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Degradation of Piezoelectric Materials for Energy Harvesting Applications

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Abstract.

The purpose of energy harvesting is to provide long term alternatives to replaceable batteries across a number of applications. Piezoelectric vibration harvesting provides advantages over other transduction methods due to the ability to generate large voltages even on a small scale. However, the operation in energy harvesting is different from typical sensors or actuators. The applied stress is often at the material limit in order to generate the maximum power output. Under these conditions, the degradation of the materials becomes an important factor for long term deployment. In this work bimorph piezoelectric beams were subjected to lifetime testing through electromagnetic tip actuation for a large number of cycles. The results of two measurement series at different amplitudes are discussed. The dominant effect observed was a shift in mechanical resonance frequencies of the beams which could be very detrimental to resonant harvesters.

1. Introduction

In the field of energy harvesting, i.e. generating electricity locally from surrounding sources, piezoelectric materials convert mechanical into electrical energy. The advantage of piezoelectric transducers compared to electromagnetic systems is that they provide sufficiently high voltages for efficient power processing, even at a small device scale [1]. At the same time, they do not need high priming voltages or small, i.e. hard to fabricate, gap sizes as do electrostatic transducers.

Piezoelectric materials can be used in two ways. They either generate a voltage when a stress is applied (sensor or generator), or, vice-versa, they deform when a voltage is applied (actuator). In sensor applications, very small stresses are usually sufficient in order to create a readable voltage, e.g. in pressure gauges. Research has been published on fatigue of PZT [2,3], AlN [4] and the lifetime of multilayer stack actuators [5,6]. However, most of these articles look at the problem from the electrical side rather than investigating the effects of mechanical loading. Even in papers that address mechanical degradation, as in [7,8], the focus is not on energy harvesting from bending beams where the goal is to extract the maximum possible power. Nevertheless, [8] suggests that the mechanical degradation behaviour of piezoelectric materials could be much worse than the electrical one.

The present paper therefore investigates degradation behaviour of piezoelectric bimorph bending beams as they are commonly used for energy harvesting: namely at high stress levels.



2. Prototype And Experimental Set-Up

Figures 1 and 2 show an experimental set-up comprising a series connected bimorph piezoelectric bending beam ($19.5 \times 1 \times 0.37$ mm) that is actuated via an electromagnet and a permanent magnet at its tip. In contrast to a previous set-up with base excitation, this method allows large tip deflections even when operated “off-resonance”. An Agilent E4980A precision LCR meter is used to record impedance spectra and material parameters such as capacitance and Q-factor. The system is controlled via a Labview program. Furthermore, a laser displacement sensor monitors tip deflection and the measured output voltage of the piezoelectric beam can be recorded after running it through a voltage attenuation op-amp circuit.

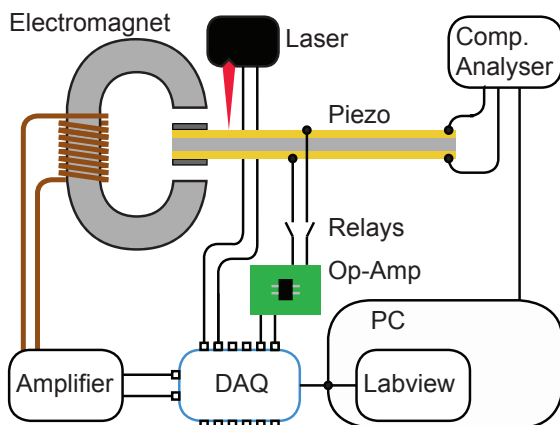


Figure 1: Layout of the measurement set-up

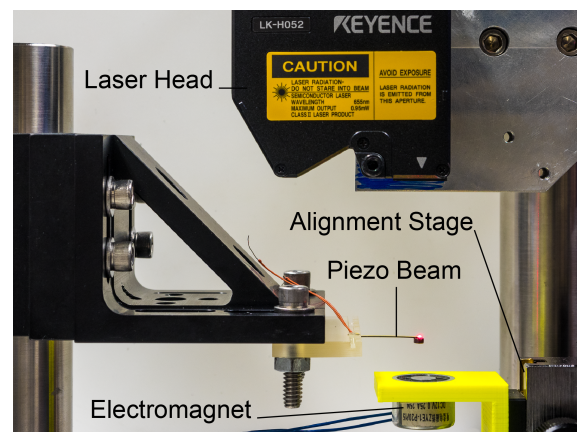


Figure 2: Photograph of the laser head, electromagnet and piezoelectric beam

In order to achieve reliable impedance values, no additional circuitry can be connected to the piezoelectric element during this measurement. This is why the measurement procedure follows three steps. First, reed relays are used to disconnect the op-amp circuit and connect the LCR meter to the piezoelectric beam for the measurement of electrical parameters. Second, the op-amp circuit is connected, the LCR meter disconnected and a low amplitude chirp signal is applied to the electromagnet. The resulting voltage and displacement recordings are used to determine the resonance frequency of the beams at this stage by applying an FFT to the signals. Finally, a fixed number of sinusoidal oscillations, e.g. 50000, with a set tip deflection is applied to the beam at a driving frequency of 100 Hz (below resonance), before repeating the entire procedure for a number of iterations.

3. Results

The above measurement procedure was applied to two beams separately. The only difference between the two measurements was the peak to peak tip deflection, set to 1 mm (yielding a maximum tensile beam strain of 0.073%) for beam 1 and set to 0.85 mm (maximum tensile beam strain of 0.062%) for beam 2. Beam 1 snapped to the electromagnet at 1.2 million cycles due to the close proximity of the electromagnet to the beam tip required to achieve 1 mm tip deflection, which ended the experiment. The tip deflection for beam 2 was consequently lowered to prevent this from happening. In addition, the resolution for the resonance frequencies and impedance spectra was improved for the measurements on beam 2. This beam was tested for 20 million cycles.

Figures 3 and 4 show the impedance magnitude spectra for both beams at the start and at the end of the measurements. The 1.2 million cycles impedance spectrum for beam 1 was recorded just before it snapped. Interestingly, the first beam shows a much larger shift in the curve with

a dramatic difference in electrical resonance frequency even after only 1.2 million cycles. This is reflected in the corresponding impedance phase spectra in figures 5 and 6.

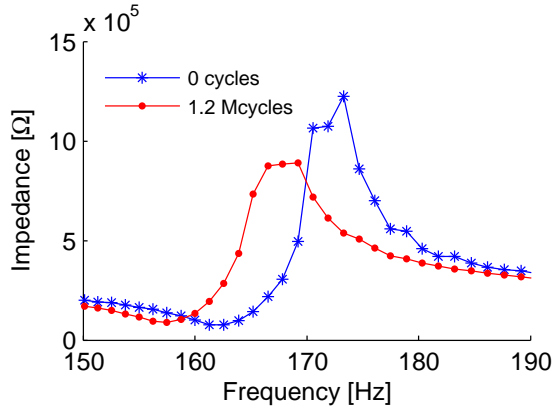


Figure 3: Impedance magnitude spectra (beam 1)

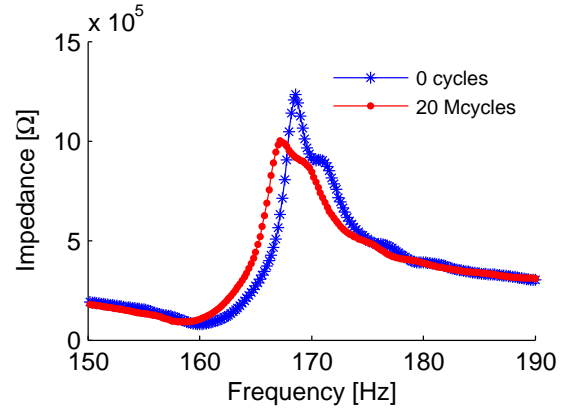


Figure 4: Impedance magnitude spectra (beam 2)

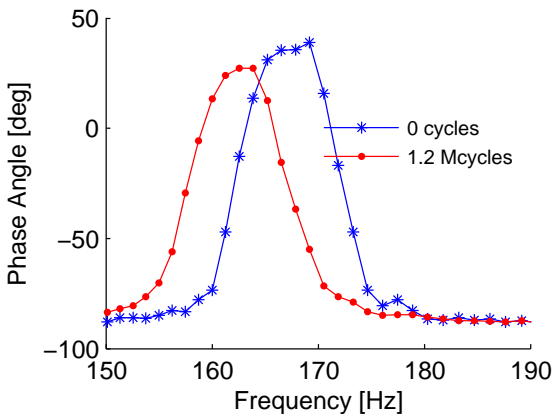


Figure 5: Impedance phase spectra (beam 1)

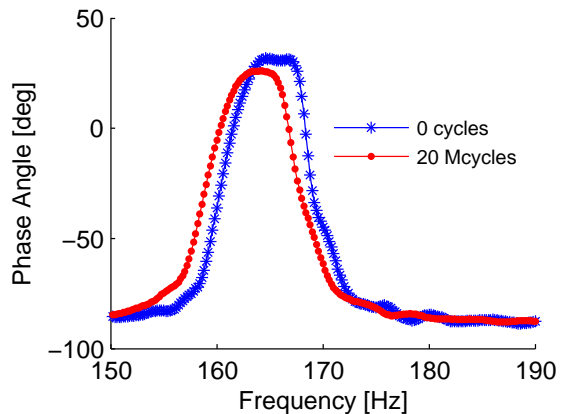


Figure 6: Impedance phase spectra (beam 2)

These results suggest that the small difference in peak to peak tip deflection can dramatically affect the cycle life of these piezoelectric beams.

Figures 7 and 8 compare the mechanical resonance frequencies as determined by the laser signal and the piezoelectric voltage, the electrical resonance frequencies from the impedance spectra and the frequencies of the impedance maxima for both beams up to 1.5 million cycles. After 1.5 million cycles, the frequencies for beam 2 started stabilising and showed little change over the following 18.5 million cycles. Congruent with the previous findings for the impedance spectra, the initial change in frequencies is much less pronounced for beam 2 than it is for beam 1, indicating a faster degradation in beam 1 due to the higher tip deflection. Nevertheless, in both cases a drop in mechanical resonance frequencies of 3 to 4 Hz can be observed. This is a dramatic shift, given that the bandwidth, based on Q-factors and a starting frequency around 165 Hz, is less than 4 Hz. This would be highly detrimental for a resonant harvester designed to operate around that frequency as the operation would be pushed beyond the half-power point and the entire system might fail. It is also important to note that the most significant shifts

happen within the first million cycles, which, at a driving frequency of 100 Hz, equates to less than three hours of continuous run time.

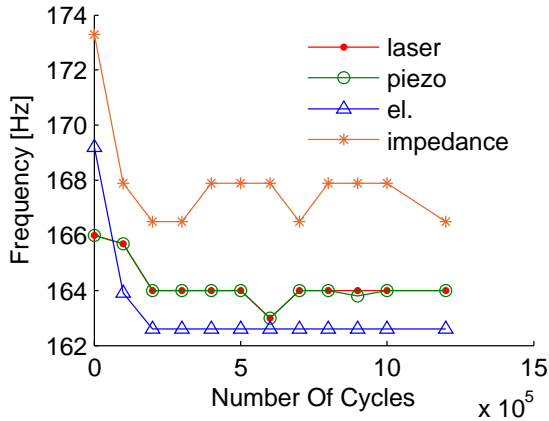


Figure 7: Resonance frequencies and frequencies of the impedance maxima vs. number of cycles (beam 1)

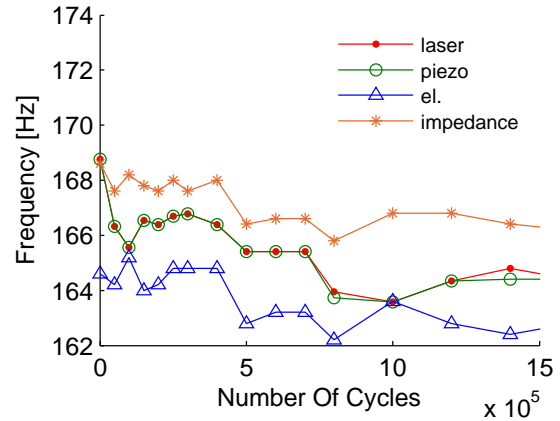


Figure 8: Resonance frequencies and frequencies of the impedance maxima vs. number of cycles (beam 2)

The variations in capacitance and Q-factor for beam 2 over the entire 20 million cycles are shown in figures 9 and 10 respectively. At this stage it is not entirely clear what causes the various spikes in both graphs. It is suggested this might be due to difficulties experienced when connecting to the LCR meter through LabView and will be investigated further. Nevertheless, a slight reduction in both capacitance and Q-factors appears to be the trend. In combination with the previous graphs, shifts in mechanical resonance frequencies are the clearest indicator of degradation.

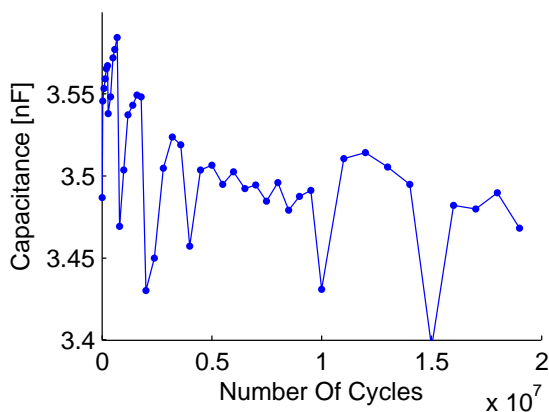


Figure 9: Capacitance vs. number of cycles (beam 2)

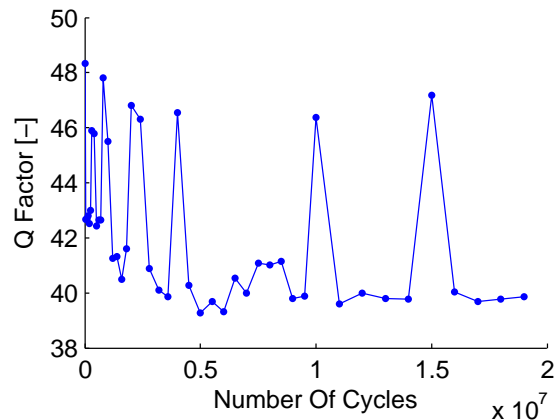


Figure 10: Q-factor vs. number of cycles (beam 2)

These shifts can be caused by micro-cracking of the piezoelectric layers as observed under magnification on a damaged sample of a piezoelectric beam, see figure 11. Such fractures provide an explanation for a stiffness reduction that causes the resonance frequency to decrease.

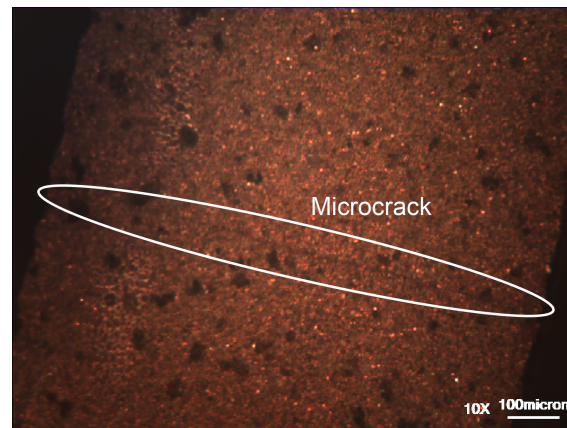


Figure 11: 10 times magnified image of a hairline crack on a damaged piezoelectric beam

4. Conclusions

This paper presents experiments on the degradation of piezoelectric bending beams with the particular application of energy harvesting in mind where the materials are operated close to their limits. At the same time, such systems are to be deployed in the field for many years and their lifetime needs to be guaranteed in order to inspire confidence and widespread adoption.

Experiments on two beams with different peak to peak tip deflections suggest that small changes in operating conditions can have a large effect on lifetime. The most pronounced effect was a shift in mechanical resonance frequency which could be especially detrimental for resonant harvester designs that might lose a significant amount of their power output even after short run times.

Ultimately, there is a broad scope for future research on this topic. Experiments will be performed on a larger number of piezoelectric beams at different tip deflections, different material compositions, larger cycle counts, different electric loads, etc. Further improvements on the experimental set-up are necessary and an analysis relating tip deflection and material stress will be helpful in order to make recommendations for safe operation of these materials in energy harvesting.

Acknowledgments

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