

# Reliability study of Piezoelectric Structures Dedicated to Energy Harvesting by the Way of Blocking Force Investigation

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**Abstract.** In this paper we propose an approach to study the reliability of piezoelectric structures and more precisely energy harvesting micro-devices dedicated to autonomous active medical implants (new generation pacemakers). The structure under test is designed as a bimorph piezoelectric cantilever with a seismic mass at its tip. Good understanding of material aging and mechanical failure is critical for this kind of system. To study the reliability and durability of the piezoelectric part we propose to establish a new accelerated methodology and an associated test bench where the environment and stimuli can be precisely controlled over a wide period of time. This will allow the identification of potential failure modes and the study of their impacts by the way of direct mechanical investigation based on stiffness and blocking force measurements performed periodically.

## 1. Introduction

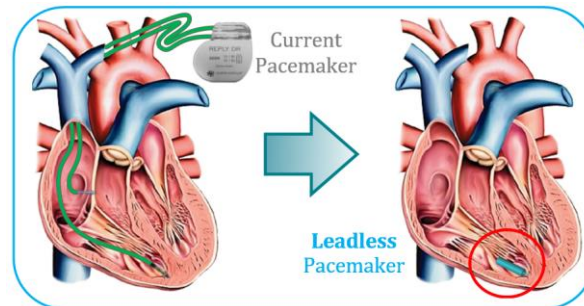
Recent advances in microfabrication and biotechnology have allowed the development of a wide variety of implantable miniaturized systems. Their application can range from monitoring and diagnostics to localized treatments. All these systems include, among other things, electronics parts and require an energy source to be supplied. Even if the use of a battery is still possible, the replacement of it (and more generally the whole system) is not a common and simple procedure especially in the case of a leadless pacemaker that is directly implanted within a heart cavity of the patient (Figure 1). In this case energy harvesting is an interesting alternative to traditional batteries making the targeted systems fully autonomous and allowing further miniaturization and enhanced functionalities.

Academic and industrial studies have shown through different proofs of concept the viability of this approach, particularly for leadless pacemakers [1]. Different principles/architectures were developed and evaluated in the literature. As example, some of them use electrostatic transduction [2] [3], blood pressure variations [4] [5] or piezoelectric stacks as the targeted system developed by SORIN CRM (Cardiac Rhythm Management) and studied in this paper.

In all these cases, maximizing the power density invited to use different materials to their full potential. However, the long term reliability of these devices/materials is largely unknown today, and detailed study is needed to pass from proof concepts to demonstrators and finally to industrialization. Indeed, the knowledge of the lifetime materials, components and assemblies is necessary to ensure



proper long-term operation of the implant, and optimize device performance. In the field of medical implants like pacemakers, their long-term reliability is crucial because it could impact patient survival.



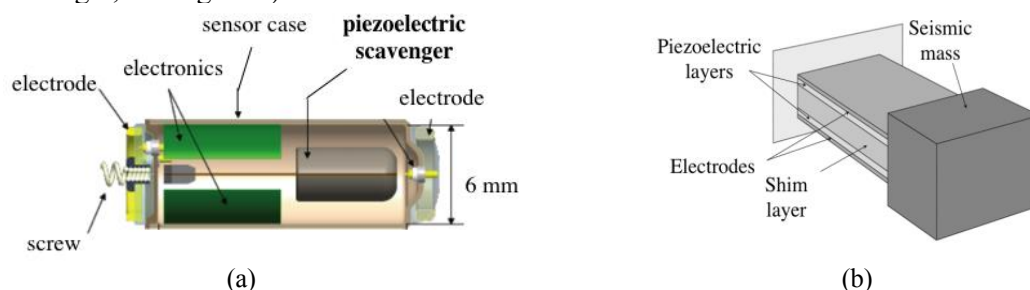
**Figure 1.** Current Pacemaker versus Leadless Pacemaker.

To investigate electro-mechanical properties and so the reliability of a piezoelectric-based device over its lifetime, several approaches are possible. The most common is certainly impedance spectroscopy that allows extracting from the measurement of impedance/admittance over frequency the main electro-mechanical parameters (resonant frequencies, associated Q factors, coupling coefficient [6]). Nevertheless, due to excitation amplitude generally provided by the commercial impedance meters and the underlying formalism (small-signal hypothesis), this method doesn't allow to investigate large signal behaviour and so possible piezoelectric/mechanical nonlinearities.

In our case we propose an original massively parallel aging test bench (up to 36 structures could be simultaneously tested) where the device under test is actuated through its base by the way of a shaker. Thanks to a custom system associated to each structure under test, it makes possible to extract the structure stiffness measuring the reaction force for a given movement but also the blocking force for a given excitation voltage. That allows to extract periodically electro-mechanical parameters of the device under test (mainly Young's modulus, piezoelectric coefficient  $d_{31}$ ) and so the evolution of them to monitor material aging or ruptures (cracks and/or delamination).

## 2. Studied structure architecture

Aside from the associated circuitry and the seismic mass (a few grams in tungsten) that allows the reduction of the system resonant frequency ( $\sim 10$  Hz) to tune the bandwidth over the vibration environmental spectrum, the energy harvester is mainly composed of a rectangular-shaped bimorph with a low thickness with respect to its others in-plane dimensions (a few millimeters wide and about 20mm in length, see Figure 2).



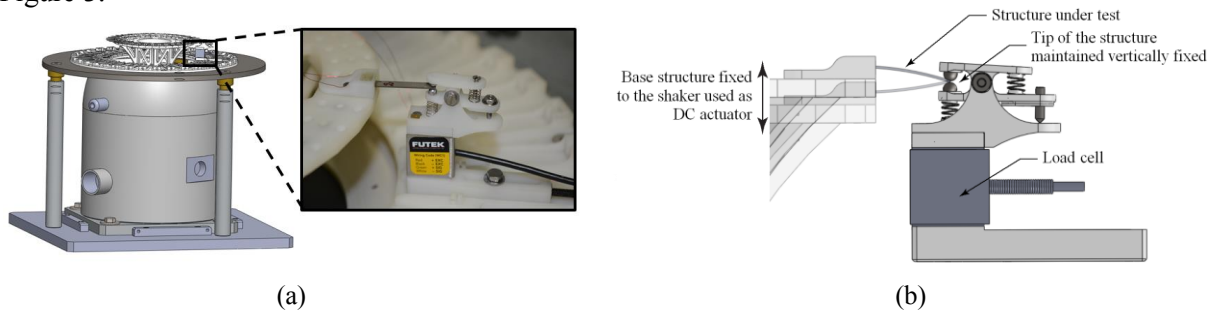
**Figure 2.** Leadless pacemaker architecture (a). Piezoelectric scavenger (b).

The structure consists of a stack of different layers: two ceramic PZT (Lead Zirconate Titanate) films are bonded onto a structural metallic layer (shim). Finally both sides are metalized to collect the generated electrical charges and to make possible wire bonding. In the final application, the structure will operate by inertia effect during the heartbeat. Successive constraints elongation and compression of PZT layers will provide electrical energy by piezoelectric coupling.

### 3. Accelerated aging test bench

In this paper the proposed test bench mainly consists of a shaker that can actuate simultaneously up to 36 piezoelectric energy scavengers samples for long time periods (up to  $10^9$  cycles). The shaker will mimic same mechanical deformation and the same electrical loading as in a real use but at much higher frequency (from 100 to 200Hz). By this way, the ageing is expected to be accelerated by a factor proportional to the frequency ratio. The scavenger operation frequency in real environment is of nearly 10Hz, so the aging is expected to be accelerated by a factor in the range of 10 to 20. If necessary, the aging may be largely increased using large deflection. To be under realistic conditions, the structures under test will be placed in a controlled environment to maintain the temperature at 37°C (98.6 °F) which is the working temperature of implanted devices. To control the induced mechanical deformation under imposed displacement the shaker movement is continuously measured by the way of a laser vibrometer system.

So as to impose the mechanical deformation corresponding to the first flexion mode of a cantilever beam as in real use, the tip of the scavengers (without the seismic mass always omitted during testing) will be maintained vertically fixed by a custom "pinch system" nevertheless leaving free the rotation in both directions thanks to sphere-plan hertzian contacts ensured by a calibrated spring as shown in Figure 3.



**Figure 3.** (a) Global view of the proposed test bench that can test simultaneously up to 36 piezoelectric scavengers. (b) Pinch system that allows to maintain vertically fixed the tip of the structure under test.

The majority of the mechanical parts make up that system were realized by the way of stereolithography that allows to obtain resistant and light elements. This is well suitable for those in movement (attached to the shaker rod) where the weight bounds the maximal frequency for a given amplitude (typical amplitude of 2mm peak to peak). The two beads used for hertzian contacts have a diameter of 3mm and are made of treated and rectified stainless-steel that provides an excellent wear resistance minimizing surface damage at the sample level (electrodes).

### 4. Electro-mechanical investigation methodology

Throughout the test the accelerated aging cycle at "high" frequency is periodically stopped (every couple of hours) to monitor the health of the structures performing DC characterization. Thus in the case of the proposed test bench the device under test could also be moved through its base by the way of the shaker operating at DC thanks to a custom power amplifier. Indeed standard power amplifiers generally associated with this kind of equipment has a cut-off frequency of a few Hz prohibiting DC actuation. As in AC long-term excitation, the amplitude of the DC movement is precisely controlled via a laser vibrometer system having a repeatability of about 100nm (Keyence vibrometer). As shown in Figure 3, for each structure, the pinch system used to maintain vertically fixed the tip of the structure is itself mounted onto a 50gf load cell (LSB200 from Futek) that makes possible to extract the structure stiffness measuring the reaction force for a given base displacement (in open or short circuit) but also the blocking force for a given excitation voltage (in this case the based is maintained in a fixed position). The measurement of the stiffness gives us

informations about the Young's modulus of the different materials but also about the mechanical integrity of the structure (cracks, delamination ...). In other hand the blocking force is directly related to the transverse piezoelectric coefficient  $d_{31}$  as shown in [7].

The load cell is associated to a custom readout electronics based upon an AD7780 converter from Analog Devices (24-bit resolution). According to the datasheet, this sigma delta ( $\Sigma\Delta$ ) ADC has a p-p resolution for 18.8 effective bits (PGA gain set to 128V/V, 10SPS update rate). Considering the sensitivity of the load cell (2mV/V at rated load), the detection limit is better than 1mgf ( $\sim 10\mu\text{N}$ ).

The main drawback of the used pinch system is to induce a restoring couple attributable to the hertzian contacts. This has as effect to modify the effective stiffness of the structure. Thus, in the case of small deflections the restoring couple  $M$  could be expressed as:

$$M(\alpha) = -\frac{F_B \cdot (2R + e) \cdot \tan(\alpha)}{\cos(\alpha)} \approx -F_B \cdot (2R + e) \cdot \tan(\alpha) \quad (1)$$

Here  $\alpha$ ,  $e$ ,  $F_B$ ,  $R$  are respectively the tip angle deflection with respect to the horizontal, the thickness of the scavenger, the pinch force and the beads diameter. Using the stiffness matrix of Euler-Bernoulli beam (scavenger is equivalent to a thin cantilever) [8], it's possible to calculate the effective stiffness  $k_{eff}$ :

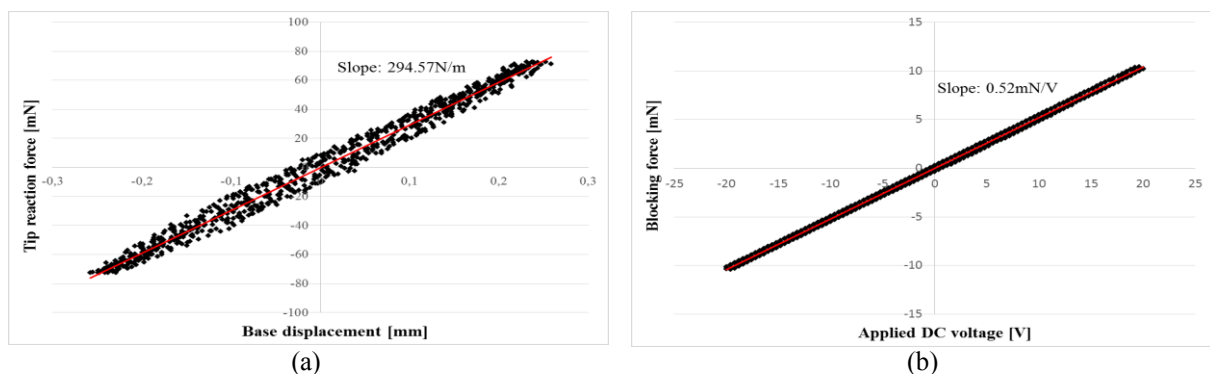
$$k_{eff} = k_0 \cdot \left[ 1 - \frac{9}{4} \cdot \frac{F_B \cdot (2R + e)}{L^2 \cdot k_0 + 3 \cdot F_B \cdot (2R + e)} \right]^{-1} \quad (2)$$

Here  $k_0$  is the initial stiffness of the scavenger (without pinch system) and  $L$  the structure free length between the anchor and the hertzian contact point. The last expression clearly shows that the effective stiffness  $k_{eff}$  increases with respect to the pinch force  $F_B$ .

Others contributions such as the stiffness of the association of the load cell topped by the pinch system could affect the mechanical measurements. Nevertheless the stiffness of the whole system has been experimentally evaluated to more than  $2.5\text{kN}\cdot\text{m}^{-1}$ . This value is to compare to the stiffness of the scavengers that is equal to about  $350\text{N}/\text{m}^{-1}$  that allows us to conclude that the influence of it is more than negligible.

## 5. Experimental results

A number of preliminary tests were carried out using damage-free scavengers from Piezo Systems Incorporated. A set of measurements of the reaction force for a given base displacement and the blocking force for a given excitation voltage is shown in Figure 4.



**Figure 4.** (a) Tip reaction force versus base displacement. (b) Blocking force versus applied voltage.

The scavenger stiffness and the blocking force coefficient have been extracted by linear regression and compared to the theoretical values calculated using the material parameters provided by the manufacturer. All these data are summarized in the table 1 below:

**Table 1.** Experimental values compared to theoretical ones.

Parameters	Theory	Measurements	Variation
Scavenger stiffness [N.m <sup>-1</sup> ]	359	294±10	19.7%
Blocking force coefficient [mN.V <sup>-1</sup> ]	0.618	0.52±0.05	17.1%
Transverse piezoelectric coefficient $d_{31}$ [pC/N]	-320	-329±40	2.7%

The different curves have been plotted following several loading cycles and exhibit a slight hysteresis behaviour. This could be explained, amongst others, by drift and possible stiction between the steel beads and the structure surface. Concerning the theoretical variation of the stiffness with respect to the pinch force, this phenomenon cannot be verified hidden by the uncertainty concerning the structure free length that plays a crucial role in the calculation (the stiffness is proportional to  $L^{-3}$ ).

## 6. Conclusion

This paper presents a massively parallel test bench that allows to study the reliability of up to 36 energy harvesting micro-devices. Here the mechanical integrity of the structures but also the piezoelectric material aging could be monitored by the way of direct mechanical investigation based on stiffness and blocking force measurements. This especially allows us to investigate large signal behaviour unlike impedance spectroscopy commonly used for this kind of system as reported in the literature. However the presented method doesn't allow to obtain the Young's modulus of each material but just the value of the effective one related to global structure. Similarly impedance spectroscopy is still necessary if the knowledge of the electrical permittivity is needed.

Notwithstanding this, preliminary test results on undamaged structures show that experimental and expected values are close together demonstrating the pertinence and the efficiency of this testing/characterization methodology. Our future work will focus on the analysis of the impact of the pinch system especially on the sample surface that could be damaged by sphere/plan contact. A particular effort will be also made to automate the different measurements so as to study, for this time, the long term reliability of a complete set of 36 structures.

## 7. References

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