Aging assessment of piezoelectric energy harvester using electrical loads

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Abstract. Vibrational energy harvesting is an alternative solution for replacing batteries in autonomous wireless devices. Besides the performance of piezoelectric energy harvesting generators, the reliability of such structures must be considered when long lifetime is required. In this paper, we propose a new approach based on stress electrically induced to deal with aging of piezoelectric bimorph structure for vibrational energy harvesting. To this end, induced mechanical stress in bimorph structure using electrical solicitation is investigated and compared with mechanical excitation by using finite element modelling. A dedicated test bench was developed. An accelerated aging test of a piezoelectric bimorph operated at 178.5Hz (9x resonance frequency in real use) under a maximum stress of 50MPa using stress electrically induced approach was performed during 4 months. The results are discussed and showed the feasibility of this electrical approach for reliability studies of piezoelectric energy harvesting devices.

1. Introduction
Recently, piezoelectric materials have been designed and processed to address energy harvesting applications. Mechanical energy available in surrounding environment is converted into electrical energy by using the direct piezoelectric effect. This allow to power up industrial, domestic, automotive wireless sensors or implantable medical devices. Ferin et al [1] reported that miniaturized piezoelectric energy harvesting generator based on thinned bulk piezoelectric material process showed a promising normalized power density of 6.6mW/cm3/g2 at very low frequency (23.2Hz) and can provide enough energy to operate implanted medical devices. However, implanted medical devices would require extensive lifetime (>20years) since periodic replacement represents an unacceptable risk for the patient. Thus main failure modes have to be identified and investigated to ensure the long lifetime operation of implant and help its design optimization.

The reliability has extensively been studied for piezoelectric sensors and actuators [2], researchers are now interested to study the reliability of energy harvesting devices [3,4]. Induced mechanical stress using mechanical solicitation approaches are used to evaluate device’s reliability but aging capabilities of such semi-perpetual system are difficult since a representative test would require several billion cycles and would mostly be an aging test for the test equipment itself.

We herein propose an alternative relying on the resonating property analysis of a well-known clamped-free cantilever beam when electrically stressed on its first eigen flexural mode. Such a strategy allows to significantly simplify the mechanical fixture to reduce its own aging impact and dramatically accelerate the aging process.

2. Structure architecture
The most common structure used in vibrational energy harvesting is a clamped-free cantilever. The structure consists of two piezoelectric layers laminated on a conductive shim layer. A seismic mass is generally attached at the free end of the bimorph to tune the resonance frequency of device to vibrational environmental spectrum (<200Hz). The two faces are plated with titanium/gold metallic electrodes deposited by Pressure Vapour Deposition (PVD) techniques. The structure architecture is presented in Figure 1. In this paper, the cantilever beam stack-up is depicted in the Table 1.

![Figure 1. Piezoelectric energy harvesting generator.](image)

| Type           | Piezo layer | Shim layer | Piezo layer | Electrode |
|----------------|-------------|------------|-------------|-----------|
| Type           | Hard PZT    | Brass      | Hard PZT    | Ti/au     |
| Thickness (µm) | 60          | 12         | 60          | 0.5/0.25  |
| Length (mm)    | 20          | 20         | 20          | 20        |
| Width (mm)     | 4           | 4          | 4           | 4         |

3. Stress electrically induced approaches

In the real use case of energy harvesting from heart beats for example, the bimorph cantilever is excited from its base by a vibration signal (cf. Figure 2.a). It will vibrate at its first flexural mode which is close to the spectrum of the excitation source (~20Hz).

The reliability of such piezoelectric energy harvesting generator is studied using mechanical stress induced approaches [3,4] in which the tip of the cantilever beam is actuated out of its resonance frequency with a sinusoidal deflexion. Alternative mechanical stress is then applied to the bimorph structure (cf. Figure 2.b) using complex mechanical fixtures that impact the accuracy of the whole testing process.

We herein propose a new method based on an actuation mode using electrical solicitation to generate representative mechanical stress in the clamped-free bimorph structure. A sinusoidal voltage is indeed applied between the top and bottom electrodes of the piezoelectric bimorph, making the beam oscillating accordingly (cf. Figure 2.c).

![Figure 2. Stress induced in real use case with a tip mass a) or using mechanical b) and electrical c) solicitations.](image)
Generating high stress level would require high voltage excitations that could exceed the coercive field voltage (0.5kV/mm) of each piezoelectric layers which would shorten the device lifetime or at least its aging behaviour. To avoid any electrical aging effect, the bimorph is cycled at its first eigen flexural resonance with much smaller excitation voltages generating the same stress level.

Finite element analyses using Comsol Multiphysics® software are carried out to investigate the electromechanical behaviours of piezoelectric bimorph cantilever in the above-mentioned cases, a real seismic solicitation and mimicking electrical and mechanical solicitations. The Table 2 describes FEM analyses of each case. The induced deflection at the tip of bimorph cantilever has been fixed at 0.912mm.

To induce such level of deflection: an acceleration of $6.1mG$ is applied to the bimorph in the real use case and a 2Vpp voltage is applied to the bimorph in the case of electrical solicitation.

Table 2. Summary of FEM analyses

| Case                           | Real use case | Mechanical solicitation | Electrical solicitation |
|-------------------------------|--------------|-------------------------|------------------------|
| Excitation frequency          | 20Hz         | 100Hz                   | 183Hz                  |
| First flexural mode           | Yes          | No                      | Yes                    |
| Tip masse (dimension and weight) | Tungsten     | None                    | None                   |
| Input excitation              | $6.1mG$      | 0.912mm                 | 2Vpp                   |
| Tip deflexion                 | 0.912mm      | 0.912mm                 | 0.912mm                |
| Maximum stress-induced        | 50MPa        | 56MPa                   | 52MPa                  |

Figure 3 shows the comparison of induced stress on the top surface of the bimorph cantilever between electrical, mechanical solicitations and real use case. It is observed that the distribution of induced stress along the cantilever’s length is equivalent to all cases. It means that we can utilize electrical solicitation to generate the same stress distribution in bimorph structure.

![Figure 3. Stress distribution in a piezoelectric bimorph cantilever on the top surface with different solicitation types.](image)

4. Experimental investigation

The electrical way is therefore used to experimentally oscillate the bimorph cantilever. Figure 4.a shows a schematic of experimental set-up for stress induced using electrical solicitation approach. The sample is a clamped-free bimorph structure described in table 1. The sample has been solicited with a sinusoidal
voltage of 2Vpp at its first natural frequency by using an arbitrary waveform generator (Gwinstek GFG-3015). The generated deflection at the tip of the bimorph has been measured by a laser telemeter. Based on this principle, we developed a dedicated and fully automated test bench where the beam shape and the displacement at the tip end of each beam is continuously monitored using high frequency LASER telemeter (Keyence LK-G5000). The arbitrary waveform generator is replaced by an electronic circuit which allows to supply an alternative voltage for each bimorph. The test bench is placed in a controlled environment with regulated temperature and humidity (37°C and 40%) (cf. Figure 4.b).

5. Results and Discussions

Figure 5 shows a preliminary result of one tested bimorph cantilever. The peak to peak tip deflection is set to 1.75mm at T = 0 cycle which is consistent with 50MPa of maximum stress at the clamped end. The tip deflection in function of number of cycles has tendency increased but it still remains around 1.8mm. After 6.7 billion cycles, the tip deflection is dropped below 0.1mm.

Figure 5. Displacement at the tip of a cantilever beam in function of number of cycles.

It is known that to examine electro-mechanical properties and reliability of a piezoelectric based device over its lifetime, the impedance spectroscopy is mostly utilized [5]. Indeed, impedance spectra of the sample was measured. Figure 6 shows the measured impedance of the tested bimorph. The resonance frequencies slightly decreased by 0.6Hz from 0 cycle to 5.3 billion cycles and dramatically shifted at 6.7 billion cycles. It could be explained that under repeated stress, the bimorph cantilever becomes softer. The flexural stiffness of the beam has decreased and then the mechanical resonance frequency as well.
Figure 6. Measured impedance of bimorph cantilever beam.

A dramatic change in the magnitude of impedance modulus is also observed at both resonance and anti-resonance frequencies. It means that the mechanical quality factor (Q factor) has changed, it has dropped from 234 at the beginning of the test to 107 at 6.7 billion of cycles.

6. Conclusions
This paper presents a new approach for aging studies of piezoelectric energy harvesting generators using electrical solicitation. FEM analyses and experiments has proven that electrical solicitation can be used to assess the reliability of energy harvesting generator.

Using this electrical solicitation approach, it is possible to accelerate the aging test by shortening the beam length. A larger number of piezoelectric bimorph beams of 4mm x 11.5mm (width x length) and different tip deflections will be cycled at their resonance frequency around 560Hz (28 times the real use case) to build an S-N curve (maximum stress versus the number of cycles to fracture). This is helpful in order to give recommendations for safe operation of these vibration energy harvesting devices.

References
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