

# Experimental Investigation of Fatigue in a Cantilever Energy Harvesting Beam

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## ABSTRACT

Over the last decade, cantilever energy harvesters gained immense popularity owing to the simplicity of the design and piezoelectric energy harvesting (PEH) using the cantilever design has undergone considerable evolution. The major drawback of a vibrating cantilever beam is its vulnerability to fatigue over a period of time. This article brings forth an experimental investigation into the phenomenon of fatigue of a PEH cantilever beam. As there has been very little literature reported in this area, an effort has been made to scrutinize the damage due to fatigue in a linear vibrating cantilever PEH beam consisting of an aluminum substrate with a piezoelectric macro-fiber composite (MFC) patch attached near the root of the beam and a tip mass attached to the beam. The beam was subjected to transverse vibrations and the behavior of the open circuit voltage was recorded with passing time. Moreover, electro-mechanical admittance readings were obtained periodically using the same MFC patch as a Structural health monitoring (SHM) sensor to assess the health of the PEH beam. The results show that with passing time the PEH beam underwent fatigue in both the substrate and MFC, which is observed in a complimentary trend in the voltage and admittance readings. The claim is further supported using the variation of root mean square deviation (RMSD) of the real part of admittance (conductance) readings. Thus, this study concludes that the fatigue issue should be addressed in the design of PEH for long term vibration energy harvesting.

**Keywords:** energy harvesting; fatigue; vibration; piezoelectric; damage detection.

## 1. INTRODUCTION

In the last few years, the research in the field of energy harvesting for low power sensor systems has grown by leaps and bounds. A few commercial forms of simple energy harvesters are available in the market [28]. Over the years various forms of conversion mechanisms have been thoroughly investigated [17, 20]. The major forms of conversion mechanisms include electrostatic, electrodynamic, aeroelastic and piezoelectric etc. [20]. In comparison to the other forms of energy harvesting piezoelectric energy harvesting (PEH) mechanism has an advantage of higher power density and ease of application. The first usage of PEH was stated by [7]; in the due course of time various advances in the piezoelectric transducers led to the influx of a large variety of transducers, of all these piezoelectric transduction mechanisms the macro fiber composite (MFC) is one of the most popularly relied upon transducer in both sensing and actuation owing to its simplistic design and flexibility [7, 11, 12, 16, 28]. In the realm of PEH mechanisms, several researchers proposed various designs to harvest energy from stray vibrations, a few of them being the cantilever design, the buckled beam design, the fixed beam harvester etc. [17, 25]. Of all the vast variety of harvesters proposed, cantilever design stands out owing to its modest design and wide range of applicability. PEH using cantilever beams possesses an advantage of large strain at the root of the beam in addition to the high power density of the piezoelectric materials which converts the mechanical strain into a potential difference [20]. A large number of modifications to the basic cantilever design have been proposed by various researchers to enhance the range of applicability and bandwidth of operation of the PEH beam [25]. These include the use of external nonlinear forces like magnetic forces, arrays of cantilever beams with varying fundamental frequencies and enhancement in the power management circuits etc. [17, 24, 25].

Many cantilever based designs utilize the base acceleration to convert the mechanical vibrations to electrical power; numerous studies have been conducted on the cantilever based designs in various ranges of base acceleration. To minimize the effect of various nonlinearities like geometric, inertial, piezoelectric etc., it has been proposed that a base

acceleration of less than 0.4g-0.5g ( $\sim 4 \text{ m/s}^2 - 5 \text{ m/s}^2$ ) would limit the cantilever design to function in the linear range where most of the assumptions and simplifications stand valid for the PEH beam design [11, 12]. Though there have been various studies discussing the different aspects of functioning of the cantilever PEH beam, very few studies have been reported in the literature which forays into the longevity of the designs. This paper majorly focuses on this gap in PEH research and a sincere attempt has been made to experimentally explore the various phenomenon that occur during the complete life of a simple cantilever PEH beam.

The cantilever PEH beam has an uneven strain distribution along its length, one of the major drawbacks due to the uneven strain distribution in the affinity for a potential fatigue failure of the beam due to the constant reversal of stresses at its root. This article presents a study to understand the behavior of fatigue that can occur in the cantilever PEH beams. The experiments for fatigue can be time consuming and very tedious, this article elucidates the study of three cantilever PEH beams made up of an aluminum substrate and MFC piezo composite transducers attached at the root of the beam and subjected to a base vibration using a seismic shaker. To provide a glimpse of the variation of output voltage, the variation of peak open circuit voltage ( $V_{OC}$ ) has been presented in the succeeding sections; moreover, the same MFC has been used as a health monitoring sensor to obtain the admittance readings periodically. A complimentary trend was observed in both the voltage and admittance values which convey that over a period of time, the harvester beam is overcome by the effect of fatigue and finally fails after a few million cycles depending on the base acceleration.

## 2. FATIGUE IN PEH BEAMS

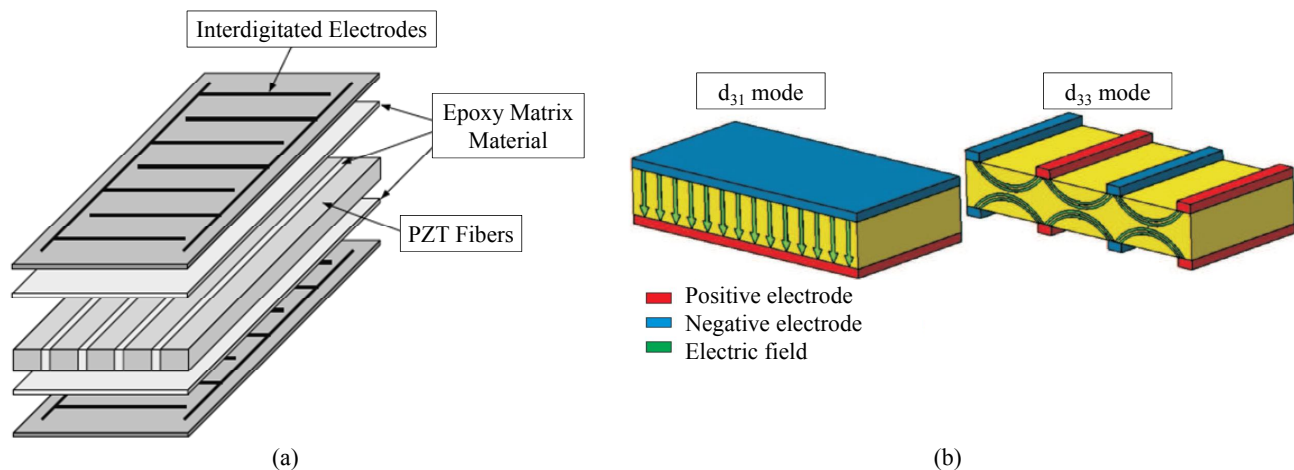
All engineering structures are subject to varying levels of stress over a period of time resulting in fatigue cracks and failure, fatigue is a phenomenon which can occur even when the stresses induced into the material are well within the limits for field strength. In the conventional engineering materials like structural steel, aluminum etc. there has been decades of research in the area of fatigue and many well defined standards and codes of practice are in place to assist in the optimum design of structures taking fatigue into consideration. But, in a contemporary area like energy harvesting, there has been little research on the longevity studies and occurrence of fatigue in the harvesting mechanisms. This paper addresses one such issue by experimentally exploring the behavior of a PEH beam when subjected to a prolonged base vibration over a period of time. The primary modes of failure for a PEH beam can be broadly classified as damage to the MFC transducer and damage to the substrate. The possible reasons for fatigue failure due to the above two mode are discussed in the sections below.

### 2.1 Damage to the MFC transducers

The commercially available MFC transducers are prepared using rectangular piezoceramic fibers, interdigitated electrodes and a polymer matrix. The inner most layer consists of the rectangular piezoceramic fibers bound together in a structural epoxy matrix for better resilience, the outer layers are made up of copper-clad kapton polyimide films with etched interdigitated electrode patterns and the layers are bound up using an epoxy and are vacuum pressed to complete the manufacturing process. The MFC is polled using high voltage DC source resulting in either  $d_{33}$  or  $d_{31}$  type of transducers depending on the layout of the interdigitated electrodes [4, 5, 9]. For energy harvesting purposes the  $d_{31}$  type of MFCs are widely used and the  $d_{33}$  type of MFCs are widely used for actuation and vibration control. The schematic diagrams for the MFC and the different types of actuation/sensing modes are shown in Fig. 1. Wilkie et al. (2002) presented a detailed reliability testing of  $d_{33}$  type MFC transducers in actuation mode; a range of testing was conducted to assess the reliability and sustainability of the transducer under the free strain conditions and static loading conditions. It was stated that under free strain conditions a maximum peak-to-peak actuation strain of approximately 2000 ppm in the longitudinal direction is typical for the transducers and a strain loss of less than 5% was observed for an electrically actuated transducer when subjected to repeated actuation cycles of over 100 million electrical cycles at 500Hz and 1500 Vp-p(peak to peak), similar cycles were carried out for a static loading case for about 10 million electrical cycles at 100Hz and 1000 Vp-p at room temperature and an enhanced temperature of 65C where the kapton layers slowly start to disintegrate. This article conferred a general idea into the performance of the piezoelectric MFC transducer when subjected to an actuation mode. When the MFC transducers are attached to a vibrating beam, the strain transfer from the beam to the sensor produces a potential difference owing to the direct piezoelectric effect; the MFC transducers exhibit creep and rate-dependent hysteresis [9] which ultimately results in disintegration of the piezoelectric fibers over a sustained period of loading. In the present work, observations from the experiments revealed that the MFC transducers deteriorate when the PEH beam is subjected to fatigue loading in the form of sustained base vibration. This has been discussed in detail in the next section on experimental setup and observations.

## 2.2 Damage to the substrate

Various researchers used different materials for the PEH beam substrate; the main purpose of a cantilever beam substrate is to produce enough strain so that the direct piezoelectricity of the transducer can exhibit considerable levels of potential difference. Steel, aluminum, tungsten, fiberglass, etc. are a few of the popularly used substrate materials [11, 17, 28]; when the PEH beams are designed for low frequency vibrations in the order of less than 50Hz, aluminum and fiberglass render the required flexibility in the beam, from prior experimental experience it was concluded that the strain levels obtained from fiberglass cantilever beams is low compared to that of the aluminum, hence aluminum was used as the substrate material in this experimental work. The fatigue behavior of different grades of aluminum has been extensively investigated in the literature, especially the work of Leong [29]. A detailed investigation into the low cycle fatigue behavior at different temperatures has been presented in the work. The endurance limit for aluminum is considered to be about 500 million cycles for untouched specimens; most practical specimens fail well below that limit. In a cantilever PEH beam, the maximum stress level occurs at the root of the beam where the beam is likely to produce fatigue cracks. It is impossible to simulate the field conditions that a PEH beam might be subjected to over its lifetime, so the beam is subjected to a uniform base vibration at its fundamental resonance frequency and the resonance frequency is maintained till the beam fails in fatigue. This is similar to the procedure followed for testing of various materials under cyclic loading with constant stress amplitude [30]. There are many approximate methods available in the literature for the calculation of the probable fatigue life of a given sample based on the data available from constant stress amplitude tests; detailed discussion of the various methods is out of the scope of this paper.



**Figure 1.** (a) Schematic of MFC piezo transducer after Williams et al. (2002) and (b) Schematic of different modes of actuation.

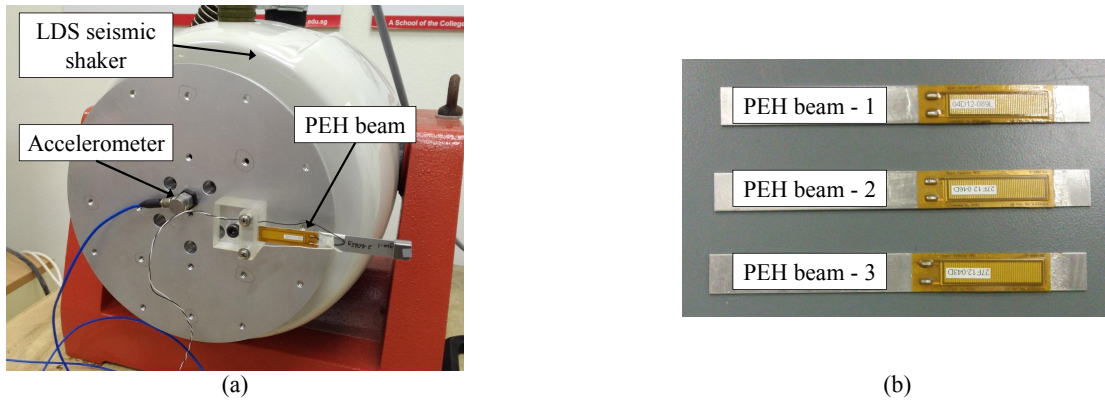
## 3. EXPERIMENTAL INVESTIGATION, OBSERVATIONS AND DISCUSSION

The description of the experimental setup, properties of the test specimens and the observations from the experiments are elucidated in this section.

### 3.1 Experimental setup

The experimental setup for the investigation of fatigue consisted of a PEH beam which was attached on an LDS shaker as shown in Fig.2. An accelerometer was attached to the shaker arm and connected to a shaker controller to monitor and maintain the base excitation levels. A small silver patch was attached to the tip of the PEH beam to monitor the displacement and the velocity at the end of tip mass from time to time, a Polytec laser vibrometer and laser head were used to obtain the velocity and displacement data. The output from the PEH beam was connected to national instruments (NI) voltage DAQ system to monitor the output open circuit voltage ( $V_{OC}$ ). In order to obtain the admittance readings, the MFC transducer was used as an actuator by connecting it to a WK high precision LCR meter. The LCR meter was used to log both the real and imaginary parts of the output admittance of the PEH beam. The PEH beam was prepared by attaching a MFC transducer on the surface of the aluminum substrate, the surface was prepared by roughening up the part where the MFC needs to be attached and cleaning the roughened surface with an MEK solution to remove any dirt

or dust. An epoxy solution was applied to the surface and the MFC was attached with utmost care, for a good fix between the MFC and the aluminum beam, a padded bench vice was used to press the MFC and the beam, and it was left to cure for about twenty four hours in a temperature and humidity control chamber (30C and 10% relative humidity), this procedure was followed to maintain the same quality of bonding over all the specimens. After curing, the excess epoxy on the sides of the beam (if any) was filed off and the lead wires were soldered to the electrode plates of the MFC. Proper care was taken while soldering the lead wires in order to avoid re-soldering at a later stage which might affect the results obtained from the PEH beam. After the preparation of the PEH beam, it was fixed on the arm of the shaker using a hard acrylic support arrangement. In total three PEH beams were prepared and tested, the properties of the PEH beams are as shown in Table.1. A tip mass weighing 4.4235 grams was used for all the three PEH beams and the three PEH beams were subjected to a base excitation level of 0.4g ( $g = 9.81 \text{ m/s}^2$ ), 0.5g and 0.6g respectively. As discussed in the previous section, the base excitation was limited to levels where the behavior of the PEH beam is considered linear and which form a limit for commonly occurring excitation levels under field conditions [12, 15].



**Figure 2.** (a) Experimental setup for fatigue monitoring of PEH beam and (b) PEH beams prepared by attaching MFC on an aluminum substrate.

S.No	Excitation level	Beam size	Tip mass	Aluminum grade
1	0.4g	90 mm X 10mm X 0.635mm	4.4235g	Al - 7075
2	0.5g	90 mm X 10mm X 0.635mm	4.4235g	Al - 7075
3	0.6g	90 mm X 10mm X 0.635mm	4.4235g	Al - 7075

### 3.2 Natural frequency, tip displacement and open circuit voltage

The PEH beams were attached to the shaker and subjected to constant excitation levels, the frequency of the excitation was maintained equal to the resonant frequency of the respective beam. At any given point of time, the maximum stress develops in the beam only when the beam is excited at its natural frequency. From elementary mechanics, it is understood that the natural frequency of a beam is dependent on its stiffness and mass, as the mass of the beam is unlikely to change, the natural frequency is solely a function of stiffness. When a body is subjected to fatigue, its stiffness changes [31] and correspondingly the natural frequency changes. In the present study, this property is utilized to correlate the change in stiffness to the change in natural frequency with increasing number of cycles. The natural frequency, the tip displacement and open circuit voltage are monitored from time to time (about every 2 million cycles); the data thus obtained is processed and shown in Fig. 3, Fig. 4 and Fig. 5 respectively. The variation of frequency for different beams is shown in Fig. 3; the initial frequency for the beams has a variation of about less than 2Hz which can be attributed to the fact that there is a small error of about  $\pm 0.5\text{mm}$  (minimum length of a ruler) in measurement of the beam sizes. Towards the end of each fatigue cycle, there is considerable loss in the stiffness of the PEH beam which results in a decrease in the natural frequency by a minimum of 2-2.5Hz. This correspondingly shows the increase in the tip displacement with passing number of cycles, it was observed that in almost all the cases, the failure in the beam occurred after the peak-peak tip displacement was beyond 10mm. As soon as the final failure occurs in the form of cracking of the substrate at its root, there is a sudden loss of stiffness and tip displacement falls considerably.

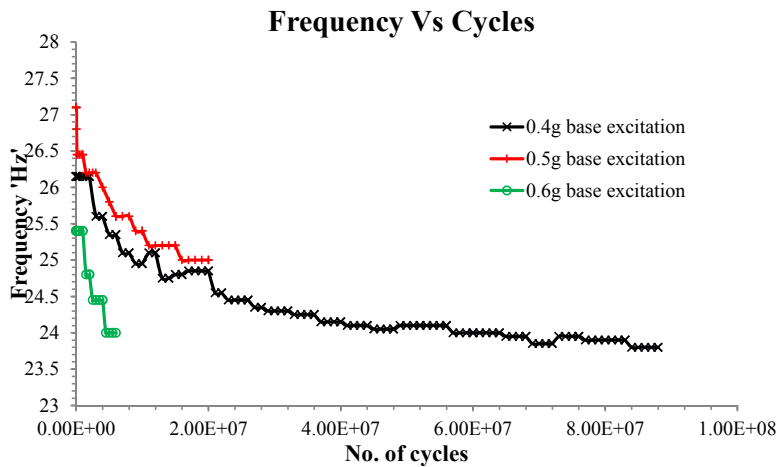


Figure 3. Variation of natural frequency with increasing number of cycles at different excitation levels.

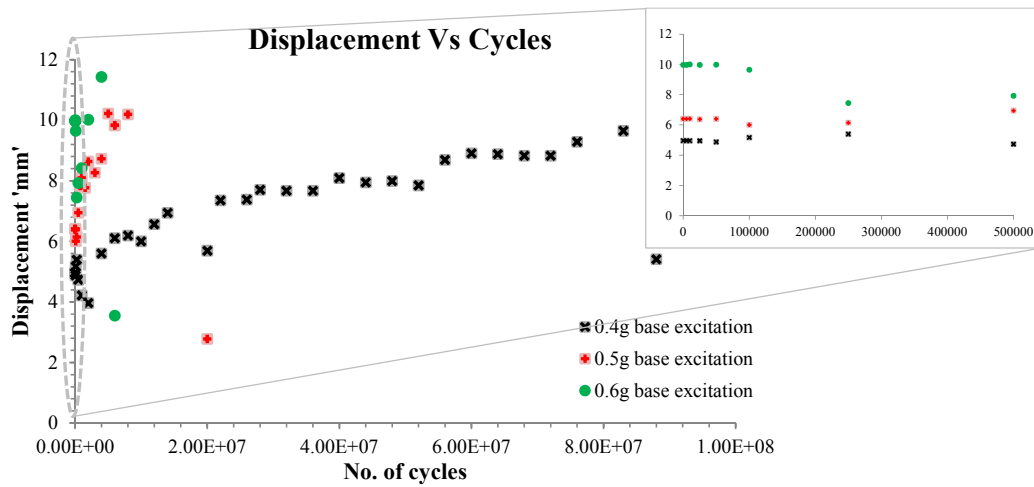


Figure 4. Variation of peak-peak tip displacement with increasing number of cycles at different excitation levels.

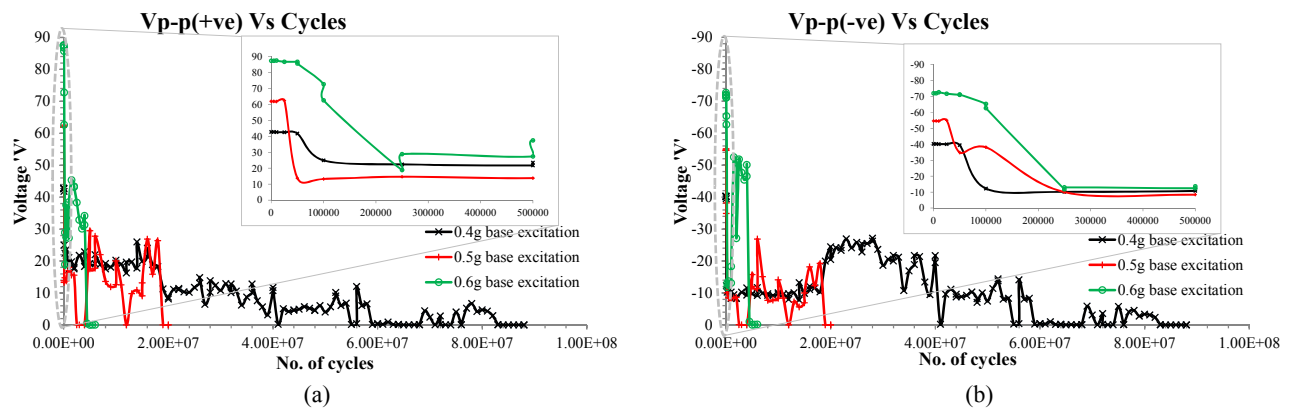


Figure 5. (a) Peak-peak (+ve) open circuit voltage (b) Peak-peak (-ve) open circuit voltage.

Fig. 5 represents the variation of the peak-peak voltage (both +ve and -ve), it is interesting to note that the initial damage in the MFC occurs well before the final damage in the PEH beam. As soon as an initial crack develops on the MFC surface, there is a fall in the voltage readings and the output obtained from the MFC is no longer a perfect sinusoidal as

represented in Fig. 6. Though there is a voltage across an electrical circuit, the positive peaks diminish to spikes and the negative peaks remain sinusoidal till further damage occurs. This presents an interesting view into the behavior of the PEH beam over an extended period of time, similar behavior was observed in all the three beams which conveys the fact that the top surface of the beam where the strain is relatively higher gives away and as the cracks propagate the voltage output slowly varies from sinusoidal to periodic spikes (+ve) to periodic spikes of both positive and negative voltage outputs to a final decimation into noise. This can be observed from the voltage plot in Fig. 5, close to the final damage of the substrate the Voltage is almost zero. The initial damage in the MFC transducers is prominently observed in the insets for the Fig. 5, as soon as some damage occurs in the MFC transducer, the voltage amplitude falls and it can be noticed that as the excitation level increases beyond 0.4g this initial damage occurs even before 50,000 cycles. From a perspective of purely fatigue behavior, it can be stated that for any given random excitation condition this experimental finding gives an estimate of the number of times the response of a PEH beam can exceed the threshold of the response to a resonant frequency before any damage to the MFC transducer can occur [30].

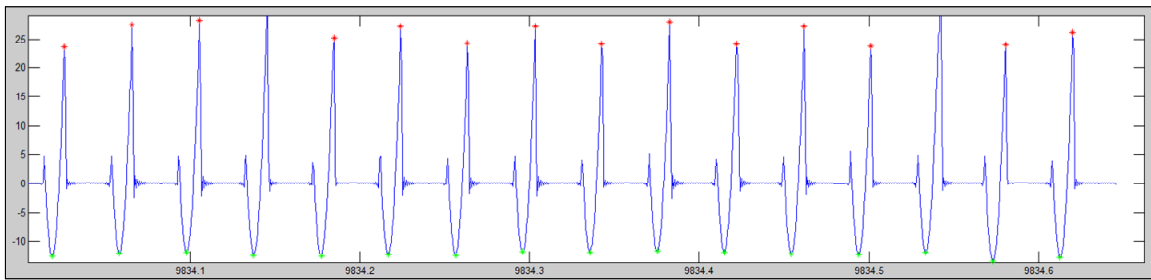


Figure 6. Open circuit voltage after initial damage to the MFC transducer.

### 3.3 Variation of Admittance function and RMSD variation

The preliminary step in a piezo based damage monitoring study is the comparison of the admittance or impedance function especially the real part, as it is more sensitive to damage. As the admittance readings obtained from a piezoelectric transducer represents a coupled function of the impedance of transducer and the structure on which it attached, an investigation of the admittance values is simpler and informative. For a more detailed investigation of the damage monitoring, the electro-mechanical impedance (EMI) techniques can be utilized [6, 7]. In this work, the admittance values obtained using a LCR meter is used to understand the overall health of the PEH beam. Fig. 7 shows the admittance readings of the PEH beam subjected to excitation levels of 0.4g. The mathematical expression for the admittance function  $Y$  is shown in eq.1, where  $G$  is the real part and is called Conductance (units: Siemens), and  $B$  is the imaginary part which is known as Susceptance (units: Siemens). The electrical impedance ( $Z$ ) is represented as the conjugate of the admittance function.

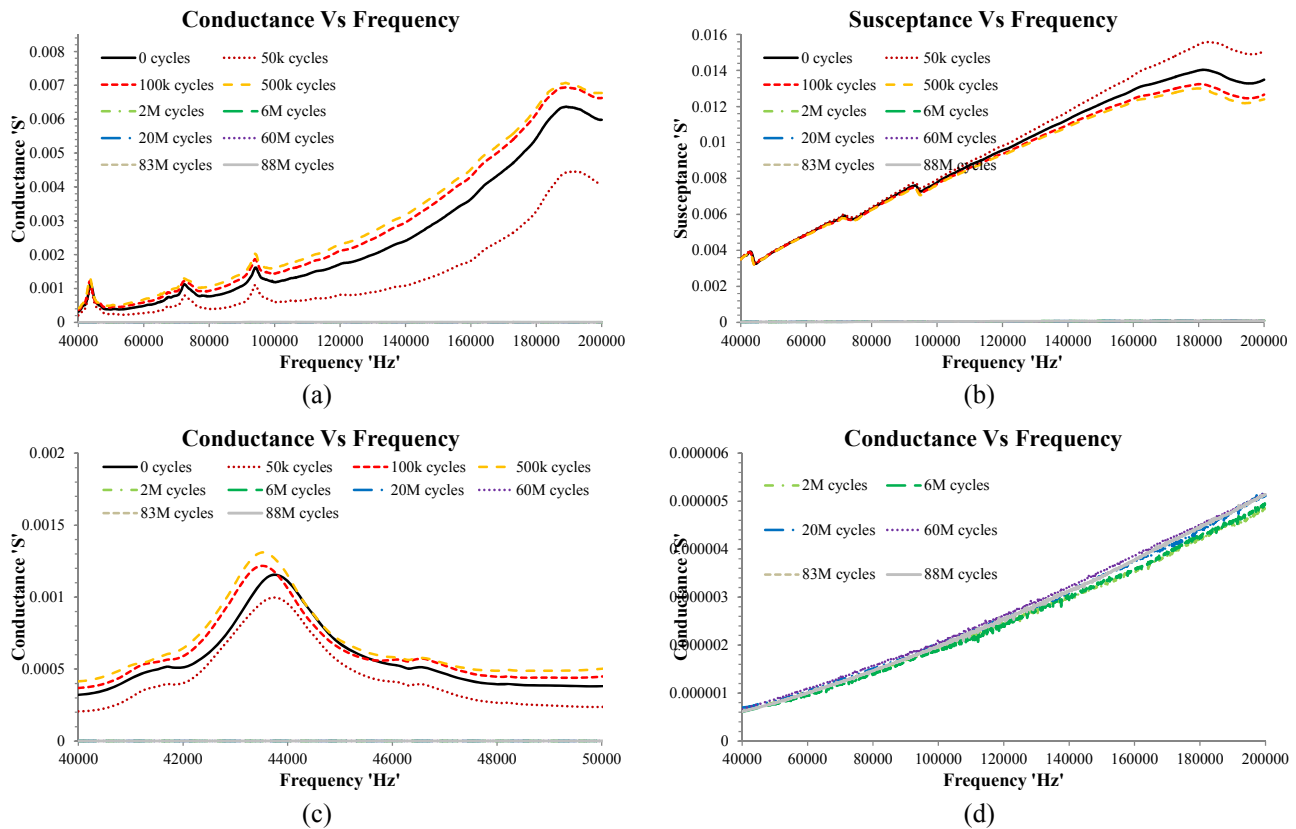
The root mean square deviation (RMSD) is popularly used to obtain the change in the values of the conductance with progression in damage; it is represented by eq. 3 [6], where  $G^j$  is the conductance values after  $j^{th}$  cycle and  $G^0$  is the conductance value after zero cycles and  $i$  is the measurement point in consideration; the RMSD values for the PEH beam subjected to an excitation level of 0.4g with passing fatigue cycles is portrayed in Fig. 8. The RMSD values are known to provide a rough estimation of the onset of the damage and other detailed EMI techniques can be used to investigate the damage thoroughly. The RMSD values obtained in the present study doesn't present a comprehensive idea into the change in the conductance values after the initial damage to the MFC, it would be an added advantage to obtain an index which can characterize the behavior of the beam near the final failure; thus, to obtain a more informative comparison of the change in conductance values, a relative RMSD (Rel.RMSD) is used which gives the change of the  $j^{th}$  cycle with respect to the  $(j-1)^{th}$  cycle as shown in eq. 4. The usage of this Rel.RMSD is proposed in the light of Fig. 7(d), where the change in the conductance values with respect to the initial base value is quite significant but the relative change between the values goes un-noticed, thus the Rel.RMSD values are represented in Fig. 8.

$$Y = G + iB \tag{1}$$

$$Y = Z^{-1} = (R + iX)^{-1} \tag{2}$$

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^N (G_i^j - G_i^0)^2}{\sum_{i=1}^N (G_i^0)^2}} \times 100 \quad (3)$$

$$Rel.RMSD(\%) = \sqrt{\frac{\sum_{i=1}^N (G_i^j - G_i^{j-1})^2}{\sum_{i=1}^N (G_i^{j-1})^2}} \times 100 \quad (4)$$



**Figure 7.** (a) Comparison of real part of admittance values (Conductance) for a PEH beam under 0.4g excitation (b) Comparison of imaginary part of admittance values (Susceptance) for a PEH beam under 0.4g excitation (c) Conductance values in a range of 40kHz-50kHz (peak comparison) (d) Comparison of Conductance values for cycles beyond 2million.

The usability of a piezo transducer after an initial damage is considered unreliable [6, 7, 8], though this claim holds good in most cases, it was observed that for an MFC transducer there is a slight variation in the slope of the conductance values as shown in Fig. 7 (d), this behavior was observed in all the PEH beams and can be clearly observed using the Rel.RMSD plots as shown in Fig. 8. Thus, a further investigation into the behavior of the cracked MFC transducers is necessary before it can be declared completely unworkable after the initial cracks. The Rel.RMSD plots expose the variation of conductance just before the final failure of the PEH beam (approx. 88million cycles – 0.4g; approx. 20million cycles – 0.5g; approx. 6million cycles – 0.6g), it was observed that two out of the three times there is a distinct peak that can be identified just before the beam cracks due to fatigue failure of the substrate.

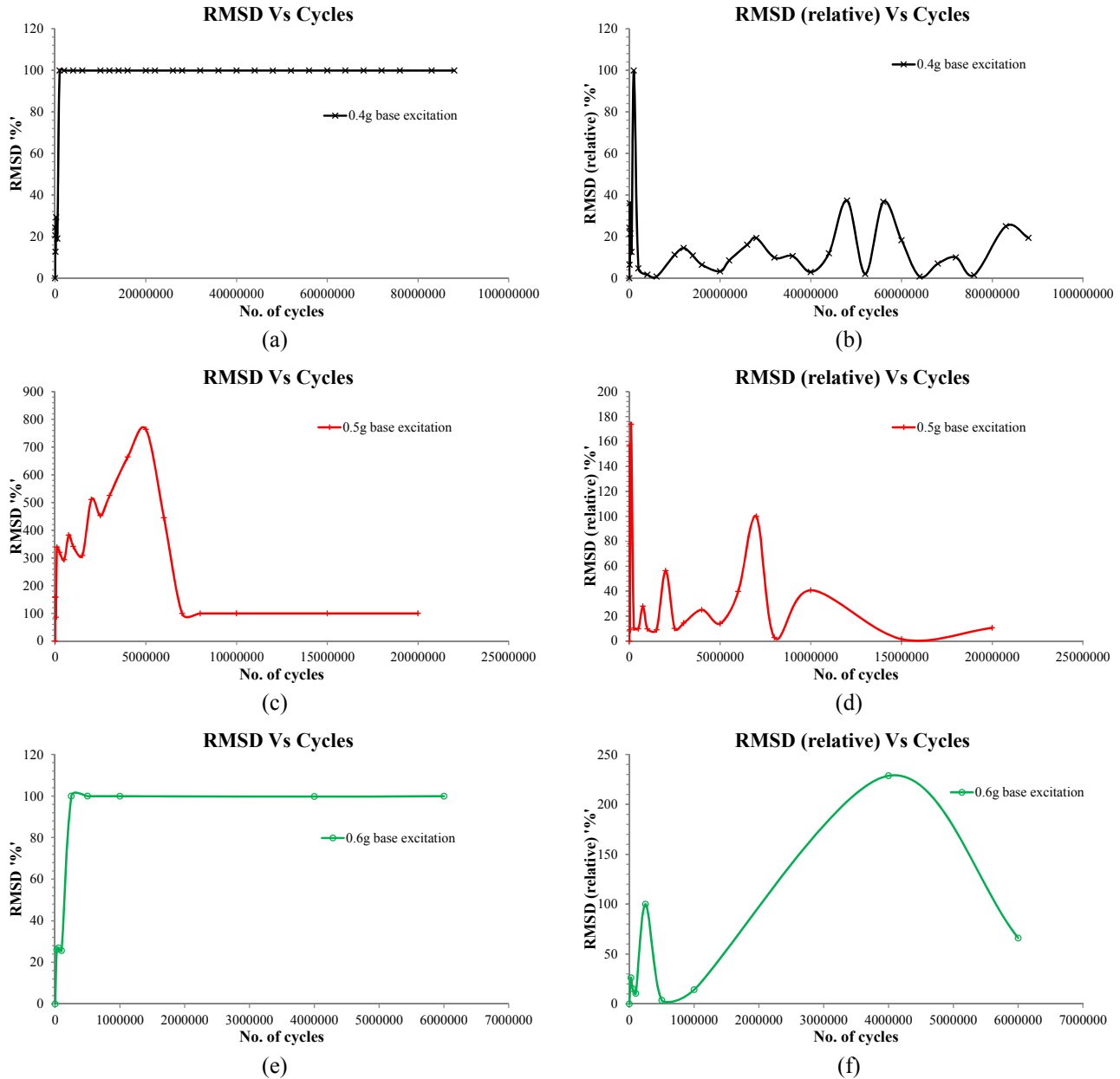
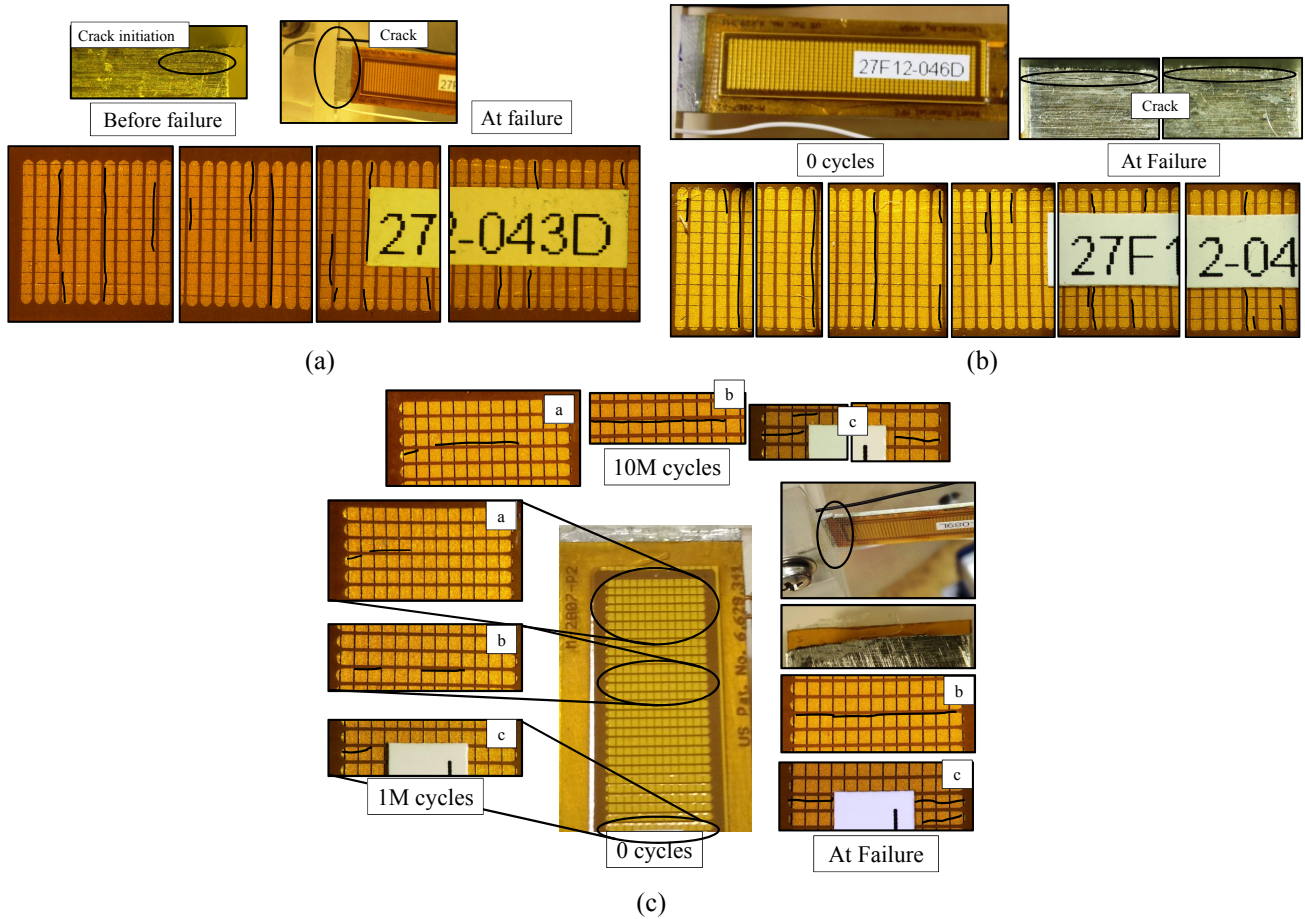


Figure 8. RMSD and Rel.RMSD plots for base excitations of: (a) 0.4g (b) 0.5g and (c) 0.6g.

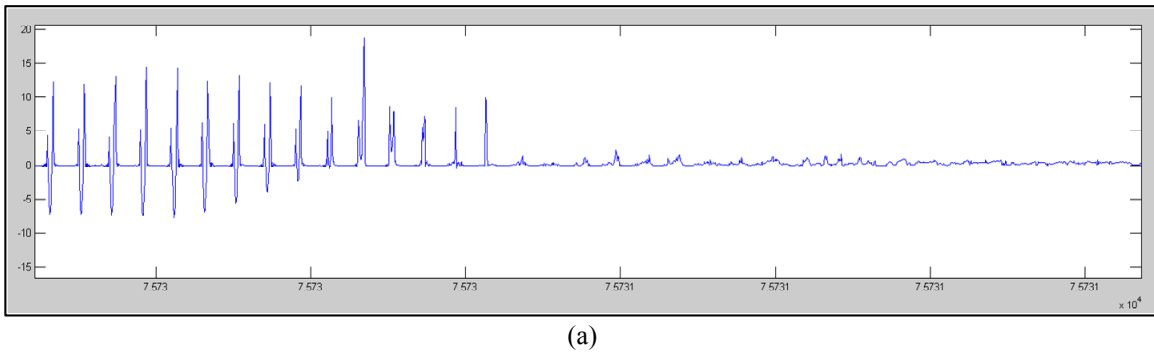
### 3.4 Final failure and damage to the MFC's

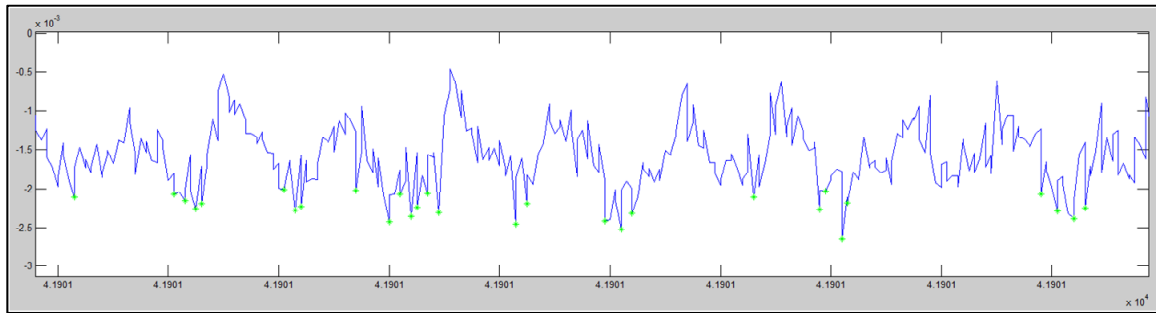
A pictorial description of the damage that occurred in the PEH beam during the course of the experiments is illustrated in this section. Fig. 9 shows the pictures of the PEH beams before and after failure, all the cracks were observed using a Nikon microscope and are highlighted with black lines for better comprehension. Due to paucity of space a lot of pictures haven't been shown in this paper. From the experiments, it was observed that all the three beams followed a similar trend in the progression of the fatigue damage. The initial damage occurs in the MFC transducer (Fig. 9 (c) illustrates the progression of fatigue damage in the PEH beam subjected to a base excitation of 0.5g) specifically near the root of the beam, the main reason for this damage is the occurrence of maximum stress near the top layer of the MFC. On examination, in all the PEH beams this resulted in a drastic change in the behavior of the open circuit voltage (change in sinusoidal behavior) and the corresponding RMSD values. Following this initial damage, the consequent cracks were

observed to progress along the length of the beam, major damage to the MFC transducers was observed near the root of the beam and near the manufacturers label towards the end of the MFC; though this is an unlikely place from the stress concentration point of view, the procedure of attaching the label needs to be further investigated to understand this behavior. With an increase in the number of fatigue cycles more and more cracks start to appear all along the length of the MFC and eventually the substrate succumbs to the effect of fatigue resulting in a complete failure of the PEH beam at its root. During the experiments it was observed that a complete damage in the MFC results in noise of the output open circuit voltage but a complete damage to the substrate results in noise that is biased towards the negative values, this is shown in Fig. 10.



**Figure 9.** Illustration of the damage in the MFC transducer for base excitations of: (a) 0.4g (b) 0.6g (c) 0.5g.





(b)

**Figure 10.** (a) Voltage plot near the complete failure of the MFC and (b) Voltage plot after the fatigue failure of the substrate.

#### 4. CONCLUSIONS AND FUTURE WORK

A detailed experimental investigation into the behavior of a set of three PEH beams subjected to fatigue under constant base excitation conditions of 0.4g, 0.5g and 0.6g respectively is presented in this work. As there has been little reported work in the literature examining the fatigue behavior of MFC transducers and PEH beams, this work presents a necessary addition into the design consideration for long term usage of a PEH beams. A detailed discussion of the variation of frequency, tip displacement and peak-peak open circuit voltage has been provided in section 3; though the investigation of the health of the PEH beam using the MFC as an actuator is not thoroughly conclusive, the variation of RMSD and Rel.RMSD values provide a fundamental understanding that the damage in the MFC transducer doesn't necessarily render it useless. A further investigation into this area would hugely benefit the research fraternity. Additionally, the description of the chronology of fatigue damage and the behavior of the MFC and PEH beam can be taken into consideration for future designs of energy harvesters associated with long term field applications. Further investigations involving lower base excitation levels might aid the PEH beam designs but the likelihood of reaching a fatigue fracture of the substrate is low and in such cases the fatigue limit of 500 million cycles for an aluminum substrate can be considered as a fatigue failure. Lastly, a mathematical basis for the present experimental study is underway and will be illustrated in the future works.

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