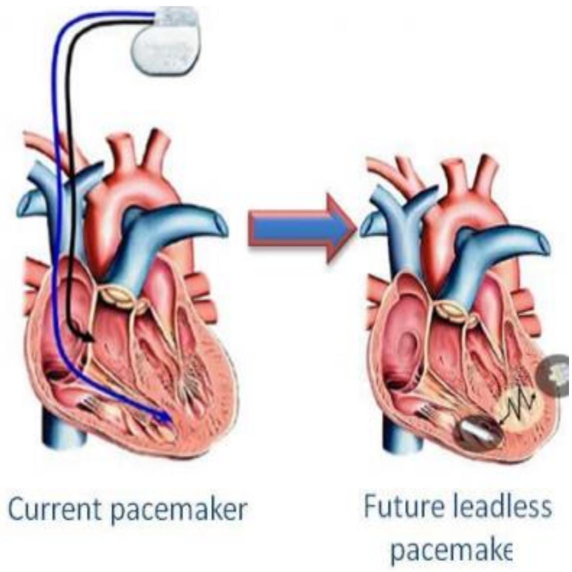

Fig.7.Energy Harvester in Heart

Table 3. Piezoelectric Harvesting Device Shapes and Their Purpose.

Device Shape	Purpose	Source
Triangular/trapezoidal cantilever	For enhancing the power output: a higher maximum vibration amplitude can beapplied to a triangular cantilever than for the same size rectangular cantilever.Fig.4	[27],[28], [29]
Pre-stressed bender.	For harvesting from an impulse	[30]
Cymbal	For increased durability, since the device does not bend (bending causes fatigue in the piezoelectric material). The device is compressed instead.Fig.3	[31]
Spiral shaped	For lowering the resonant frequency of the device (a spiral is a very compact way of arranging a long beam length).	[32],[33]
Fan folded	To reduce the natural frequency to desired range	[34]

FINITE ELEMENT MODEL ENERGY HARVESTING

Finite element method is numerical modelling for predicting how structures behave in given environment.[11]A numerical solution based on the finite element method has been developed to analyse the deformation, electric potentials of a piezoelectric smart structure subjected to external mechanical or electrical loadings. The formulation of the finite element for static analysis has been presented based on isoparametric formulation. The element considered in the study is eight noded hexahedral elements. A computer code based on the above formulation has been developed using MATLAB software to solve the three dimensional structures integrated with piezo elements.[12]The finite element model is derived based on the constitutive equation of piezoelectric material accounting for coupling between the elasticity and the electric effect by two nodes Hermitian beam element. The finite element is modelled with displacement components and electric potential as nodal degrees of freedom. The Functional Graded piezoelectric beam with a higher volume fraction index has lower natural frequencies, and aclamped-clamped beam possesses much greater natural frequencies than the cantilever and simply supported beams. [13]A finite element model is developed for a cantilever beam structure with partially covered, enhanced active constrained layer damping treatment. Element has 4 DOF at each node.[14] The power output can be increased and the frequency bandwidth can be improved when the single degree of freedom (SDOF) elastic system has a larger lumped mass and a smaller damping ratio. [15] There is a lack of 2D curved and Active Constrained layer damping (ACLD) shell finite elements, and some quadratic elements with electric dofs representation. . [16] The transient dynamic behaviour of the cantilever energy harvester has been examined in FEM. As the external excitation is increased from 0.001 to 0.27 g, the output voltage across the external load is linearly increased. The maximum converted energy of 59.6mJ can be derived in 2 s under the vibration amplitude of 0.27 g.[17] here the study was on application of the higher order shear deformation theory based finite element method to piezoelectric energy harvesting. It was concluded that for higher aspect ratios of beams, the higher order shear deformation theory gives more accurate results.[18] The FE model is derived based on the Kirchhoff plate assumptions as typical piezoelectric energy harvesters are thin structures.[19] The first-order shear deformation theory (FSDT) and linear piezoelectric theory are implemented in finite element simulations.

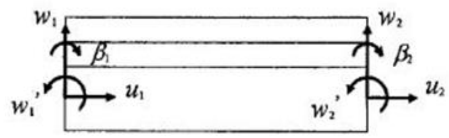

Figure.8 Nodal displacements of ACL sandwich beam element

ANALYTICAL MODEL FOR ENERGY HARVESTING

[8]In Euler-Bernoulli model, The PZT and substrate both bend about a common neutral axis which is no longer the neutral axis of the beam. Perfect bonding is assumed, and the PZT is considered to be a layer of the beam. This neutral axis is calculated by a modulus-weighted algorithm

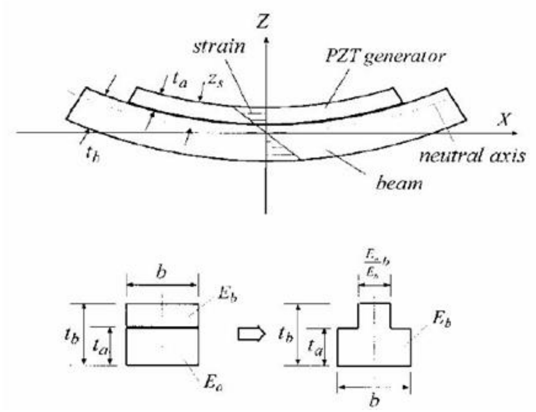

Figure 9: Euler Bernoulli model of PZT and substrate along with the modulus weighted neutral axis.

The equation for the distance to the neutral axis can be written as

$$z_s = \frac{\frac{t_a}{2} t_a \frac{E_a}{E_b} + \left(t_a + \frac{t_b}{2}\right) t_b}{t_a \frac{E_a}{E_b} + t_b}$$

To simplify the calculations, the average strain in the PZT is determined and used to find the voltage. The average strain

$$\varepsilon_a = -\frac{M}{(E_a I_a + E_b I_b)}\left(z_s + \frac{t_a}{2}\right)$$

$$I_a = \frac{1}{3} b[{z_s}^3 - (z_s - t_a)^3]$$

$$I_b = \frac{1}{3} b[(t_a + t_b - z_s)^3 + (z_s - t_a)^3]$$

The voltage on the PZT poling surfaces is related to the stress by

$$V = g_{31} t_a \sigma_a$$

$$\sigma_a = E_a \varepsilon_a$$

By substituting'σa' in V

$$V = -\frac{6\, g_{31} M\varphi(1+T)}{b t_a [1 + 2\varphi(2+3T+2T^2) + T^2\varphi^2]}$$

Where

$$\varphi = \frac{E_b I_b}{E_a I_a}$$

$$T = \frac{t_b}{t_a}$$

[20]The analytical model shows that the vibration-induced voltage is proportional to the excitation frequency and the width of the device but is inversely proportional to the length of the cantilever beam and the damping factor.

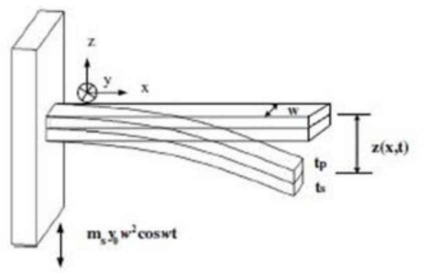

Figure10: Schematic illustration of the cantilever bimorph.

[21] The deformation of piezoelectric structures can be sensed via measurement of the capacitance of the patches, and controlled through adjustment of the measured capacitance by changing the imposed voltage. Here the relationship of the strain state of beams or plates with the capacitance of piezoelectric patches is determined analytically.

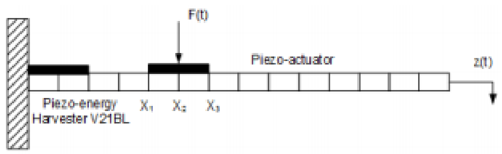

Fig9.The Cantilever beam with piezo actuator and harvester

The obtained values of voltage stored on the capacitor showed the best resultsand are achieved for the beam excited to vibration with third natural frequency.

MATHEMATICAL OPTIMIZATION

Optimization is achieving the best with the available resources while satisfying the constraints. [22]Genetic algorithms are different from traditional optimization methods in that they usually work with a coded set of variables and not with the variables themselves; they search from the population of points rather than by improving a single point; they use objective function information without any gradient information, and their transition scheme is probabilistic compared to traditional methods that use gradient information [23] The author developed a low order model that can be used to describe the behaviour of a unimorph or bimorph annular-shaped piezoelectric vibration energy harvester, and then successfully used the model in an optimization problem to maximize the power output of the device while constraining the minimal inner radius and maximal outer radius. [24] Genetic Algorithm is used to optimize the location of piezoelectric patch on flexible plate structures.[19] The genetic algorithm (GA) optimization approach is carried out to optimize the structural parameters of mechanical energy-based energy harvester for maximum power density and power output.

OUTCOMES

[10] Most of these models have been for materials such as PZT, whose performance is not significantly influenced by temperature.[18] The electrical power generated from structural vibrations can be used to power small electronic components [25]the intended location of the PZT on the host beam or structure needs to be studied so that its displacement can be optimized and the excitation range realized to allow for the tuning of power harvesting device and consequently increase the output power.[26]Practical applications for power harvesting systems such as wireless sensors and self-power damage detection units must be clearly identified to encourage growth in this area of research, thus allowing the contributions and in flow of ideas to increase in this area.

CONCLUSION

This paper reviews design, analytical, FEM model of piezoelectric energy harvesting from vibration with Mathematical optimization and reports on the major efforts and findings documented in the literature.

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