Optimization of Energy Harvesting concepts from vibration by piezoelectric actuator design

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Abstract

The power supply is a major need in the sensor network deployment for structural monitoring applications in non-accessible structures and components. To develop smart structures within the Industry 4.0 and the smart anything everywhere concepts, autonomous integrated sensors are needed. Under this premise, the present work presents several low cost energy harvesting solutions to support the design phase as a function of the surrounding available vibrations and the electronic components requirements. The simplest system to evaluate the potential design strategies is the evaluation of the piezoelectric sensor in a cantilever configuration that induces the mechanical stress in the piezoelectric layer to produce the voltage to be stored in the battery. The most efficient design is the bimorph concept, where two thin piezoelectric layers separated by a non-active intermediate layer are used. The flexibility, robustness and efficiency of homemade and commercially available bimorph PZT and PVDF sensors designs has been tested by authors under similar acceleration forces.

1 INTRODUCTION

One of the most important concerns in the use of sensors in Structural Health Monitoring systems, and their integration into transport applications, is the need of wires and connectors to provide energy to sensors networks. This could impact negatively in development of SHM technologies or their use in non-accessible structures, where the wire integration is not allow due to structural or weighing requirements. Dual use of piezoelectric smart systems as sensor, to monitor the structure defect, damage or failure, and as harvester to scavenging the surrounding energy losses, allows the design of self-powered sensors network. The Energy Harvesting concept, EH, is based on the capture of energy losses from the operating environment to transform it into electrical energy. This is stored into capacitors or batteries to maintain the sensors network power as long as the operating environment guarantees the energy losses. The combination of EH concepts with the recent advances in low power systems forecasts an important market impact in the next years on the wireless sensors network development.

In the aeronautical sector, the scenario where the EH concept has an important relevance is when SHM sensors network are integrated into structures not accessible to replace the battery, and when sensors are not connected to Auxiliary Power Units. Piezoelectric sensors/actuators are the alternative energy source for the next generation of integrated sensors.

Piezoelectric actuators generate an electric voltage when a force is applied on it, as pressure or vibration, using the kinetic energy available in the environment. In principle, any piezoelectric sensor can be used to energy harvesting allowing a few milliwatts of power converting mechanical vibration into electrical voltage even for low working frequencies. This technology aims to significantly reduce the use of batteries substitution in many current applications and increase the life cycle of several devices [1].

In the present work, the characterisation of several piezoelectric sensors (PZT, PVDF) configurations is carried out by the authors to optimise the Energy Harvesting from surrounding vibrations. Three piezoelectric materials, PZT-4, PZT-A5 and PVDF, are compered under a bimorph configuration to evaluate how to increase their harvesting power. These systems will be compared as function of their price to define new low cost solution easy to implement into final applications. Due to the fact, that commercial available EH piezoelectric systems are laboratory test kits and usually the piezoelectric systems provided in the kits have been developed for other applications; it is necessary to develop piezoelectric systems specifically designed for the energy scavenging and to explore the potential power that could be harvested for the SHM sensor network to maintain batteries energy.

The use of piezoelectric systems for energy generation is a recent discipline in which many researchers over the past few decades have focused their effort mainly in the development of new circuits. New dedicated electronic circuit developments for efficient storage of the harvested energy require dedicated piezoelectric solutions.

2 MATERIALS AND BIMORPH CONFIGURATIONS

Three different piezoelectric materials have been selected to compare their efficiency, their robustness and their cost; two electroceramic families of PZT, PZT-4 and PZT-A5, and one piezoelectric polymer PVDF. Their constants and their geometrical dimensions are shown in Table 1. Materials selection has been carried out based on their cost, their uses and their properties. The cost of PZT-A5 is three orders of magnitude higher than PZT-4 and the PVDF potential commercial price is closer to PZT-4. PZT-4 is intensively used on SHM sensor network applications whereas PVDF presents high flexibility, lower thickness and higher g_{31} constant.

Table 1: Piezoelectric constants and dimensions of the materials employed for the bimorph system manufacture.

Piezoelectric constant	PVDF (PiezoTech)	PZT-4 (Sumida)	PZT-A5 (Piezo Systems)
d_{33}	$-1{,}6.10^{-11}$	$2{,}25.10^{-10}$	$3{,}5.10^{-10}$
g_{33}	$-1{,}5.10^{-1}$	$8{,}5.10^{-3}$	$1{,}66.10^{-2}$
d_{31}	6.10^{-12}	$-1{,}45.10^{-10}$	$-1{,}9.10^{-10}$
g_{31}	$1{,}9.10^{-1}$	$-1{,}3.10^{-2}$	$-1{,}37.10^{-2}$
L (mm)	64	26	63,8
w (mm)	32	26	31,8
h (μm)	9	$2{,}2.10^{2}$	$1{,}75.10^{2}$
m (gr) total	$3{,}4.10^{-2}$	$8{,}67.10^{-1}$	2,77

Six bimorph configurations, one based on PVDF layers and five based on PZT-4 discs, have been manufactured for a comparison with a bimorph piezoelectric bending transducer used as a harvester, as supplied from Piezo System. PDVF sheets from Piezotech S.A.S, were used for the manufacture of the polymeric bimorph harvester. PZT-4 discs are extensively used in the Structural Health Monitoring field as sensors or actuators and are independent of the interrogation strategy, impedance, acoustic, ultrasound, etc. PZT-4 discs with reference PKG21 have been used to develop both series and parallel connected bimorph harvesters. Detailed information of the six bimorph configurations is given on Table 2 and the schematic representation of bimorph configurations is shown in Figure 1. All samples were manufactured with the same cantilever beam dimensions as the PZT-A5 bimorph harvester from Piezo Systems, D220-A4-503YB, referenced as sample No. 7. For PZT-4 discs a brass interlayer of 250 μm and for PVDF sheet a Polyethylene terephthalate (PET) interlayer of 500 μm were used.

Table 2: Bimorph systems manufactured as harvester units.

No.	Material	Interlayer	Connection	No. Bimorph unit
1	PZT-4	Brass	Series	1
2	PZT-4	Brass	Series	2
3*	PZT-4	Brass	Series	1
4	PZT-4	Brass	Parallel	1
5	PZT-4	Brass	Parallel	2
6	PVDF	PET	Series	1

*Same configuration as No. 1 with the bimorph PZT located far from the attachment.

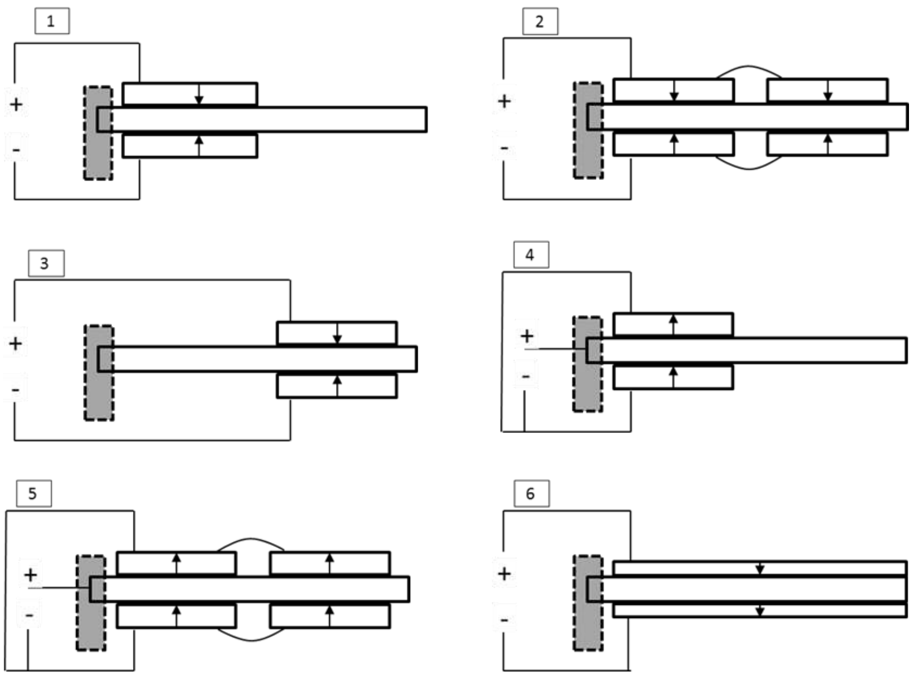

Figure 1: Bimorph schematic configurations of samples described in Table 2.

3 EXPERIMENTAL SETUP

To analyse the harvesting power of piezoelectric sensors, two potential experiments could be designed: 1) inertial energy harvesting and 2) kinematic energy harvesting. The first test is related to the resistance provided by the bimorph cantilever to the acceleration of their mass when placed in a mass-spring system [2]. The second test is performed when a direct coupling of the harvester to the relative movement from which the energy will be extracted exists and which does not rely on inertia or resonance. The most common reported arrangement in the literature is the inertial energy harvesting experiment, consequently this paper present the harvesting power of several bimorph systems, as listed in Table 2. Those systems based on PVDF, PZT-4 and PZT-5A were tested under simulated mechanical vibrations that could be found on transport vehicles (ships, cars, aircraft or railway), civil engineering structures or industrial machines.

Bimorph harvesters were tested as cantilever beams with dimensions of 70mm length and 32mm width. The dimensions were chosen as that of the D220-A4-503YB commercial harvester because no modification of its geometry was possible. This enabled comparative results to be obtained. Electromechanical excitation was carried out by the beam (bimorph harvester) attached to an electrodynamic shaker from Smart Materials [3]. The peak to peak voltage generated by the harvester during the power harvesting experiment was analysed using an oscilloscope, see Figure 2.

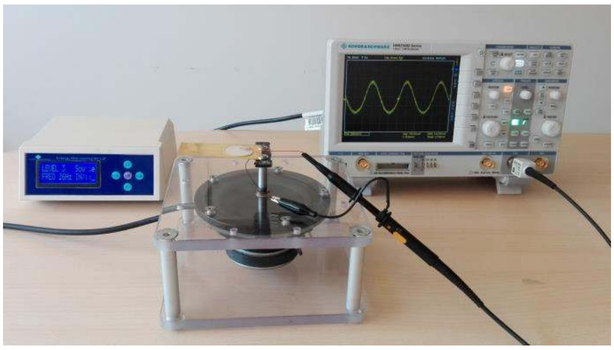

Figure 2: Shaker experimental setup.

The range of the vibration signal induced by the function generator in the bimorph systems was between 0,25G to 3,5G corresponding to the generator levels 1 to 5. Real acceleration in the bimorph cantilever beam for each specimen was measured using an optical sensor AccuRange200^{TM} from Acuity Laser Measurement Ltd. All piezoelectric bimorph sensors used the cantilever beam format connected in open circuit to record the maximum peak to peak voltage for frequencies ranging from 10 to 40 Hz and for acceleration levels from 1 to 5.

The efficiency of each bimorph system was calculated for a similar resonance frequency, where the peak to peak voltage for an intermediate acceleration level of 3 was used to reduce random signal oscillation in the cantilever beam system. The energy charging level and voltage generated by the different piezoelectric bimorphs were measured using an EH301 circuit from Advanced Linear Devices [4], which is designed for low power intermittent duty and long-term storage applications. The diode chosen for the experiment was a 6,6mF located after the rectifier circuit. The EH301 circuit was selected because of its instantaneous input voltages ranging from 0.0V to +/-500V AC or DC, and input currents from 200nA to 400mA.

4 RESULTS

4.1 Open circuit test results

The 6 bimorph systems manufactured for the trials and the commercial reference, specimen no. 7, were tested under open circuit condition in the shaker as cantilever beam samples. The frequencies range, where the peak to peak voltages were recorded, was between

10Hz to 40Hz and the acceleration range tested was from level 1 to 5, approximately from 0,25G to 3,5G.

In Figure 3, the open circuit voltages of the 2 PTZ-4 cantilever beams, specimen nos. 2 and 5, is compared and which used, respectively, series and parallel connections . The open circuit voltage of the series connection, in the case of 2 units of bimorphs, was significantly higher than that of the parallel one. Comparing the same series and parallel connections for 1 PZT-4 bimorph, located near the cantilever beam attachment, the open circuit behaviour was observed to be similar to samples with 2 bimorph units, see Figure 4.

Surprisingly, the open circuit voltage of specimens with 1 bimorph unit is higher than those composed of 2 PZT bimorph units. This could be associated to an overlapping of the two bimorph waves, which results in a decreasing voltage due to the cantilever length. Length optimization to maximize the voltage output is required.

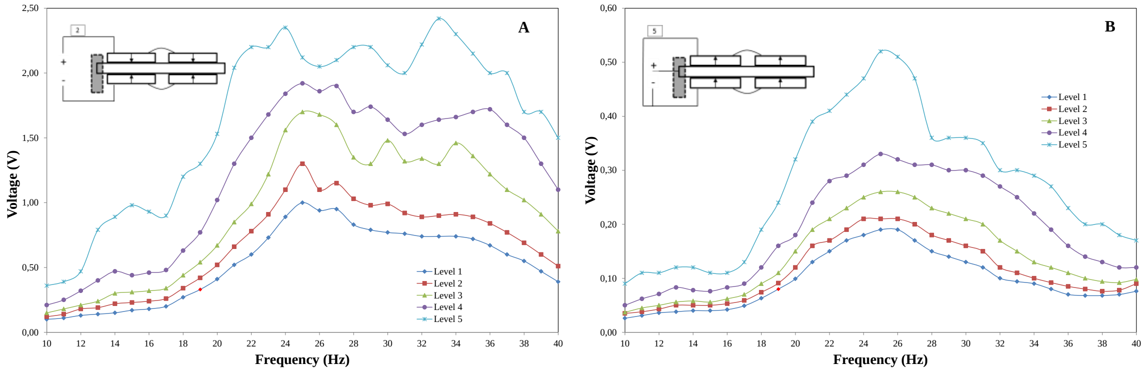

Figure 3: Open circuit voltage recorded from bimorph composed of 2 units of PZT-4 under brass intermediate layer (A) no. 2- series connection and (B) no. 5 - parallel connection.

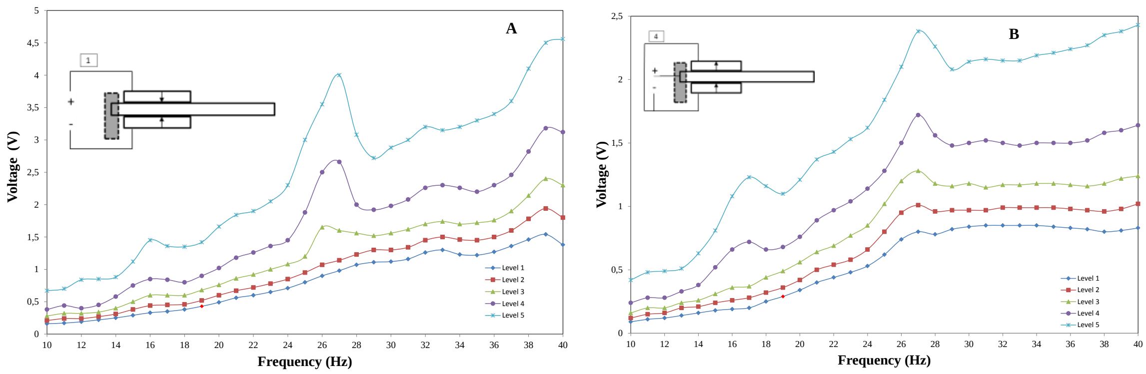

Figure 4: Open circuit voltage recorded from bimorph composed of 1 unit of PZT-4 under brass intermediate layer (A) no. 1- series connection and (B) no. 4 - parallel connection – placed near the brass tie up.

To compare the bimorph output voltage of 1 bimorph unit, as a consequence of its location along the cantilever beam length, sample no. 3 was manufactured. The piezoelectric bimorph was fabricated as far as possible from the beam attachment to the shaker and connected in series. The open circuit voltage is shown in Figure 5. The resulting voltage output is smaller than that observed for specimen no. 1 in the open circuit test. This is due to the piezoelectric materials experiencing higher deformations, when they are located near the attachment, for the same given cantilever length.

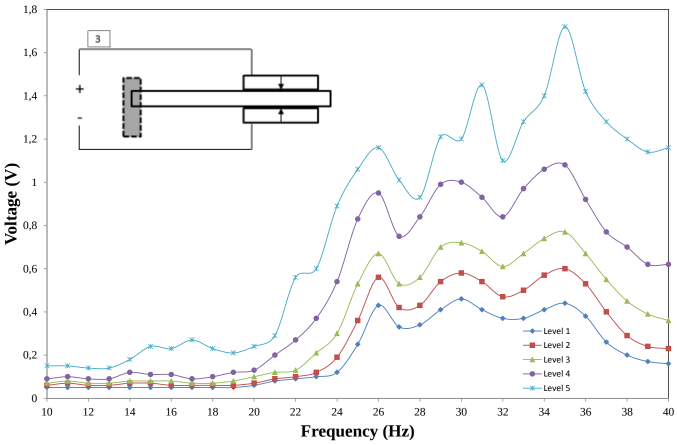

Figure 5: Open circuit voltage from specimen no.3.

Samples no. 6 and 7 were tested in an open circuit and natural resonant frequencies around 25 Hz were observed.

4.2 Capacitor charge test result

To define the capacitor charging test conditions, several options were considered by the authors:

1. To make the harvesting experiments at the first natural resonant frequency.
2. To select real application boundary conditions for the tests.
3. To select the largest voltage output with the most appropriate force input and voltage output characteristics.
4. To select the frequency at optimal working conditions for reference no.7, commercial bimorph, in order to demonstrate that there is still a significant amount of research required to fully investigate the piezoelectric energy harvesting design of bimorph systems.

The first option was ruled out for two reasons:

- Not all samples showed a coherent first resonance frequency peak.
- The potentially low voltage of some samples could have resulted in not achieving the full charge of our 6,6mF capacitor.

The identification of real application boundary conditions enables the author to obtain specific conclusions for a target bimorph harvester and elaborated design guidelines. However the selection of the largest voltage output for all specimens prevents a direct comparison of the results. This is due to the different values of the operational frequency and force input needed to achieve the maximum voltage output. These differences could also appear in the samples with the same number of bimorph units whether connected in series or parallel. For this reason, authors have chosen the fourth option.

To define the charging test operational frequency, open voltage circuit specimen results were analysed. Samples no. 2, 3 and 5, 2 PTZ-4 cantilever beams in series and in parallel, and 1 bimorph PZT-4 placed opposite to the tie up, do not exhibit evidence of the presence of any resonance frequency up to approximately 20Hz and for levels 1 to 5. This is true except in the case of specimen no. 2, which manifests some resonance around 14Hz. In samples no. 1, 4 and 7, 1 PZT-4 bimorph placed near the brass attachment and the commercial bimorph, showed a first resonance frequency around 16 Hz for level 4 and 5. It is also possible to infer the presence of this peak at level 3. The frequency selected was 25Hz, because of the presence of this resonance frequency peak in all specimens at a testing acceleration level 3. A second reason for selecting level 3 has been to guarantee the charging experiment for all designed concepts.

The voltage output of the bimorph of PZT-4 cantilever specimens were subjected to level 3 accelerations at a frequency of 25Hz as shown in Figure 6. Specimen no. 3, with 1 bimorph unit separated from the cantilever beam attachment, resulted in a lower output voltage due to the smaller deformation induced by vibration. Sample no. 1, one PTZ-4 bimorph unit connected in series, shows a lower voltage output during the charging experiment than equivalent samples connected in parallel; even if the open circuit experiment exhibits with the opposite behaviour. The real energy charged in the 6,6mF capacitor for all PZT-4 specimens (samples no.1 to 5) is shown in Figure 7. The energy charge increase, in case of specimen no.4, as opposed to no.1, could be due to different electrical current induction in the piezoelectric material during the experiment for the same force input. The resulting energy charge harvested by the capacitor is a consequence of the electrical current and the voltage harvested by the piezoelectric material.

The two PTZ-4 bimorph cantilevers, series (no.5) and parallel (no. 2), have similar charging behaviour until 180 seconds. This is surprising, since the parallel samples exhibited very low voltage in the open circuit experiment. From 210 seconds to the end of the experiment, the tendency is the opposite to that of the single PTZ-4 bimorph unit specimen. This evolution reflects the fact that the voltage contribution to the total energy is higher than in samples manufactured with one piezoelectric bimorph unit. In addition, the energy obtained is lower than expected. This may be due to overlapping waves between the two bimorph harvesters caused by the geometrical restrictions of their vibration modes.

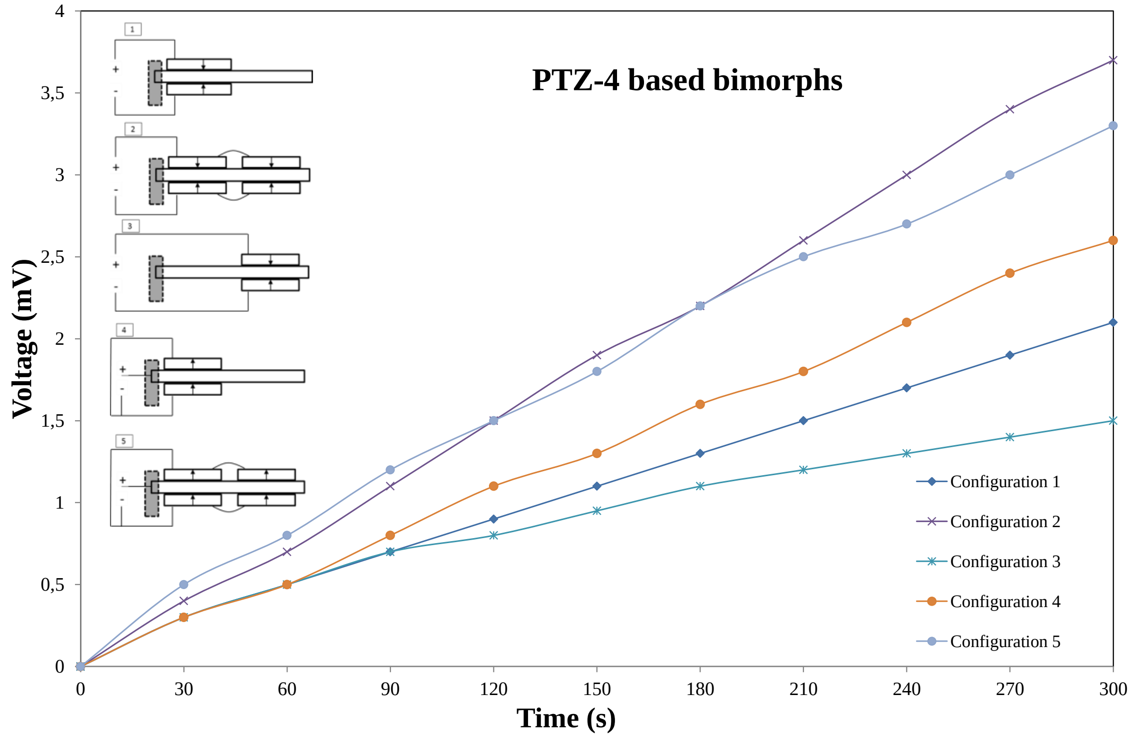

Figure 6: Voltage output charge history for samples no. 1 to 5.

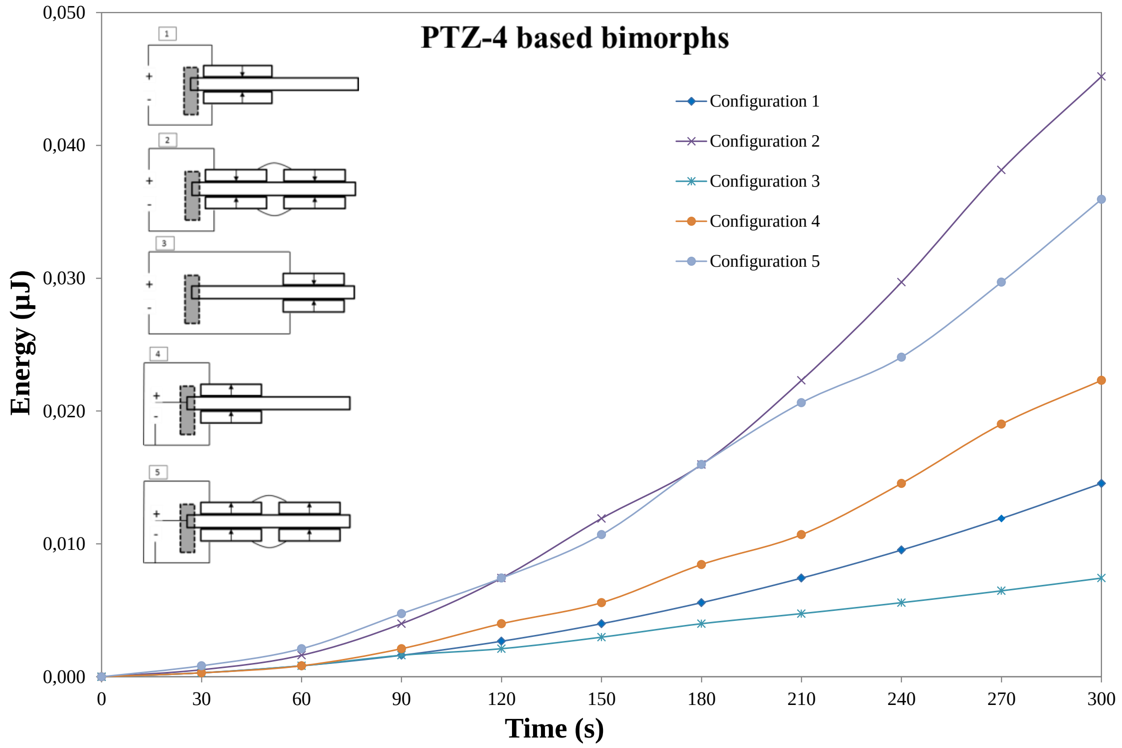

Figure 7: Energy charge history of PZT-4 bimorph samples from no.1 to 5 at level 3 and 25Hz.

The voltage output and energy charge of the bimorph PVDF cantilever beam is higher than PZT-4 samples, even when the experiment was carried out under sub-optimal conditions, see Figure 8. Their high flexibility makes it possible to stress the test under higher frequencies and accelerations than for the electroceramic bimorph systems. The energy obtained during the charging experiment with a 6.6mF is three time higher than that of the PTZ-4 specimens. Even if these figures of merit are not in the range of that achieved by the commercial actuator, Figure 9, the new systems open the possibility to design dedicated bimorph polymeric sensors to harvest the vibration and motion energy losses in industry, transport and civil applications. The new systems could also be used to explore the harvesting potential of the sensor network, deployed for structural health monitoring, when used to maintain a constant level of energy in batteries installed on electronic management nodes or communications units.

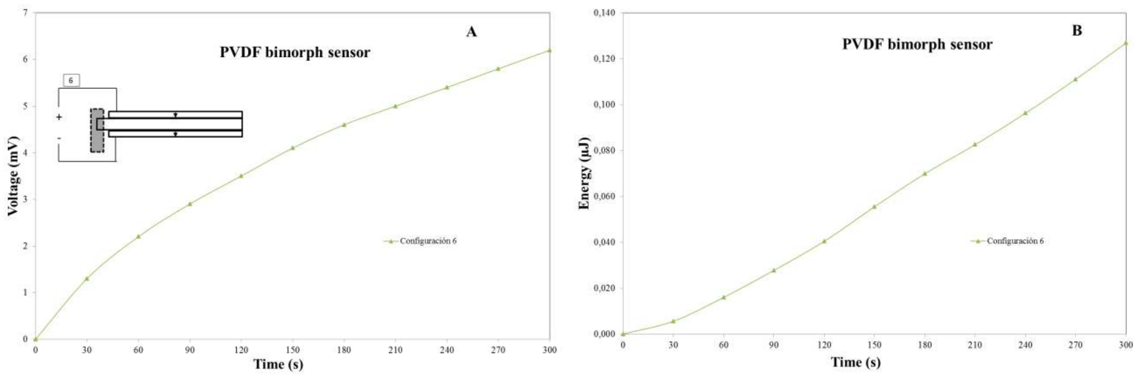

Figure 8: Voltage output (A) and Energy (B) charge history in PVDF bimorph cantilever beam sample at level 3 and 25Hz.

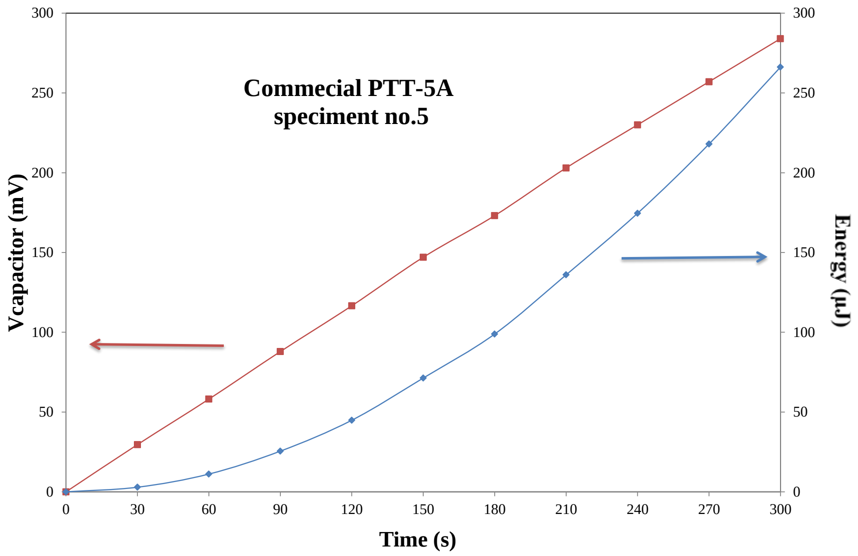

Figure 9: Voltage output (left) and Energy (right) charge history in commercial bimorph specimen.

5 CONCLUSIONS

This work demonstrates the potential use of bimorph materials as charging sources for re-chargeable batteries on low power electronic components and communication networks based on ad-hoc designed piezoelectric systems, for structural health monitoring systems, SHM, for transport and civil building applications.

The generated electrical energy from inertial energy harvesting tests of several bimorph configurations has been evaluated in three piezoelectric families of materials, PZT-4, PZT-A5 and PVDF. Samples used a cantilever beam type geometrical configuration for the energy charging experiments. The energy charging level and voltage output were measured using conventional electronic circuits. The boundary conditions of the experiments were based on the best force in and voltage out characteristics for the newly developed ad-hoc samples.

Whilst the testing conditions of the ad-hoc piezoelectric bimorph configurations were outside of their optimal force and voltage ranges, the charging experiment reflected their potential viability as harvester units. Two main research lines in the piezoelectric harvesters should be explored, the optimization of polymeric harvesters based on PVDF, or co-polymers, and the use of low cost PZT sensors, usually employed in SHM networks, to guarantee energy level maintenance on re-chargeable batteries.

PVDF polymer based harvesters have an incredible potential based on the fact that the generated electrical energy is proportional to the product of the piezoelectric system energy charge and the voltage, $E = {}^{1}/_{2} . Q . V$.

The generated electrical charge Q is:

$$Q \sim \frac{3. d_{31}. L^2}{4. h^2}. F$$

And voltage equation is:

$$V_{OC} \sim \frac{3. g_{31}. L}{8. w. h}. F$$

Based on the previous equations, and taking into account the different piezoelectric materials values in Table 2, the potential for energy charging in PVDF harvester is four orders of magnitude higher than that of the PZT families.

The efficiency and potential improvement of PZT-4 harvesters comes from the dual use of the SHM sensors network to harvest energy, even if these amounts are small, and to maintain the battery's charge level constant. Their main strength is that the SHM sensor network is deployed in the structure or component and can be partially used as harvesters, when they are not on for measurements, to generate extra energy charge.

The evaluation of interlayer thickness and the influence of material nature is also an open field of research for both families of ad-hoc harvesters. Also, new piezoelectric harvester manufacturing technologies should be employed to reduce the bimorph sample thickness whilst maintaining robustness of performance.

In both cases, additional research determining energy harvesting conditions, force, voltage and frequencies is required to optimize the figures of merits in the homemade harvester specimens. This is due to the very broad range of frequencies (from several Hz to 1000Hz) and forces that could be used for scavenging the energy in transport and civil building applications.

In addition, direct battery charging experiments are required to develop more efficient capturing methods for the harvested energy, due to the fact that capacitors, which only provide short bursts of power, are not ideal candidates.

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