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An Experimental Study On Fatigue And Durability Of Energy Harvester

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A B S T R A C T

Fatigue failures of the designed products is merely bothering the modern engineers and scientists for the research communities of all fields. Especially in the field of Micro Electromechanical Systems(MEMS) durability of low power systems is very important under the climates of both at high temperature and low temperature zones. And also continuous electrical power requirement is also important for the MEMS and wireless sensor networks. Electricity is the greatest crisis in the world on one side and another side durability of smart devices such as mobile phones, laptops, compact devices, computer spare parts, unrecyclicable batteries etc for reducing the rate of pollution in the environment. By considering these problems authors are taken up a research in finding the fatigue characteristics are fatigue failure and durability of lead zirconate titanate (PZT)and then studied the scavenging device under harmonically excited vibrations . The optimum power output is observed about 0.0025 W. Under the resonance operated condition at the frequency of about 45 Hz , the durability of scavenging device is 9 years

*Keywords:*Lead Zirconate Titanate; Lead Ball; Impact mass; Scavenging Device; MEMS;

1. INTRODUCTION

Durability of PZT at different environmental conditions plays a very important role for the continuous function of low power devices. The output of PZT may change when the working time increases in addition with the mechanical properties. The process of acquiring the energy surrounding a system and converting it into usable electrical energy is termed power harvesting. At present, next-generation energy technology is a technology to harvest electrical energy using piezoelectric ceramics based on piezoelectric effect. Piezoelectric effect is the phenomenon where electrical energy is obtained when mechanical energy is applied to piezoelectric ceramic. Technologies are developed because of a shortage of energy in the world. One of the next-generation energy technologies is piezoelectric energy harvesting technology. Piezoelectric energy harvesting technology is very eco-friendly and useful because of the use of discarded physical energy around our living atmosphere. For example, electrical energy is harvested from a vibration of a road when people and cars pass the road. For this method, the piezoelectric energy harvesting technology needs proper piezoelectric generator. The world energy production sector is in transition and is nowadays called to face great challenges in a context in which the fossil fuel reserves are being reduced , while the energy demand is increased rapidly. On the other hand, the rising cost and the related environmental issues make the use of conventional energy resources more and more difficult. The increment of the world energy demand, mainly fulfilled by fossil fuels has brought to an increment in greenhouse gas emissions with serious consequences on our environment. Piezoelectric ceramics discovered in the 1950's, which experience much stronger piezoelectric effect. The piezoelectric ceramics should undergo a polarization process for the piezoelectric phenomenon to be happened, while crystal materials are naturally piezoelectric. The most commonly used piezoelectric ceramic is lead zirconate titanate (PZT) but also other ceramic materials, such as barium titanate, exhibit the effect. At the turn of the 19th century, Langevin began to make practical applications of "piezoelectric transducers", especially in use of submarine detection under water. As the size of the actuator becomes smaller and the need for

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structural integrity and reliability increases, ceramics with good mechanical properties are needed.

A MEMS-based energy harvesting device, micro piezoelectric power generator is planned to convert ambient vibration energy to electrical power via piezoelectric effect by Hua-Bin Fanga & Jing-Quan Liu in 2006. In this work, the generator structure of composite cantilever with nickel metal mass is devised. Device offers the advantage of good performance as far as promising voltage / power output and adjustable low natural frequency to match general vibration sources [1]. Yuantai Hu & Ting Hu analyze a piezoelectric energy harvester as an electro-mechanically coupled system. The energy harvester contains a piezoelectric bimorph actuator with a concentrated mass attached at one end. They concluded that the power density can be maximized by varying the non-dimensional inductance for a fixed non-dimensional aspect ratio together with a fixed non-dimensional end mass[2]. A nonlinear piezoelectric converter by using permanent magnet is proposed by Marco Ferrari in 2009. Experimental results show that the performances of the converter in terms of output voltage at parity of mechanical excitation are markedly improved [3]. Instead of deposition of PZT bulk film, Huicong Liua made ten PZT thin film patterns (PZT patterns) which are parallel arrayed and electrically isolated on the supporting beam of the cantilever. He studied performance of output voltage and power of PZT patterns in series and in parallel connections based on the experimental and simulation results. It is shown that PZT patterns in series and in parallel connections produce the same level of power in the corresponding matched load resistance, but PZT patterns in parallel connection is preferred because of lower matched load resistance required [4]. Meiling Zhu and Stephen Edkins proposed analytical model results of a cantilever based piezoelectric energy harvesting device (PEHD) with a large tip mass whose centre of gravity is not coincident with its point of attachment to the beam. This work can be used to evaluate the performance of the designed energy harvesting devices for self-power sensors/sensor networks in structural health monitoring applications. [5]. Xianzhi Daia described an energy harvester employing multiple laminated type magneto-electric transducers to convert ambient mechanical vibration into electrical energy. The harvester uses four magnets arranged on the free end of a cantilever beam. Experimental results indicate that the harvester employing multiple transducers can provide higher power and power density [6]. Diyana & Asan considered unimorph piezoelectric energy harvester to harvest wideband mechanical energy. The results of the frequency response are displayed in the form of voltage within frequency range of 0 to 3500 Hz, at which the comb-shaped piezoelectric beam structure shows better performance as there exist more natural frequencies in the specified range of frequency. It is seen that comb structure can be used to harvest broadband vibration energy [7]. L. Zhoua & J. Suna has done the electrical model with the piezoelectric constitutive equations and the single degree of freedom model. These are combined to describe the energy harvesting performance of shear mode piezoelectric cantilever. The proposed model is used to simulate the frequency dependence of the output peak voltage and power. The model can successfully predict the coupled electrical and mechanical responses of the piezoelectric cantilever [8].Several researchers have reported that the poling direction could change the crack growth and material properties of PZT ceramics. Zhao et al. have examined the crack growth characteristics of PZT, and they found that there exists a strong anisotropy of crack growth[9]. In the orientation perpendicular to the polarization direction, cracks grow readily whereas no obvious propagation is found parallel to the polarization direction. Fett et al. have examined the effect of the poling process on the material properties, and it appears that the PZT, poled perpendicular to the external load, shows a stronger plastic deformation than the unpoled material[10]. In the study by Okazaki, the crack extension mechanism in piezoelectric ceramics appeared to be variable because of the internal stress generated by the poling process[11]. His claims were, however, countered by the work of Mehta and Virkar, since the calculated internal stress in the ceramics was as high as 14.5 GPa, whereas the material hardness of the related ceramics was only 0.45 GPa[12]. Even though the mechanical properties of PZT ceramics could be altered by the electrode and poling direction, the reason for this has not been explained clearly and there is no clear evidence for the explanation. In addition, little work has been done to investigate the failure mechanism and the material properties during the fatigue test. The aim of this work was therefore to examine the fatigue failure characteristics of PZT 5H and design the scavenging device by using the uni-morph PZT 5H patches and conducted experiment on the 20 g Syscon Shaker to get the output power along with testing the equipment in three point bending test machine.

1.2. Fatigue Life of PZT 5 H

Factors that affect fatigue life such as cyclic stress rate, geometry, surface quality, type of material, residual stresses, size and distribution of internal defects, air or vacuum, humidity, temperature, direction of loading, environment, grain size and crack closure. These are the factors which effect the metals where as for Piezo ceramics along with the above factors electric fatigue also affect the fatigue life of PZT 5H. In this paper authors investigated the fatigue failure of PZT 5H patch due to compressive loads caused by support harmonic excitation of 12 mm amplitude to the base of scavenging device as shown in figure 5. Axial compressive load is given by lead ball in the device in the mode of d_{33}. The 20 N force is acted on the PZT 5 H with a lead ball velocity of 0.48522 m/s. The fatigue failure of PZT 5H due to vibration cyclic loads as shown in figure 4. The properties of PZT 5 H cannot be changed but the working of operating conditioned are to be rectified. If the scavenging device is operated at below 320^0 C there is no fatigue failure of PZT 5 H due to temperature because the curie temperature of PZT 5 H is 320^0 C.

2. Experimental procedure

PZT 5H patches are manufactured by APC International limited, America and having a density of 7.6 **g/cm³** , Piezoelectric voltage constant of $24.8x10^{-3}$ m^2/c, relative dielectric constant of 1900, modulus of elasticity of $6.3x10^{10} N/m^2$, curie temperature is 320^0 C and Piezoelectric charge constant of $400x10^{-12}m/V$. we have used the 9 grams lead ball as a impact loader on the PZT 5 H patches during excitation. Lead having a properties of density is 11.3 g/cm^3 , modulus of elasticity as 16 GPa and Poisson ratio as 0.44. The constitutive equations of PZT 5H are as fallows[13].

$\delta = \sigma/Y + dE$

$D = \varepsilon E + d\sigma$

Where,

δ - Mechanical strain

σ – Mechanical Stress

Y – Modulus of Elasticity (Young's Modulus)

d- Piezoelectric strain coefficient

E – Is the electric field

D – Electric Charge Displacement

ε – Dielectric constant of piezoelectric material

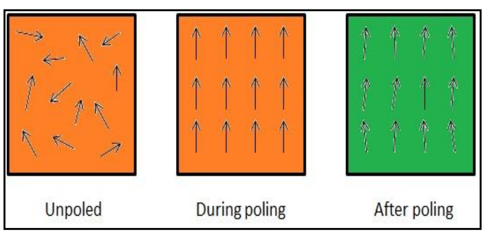

Figure1: Poling of PZT 5H

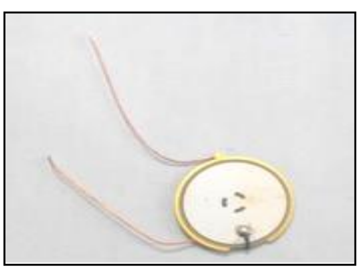

Figure 2: PZT deposited on brass

Before going to use PZT 5H patches one has to know the direction of polarization to apply the loads on the PZT 5H for the better results otherwise results will come negative way. The direction of polarization is positive Y direction as shown in figure 1. The process of polarization has been mentioned in Parvanova etal [14]. Dependable design against fatigue-failure requires thorough education and supervised experience in structural engineering, mechanical engineering, or materials science. There are four principal approaches to life assurance for mechanical parts that display increasing degrees of sophistication such as design to keep stress below threshold of fatigue limit ,fail-safe, graceful degradation, fault-tolerant design, safe-life design and damage tolerant design. Fatigue is a process that has a degree of randomness, often showing considerable scatter even in well controlled environments. Fatigue is usually associated with tensile stresses but fatigue cracks have been reported due to compressive loads[15]. The greater the applied stress range, the shorter the life. Fatigue life scatter tends to increase for longer fatigue lives. Damage is cumulative. Materials do not recover when rested. Because of having brittle property PZT 5H is failure at a stress of 140 MPa. So far fatigue considerations of PZT 5H patch was explained. The second part of the this paper is experimental study of scavenging device by using harmonic excitation. The design considerations of the scavenging device's dimensions are 50x25x10 mm. Four partitions are made 5 mm x 20 mm x 20 mm x5 mm and the 20 mm diameter and length of cylinders are inserted between them. Two lead balls are placed into the cylinders for giving impact load on the patches when they are operated at the resonant frequency of 45 Hz. In this scavenging device six PZT patches are used. The whole experimental set up and scavenging device arrangement on the host structure can be seen in figures 5 & 6.

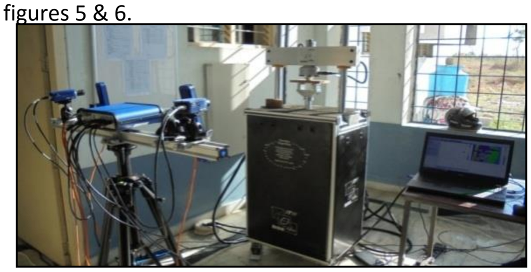

Figure3: Three point bending test with PZT 5 H on the support

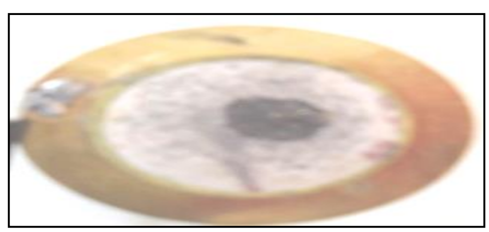

Figure 4: Damaged PZT 5H patch after test

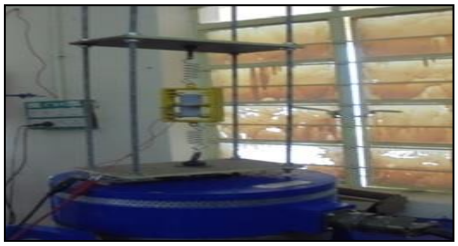

Figure5: Scavenging device on 20 g Syscon Exciter

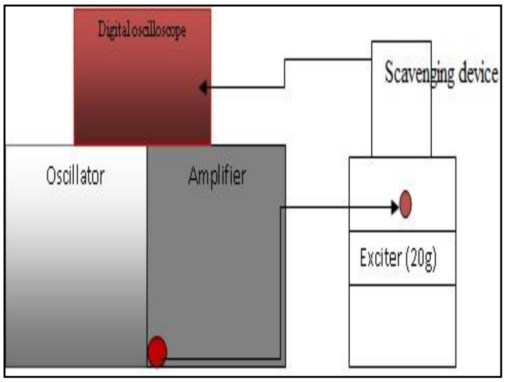

Figure 6: Schematic presentation of experiment

3.Results and discussion

Cyclic bending load was applied on the PZT 5H. We did not conduct any etching technique for seeing the domain structure of PZT 5H material. We are conducting the fatigue test to know how much force the lead ball should execute on the unimorph PZT such a way that the dynamic strain will be occurred in the PZT thus energy transduction will be taken place. One disadvantage of piezo ceramics is brittleness. It is difficult process to apply etching technique. We have chosen PZT 5H is because of this material is having maximum power density as compared to other ceramics especially while passing through ambient vibrations.The bending fatigue test was also conducted at natural frequency of 0.03 Hz and r_a = 0.02. The maximum cyclic load, *f*max, was determined on the basis of the bending strength (f_b),where f_{max} is designed to be less than 90% of f_b. The bending stress was calculated using the simple formula $f = 3M/2rt^2$, where M is the bending moment, and r and t are the PZT radius and thickness. The cyclic loading was applied along the direction of the normal to the surface of the PZT 5H patch as shown in Figure3. In this experiment we used the wooden support for supporting the PZT 5H which is having the diameter of 32 mm and a thickness of about 2 mm . In the past people had done experimentation of using the etching techniques with electron back scatter diffraction for seeing the domain structures of Piezoceramics and also used a scanning electron microscope for their studies. Nowadays piezo ceramics are readily available in the market therefore no need to go for studying the domain structure unless we require for optimization of properties by adding different dopents. The strength of PZT 5 H is 130 MPa at the strain of 0.004 mm/mm. It is observed that under three point bending test the life of the PZT 5 H is 10^7 cycles at a stress of 38 MPa as shown in figures 7a and 7b. If the host structure is operated at 25 Hz per hour per day then the life of machine 18.26 years. In this paper authors got out put voltage is about 48 V AC peak to peak at a resonant frequency of 45 Hz, by considering this frequency the durability of the machine is 9 years provided if the machine is operated one hour per day. It is observed by seeing the figures of 8 and 9 that at the resonance frequency of 45 Hz , maximum amplitude takes place in the both host structure and substructure, the lead ball can travel more distance than the given amplitude by the host structure. When the lead balls hit the PZT 5 H patches, it induces dynamic strain into the PZT material leads to generate electrical energy as an output. This effect is called direct Piezoelectric effect. Here authors are not discussing about inverse or indirect Piezoelectric effect.

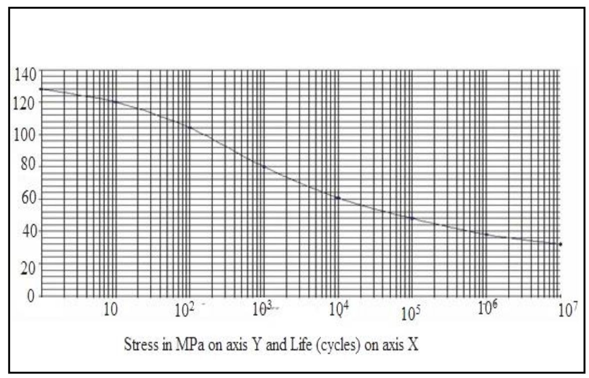

Figure 7a: stress vs strain curve of PZT 5H patch from three point bending test

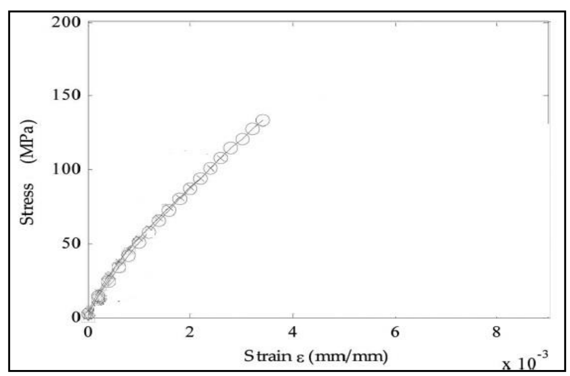

Figure 7b: S-N curve for PZT 5

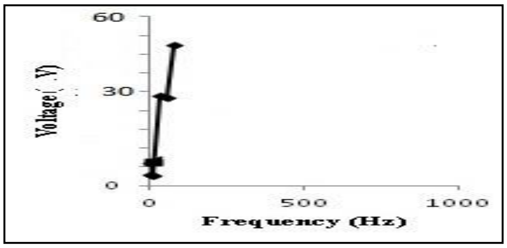

Figure 8: Voltage frequency graph of energy scavenging device

Figure 9: Output Voltage signal in digital storage oscilloscope

4.Conclusions

In this paper design of scavenging device by considering fatigue failure and durability of PZT 5H patch is discussed in briefly by using three point bending test rig and vibration exciter. It is concluded that the life of PZT 5H patch is 9 years provided if it is worked at 45 Hz per day per hour with the exciter of 2 g acceleration. In addition to this those tested PZT 5H patches are used in scavenging device and generated a voltage of 50 V and the readings are measured with the help of GWINSTEK digital storage oscilloscope and developed a power of 0.0025 W for charging the low powered smart devices.

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