Energy harvesting from earthquake for vibration-powered wireless sensors

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ABSTRACT: Wireless sensor networks can facilitate the acquisition of useful data for the assessment and retrofitting of existing structures and infrastructures. In this perspective, recent studies have presented numerical and experimental results about self-powered wireless nodes for structural monitoring applications in the event of earthquake, wherein the energy is scavenged from seismic accelerations. A general computational approach for the analysis and design of energy harvesters under seismic loading, however, has not yet been presented. Therefore, this paper proposes a rational method that relies on the random vibrations theory for the electromechanical analysis of piezoelectric energy harvesters under seismic ground motion. In doing so, the ground acceleration is simulated by means of the Clough-Penzien filter. The considered piezoelectric harvester is a cantilever bimorph modeled as Euler-Bernoulli beam with concentrated mass at the free-end, and its global behavior is approximated by the dynamic response of the fundamental vibration mode only (which is tuned with the dominant frequency of the site soil). Once the Lyapunov equation of the coupled electromechanical problem has been formulated, mean and standard deviation of the generated electric energy are calculated. Numerical results for a cantilever bimorph which piezoelectric layers made of electrospun PVDF nanofibers are discussed in order to understand issues and perspectives about the use of wireless sensor nodes powered by earthquakes. A smart monitoring strategy for the experimental assessment of structures in areas struck by seismic events is finally illustrated.

1 INTRODUCTION

Efficient power consumption, management and generation are essential in order to facilitate the large-scale implementation of wireless arrays of sensors for structural monitoring applications. In this context, common solutions for producing the required electric power are based on solar panels and small wind turbines, but the generation of energy from alternative sources is nowadays a very popular research topic. Within this framework, harnessing the energy from vibrations (see for instance Maruccio et al., 2016) is probably the most promising approach. However, vibration-powered wireless sensor nodes are not yet a mature technology and further studies are still needed. To this end, the random vibrations theory can be a powerful methodology to analyze the electromechanical response of energy harvesters under uncertain vibrations. For instance, a single-degree-of-freedom (SDOF) electromechanical system under stationary white Gaussian noise is considered in (Adhikari et al., 2009). The case of non-stationary random vibrations has been addressed recently, see for instance (Yoon and Youn, 2014). Amongst the potential practical applications of energy harvesting devices under non-stationary random vibrations, those regarding seismic events have received several attentions recently. To date, existing scientific literature is basically focused on the use of the energy harvested from seismic vibrations in order to supply the power required for driving a wireless node in the event of earthquake, see for instance (Elvin et al., 2006; Tomicek et al., 2013; Cheng et al., 2013). So doing, a designated wireless node harvests and accumulates the energy from earthquake-induced vibrations in its capacitors and, once sufficient energy is obtained, it turns on microprocessor and transceiver to perform the scheduled operations (Cheng et al., 2013). Although existing researches provide numerical and experimental evidences about self-powered wireless sensor nodes in the event of earthquake, a general computational approach has not yet been proposed. Hence, this paper develops a rational methodology based on the random vibrations theory for the analysis of piezoelectric energy harvesters under modulated and filtered white Gaussian noise. A smart monitoring strategy for the experimental assessment of structures in areas struck by seismic events is finally illustrated.

2 DYNAMIC RESPONSE OF PIEZOELECTRIC ENERGY HARVESTER

2.1 Stochastic model of the dynamic excitation

The Clough-Penzien filter is adopted to model the base acceleration (Figure 1a). Thus, the base acceleration $\ddot{x}_b$ is given as:

$$\ddot{x}_b = \ddot{x}_f = -2\xi_f \omega_f \dot{x}_f - \omega_f^2 x_f - 2\xi_g \omega_g \dot{x}_g - \omega_g^2 x_g \,, \tag{1}$$

where x_g and x_f are the solutions of the following coupled stochastic oscillators:

$$\begin{cases} \ddot{x}_g + 2\xi_g \omega_g \dot{x}_g + \omega_g^2 x_g = -\varphi w \\ \ddot{x}_f + 2\xi_f \omega_f \dot{x}_f + \omega_f^2 x_f = -2\xi_g \omega_g \dot{x}_g - \omega_g^2 x_g \end{cases} \tag{2}$$

under zero initial conditions. Here, ω_g, ω_f, ξ_g and ξ_f are the filter parameters.

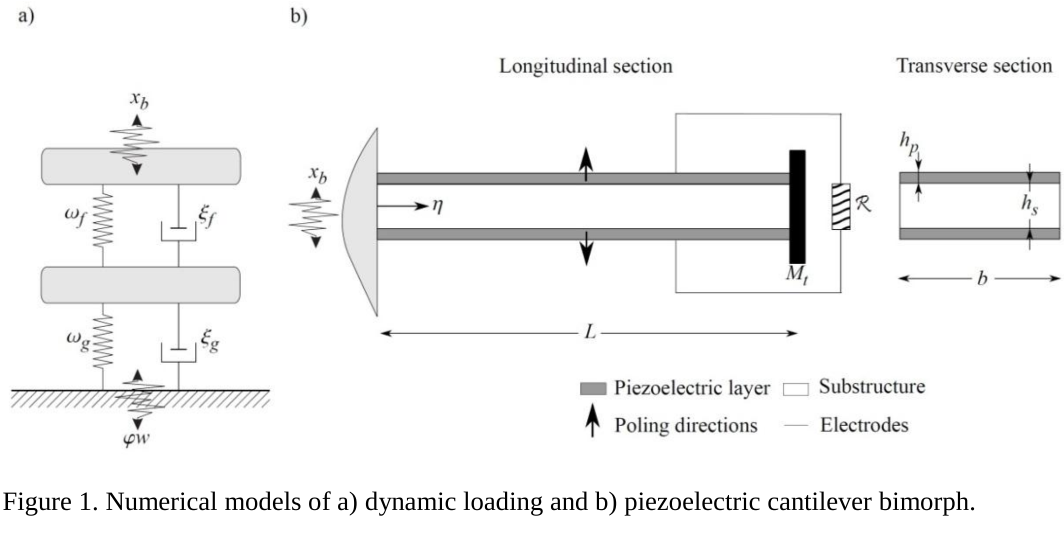

Figure 1. Numerical models of a) dynamic loading and b) piezoelectric cantilever bimorph.

Specifically, ω_g and ξ_g are dominant frequency and damping ratio, respectively. On the other hand, ω_f and ξ_f denote the parameters of the filter hindering the low-frequency components. In Eq. (2), φ is a time-dependent function that modulates the intensity of the zero-mean white Gaussian noise w.

2.2 Electromechanical model of the piezoelectric energy harvester

A bimorph energy harvester is considered, made up with series connection of piezoelectric layers (Figure 1b). The piezoelectric energy harvester is modeled as a continuous linear elastic Euler-Bernoulli beam following (Erturk and Inman, 2009). The electrode pairs on the top and on the bottom are assumed to be perfectly conductive and a resistive electrical load $\mathcal{R}$ is considered in the circuit. Moreover, it is assumed that the dynamic response of the piezoelectric bimorph is dominated by its fundamental mode, which will be tuned with the dominant frequency of the dynamic excitation ω_g (modal excitation condition). The bimorph is subjected to transverse accelerations $\ddot{x}_b$ at the base (Figure 1b). Moreover, it is assumed that the tip mass M_t can be modeled as a point mass, which implies that its rotary inertia can be neglected. Under such assumptions, the equation of motion related to the considered mode is:

$$\ddot{x} + 2\xi\omega\dot{x} + \omega^2 x + \chi v = -\Lambda \ddot{x}_b , \tag{3}$$

where x is the transverse modal mechanical response along the longitudinal axis η, v is the voltage across the resistive load $\mathcal{R}$, ξ is the modal mechanical damping ratio, ω is the undamped natural frequency of the fundamental mode in short circuit conditions (i.e., $\mathcal{R} \to 0$) and Λ is the modal participation factor. The parameter χ is the modal electromechanical coupling term (Erturk and Inman, 2009). The electric equation for the series connection of the piezoelectric layers is:

$$\dot{v} + \frac{2}{C\mathcal{R}} v - \frac{2\kappa}{C}\dot{x} = 0 , \tag{4}$$

where C and κ are capacitance and modal coupling term, respectively (Erturk and Inman, 2009).

3 STOCHASTIC ANALYSIS OF THE OUTPUT ENERGY

3.1 Covariance analysis

By introducing the state-space vector $\mathbf{z} = \left\{ x \quad x_g \quad x_f \quad v \quad \dot{x} \quad \dot{x}_g \quad \dot{x}_f \right\}^T$, the motion equation of the cantilever bimorph can be rearranged as $\dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{f}$. The time-dependent system covariance matrix $\mathbf{R}$ of the state-space vector $\mathbf{z}$ is calculated by solving the Lyapunov equation in non-stationary condition:

$$\mathbf{AR} + \mathbf{RA}^T + \mathbf{B} = \dot{\mathbf{R}} . \tag{5}$$

All matrices in Eq. (5) have size $n \times n$, where n is the length of the state-space vector $\mathbf{z}$ (namely, n=7). The matrix $\mathbf{B}$ has all zero elements except $\mathbf{B}_{6,6}=2\pi S_0 \varphi^2$, where S_0 is the constant power spectral density function. Equation (5) is solved numerically in order to calculate the covariance matrix $\mathbf{R}$. In doing so, the time window $[0,T]$ is first divided into equal intervals by adopting a constant time step ΔT between two consecutive instants (i–1) and i, with $i \geq 1$. A linear variation of $\dot{\mathbf{R}}$ within each time interval is considered (the initial conditions are assumed equal to zero).

3.2 Statistical moments of the harvested energy

Following (Elvin et al., 2006; Maruccio et al., 2016), the electrical energy is herein considered instead of the electrical power because the loading event lasts a finite time length. By making explicit the time dependence through the introduction of the time variable t, the energy harvested within the time window $[0,T]$ is calculated as follows (Elvin et al., 2006; Adhikari et al., 2009):

$$\mathcal{E} = \frac{1}{\mathcal{R}}\int_0^T v^2(t)\,\mathrm{d}t\,. \tag{6}$$

The first-order moment of the harvested energy is:

$$\mathrm{E}[\mathcal{E}] = \frac{1}{\mathcal{R}}\int_0^T \mathrm{E}\left[v^2(t)\right]\mathrm{d}t = \frac{1}{\mathcal{R}}\int_0^T \sigma_v^2(t)\,\mathrm{d}t\,, \tag{7}$$

where $\mathrm{E}[\cdot]$ is the expected value operator and σ_v^2 indicates the variance of the output voltage. The second-order statistical moment is:

$$\mathrm{E}\left[\mathcal{E}^2\right] = \frac{1}{\mathcal{R}^2}\mathrm{E}\left[\left(\int_0^T v^2(t)\,\mathrm{d}t\right)^2\right] = \frac{1}{\mathcal{R}^2}\int_0^T\int_0^T \mathrm{E}\left[v^2(t')v^2(t'')\right]\mathrm{d}t'\mathrm{d}t''\,. \tag{8}$$

A sequence of N_t time instants t_i is considered to evaluate Eq. (8). In fact, it can be demonstrated that Eq. (8) is well approximated using the following semi-analytical result:

$$\begin{aligned}\mathrm{E}\left[\mathcal{E}^2\right] &\approx \left(\frac{T}{\mathcal{R}(N_t-1)}\right)^2 \sum_{i=1}^{N_t}\sum_{j=1}^{N_t}\mathrm{E}\left[v^2(t_i),v^2(t_j)\right]\gamma_i\gamma_j = \\ &= \left(\frac{T}{\mathcal{R}(N_t-1)}\right)^2 \sum_{i=1}^{N_t}\gamma_i\left(3\sigma_v^4(t_i) + 2\sum_{j=i+1}^{N_t}\gamma_j\left(\sigma_v^2(t_i)\sigma_v^2(t_j) + 2\Sigma_v^2(t_i,t_j)\right)\right)\end{aligned}\,, \tag{9}$$

where Σ_v indicates the autocorrelation function of the output voltage. Moreover, γ_i=1/2 if i=1 or $i=N_t$ while γ_i=1 otherwise. Once the second-order statistical moment is determined, the variability of the harvested energy can be measured by means of the coefficient of variation:

$$\rho[\mathcal{E}] = \sqrt{\mathrm{E}\left[\mathcal{E}^2\right] - \mathrm{E}[\mathcal{E}]^2}\Big/\mathrm{E}[\mathcal{E}]\,. \tag{10}$$

4 NUMERICAL ANALYSIS

4.1 Numerical data

Numerical values adopted for the filter parameters are ω_g=23 rad/s, ξ_g=0.43, ω_f=2.80 rad/s and ξ_f=0.97. The parameter S_0 is given as function of the peak ground acceleration (PGA) $\ddot{x}_b^{max}$ following (Liu et al., 2016). The modulating function is:

$$\varphi = \begin{cases}(t/t_A)^2 & \text{if } t \le t_A \\ 1 & \text{if } t_A \le t \le t_B \\ \exp\left[-\mu(t-t_B)\right] & \text{if } t \ge t_B\end{cases}\,, \tag{11}$$

where $[0,t_A]$ is the rise time, $[t_A,t_B]$ is the strong motion phase whereas the decay time starts at $t=t_B$ (Jennings et al., 1969). The values proposed in (Zaharia and Taucer, 2008) for high-magnitude earthquakes are considered as reference data for t_A, t_B and and T. Therefore, it is assumed t_A=4 s, T = 50 s and $(t_B–t_A)\in[10,25]$ s. The parameter μ is taken equal to 0.4 while PGA values between 0.20g and 0.40g are assumed. The time step for the numerical analysis is $\Delta T=T/500$. The energy harvester tested by Elvin et al. (2006) is considered, with minor modifications regarding the value of M_t and the adopted polymeric piezoelectric material. Materials data used in this numerical study are listed in Table 1. The substructure is made of mylar while the piezoelectric layers are made of electrospun PVDF nanofibers (Persano et al., 2013).

Table 1. Electromechanical data (ε_0: permittivity of the free space)

Parameter	Piezoelectric layers	Substructure
Mass density [kg/m^3]	1500	1390
Young's modulus [GPa]	1.8	3.79
Piezoelectric constant d_{31} [pm/V]	32	-
Permittivity $\varepsilon_{33}{}^T$ [F/m]	$9\varepsilon_0$	-

Length and width of the cantilever are equal to 31.7 mm and 16 mm, respectively. The thicknesses of substructure and piezoelectric layers are equal to 172 μm and 28 μm, respectively. The value of $\mathcal{R}$ is 1×10^7 Ω. Moreover, it is assumed ξ=0.03. The tip mass is defined in such a way that $\omega=\omega_g$, thus obtaining M_t=7.425 g. In order to preserve the integrity of the device, it is also required that $3\max_{t\in[0,T]}\{\sigma_x\}\leq 3$ mm.

4.2 Results

Standard deviation values of tip displacement and output voltage are shown in Figure 2 for a PGA equal to 0.40g and duration of the strong motion phase equal to 25 s.

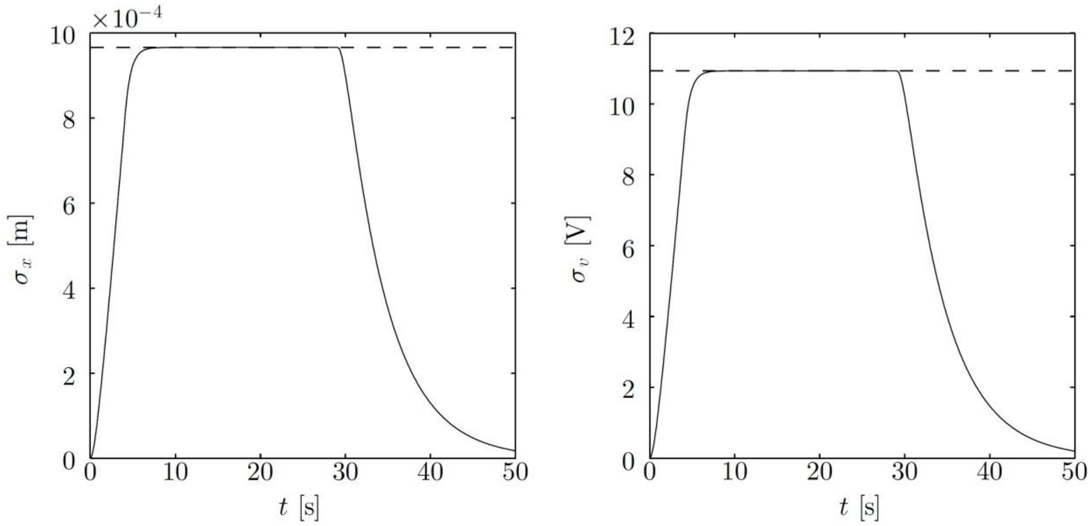

Figure 2. Standard deviation values of tip displacement and output voltage for a PGA equal to 0.40g and a duration of the strong motion phase equal to 25 s.

Mean and coefficient of variation of the generated energy for different values of PGA and strong motion phase duration are given in Figure 3.

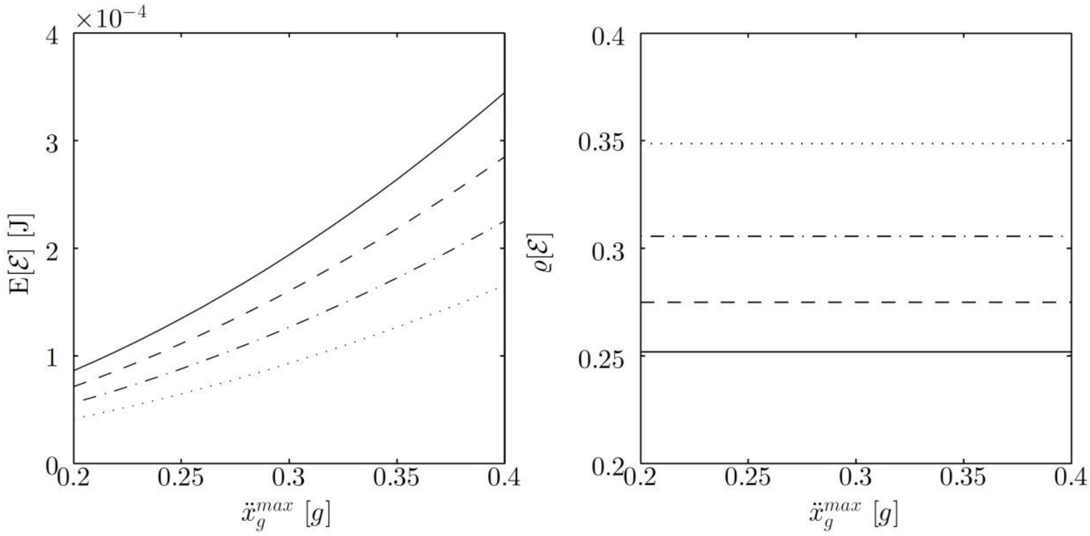

Figure 3. Mean and coefficient of variation of the generated energy for different values of PGA and strong motion phase duration (solid line: (t_B–t_A) = 25 s, dashed line: (t_B–t_A) = 20 s, dash-dot line: (t_B–t_A) = 15 s, dotted line: (t_B–t_A) = 10 s).

The mean value of the energy generated by the considered piezoelectric device is ~10^{-1} mJ. Besides the short duration of the loading event, Figure 3 demonstrates that another important issue for earthquake-powered sensors is the rather large uncertainty level due to the intrinsic randomness of the seismic events (the highest coefficient of variation in this case-study is close to 35%). Nonetheless, Figure 3 also highlights some positive aspects. First, the uncertainty level of the generated energy does not depend on the PGA value. Moreover, the larger is the strong motion phase duration, the lower is the uncertainty level of the generated energy. The perspectives for earthquake-powered sensors can be inferred from these results taking into account the typical power consumptions. According to Elvin et al. (2006), a minimum energy equal to 0.05 mJ is required for a significant data transmission (0.01 mJ for circuit start-up, 0.02 mJ for data transmission, 0.01 mJ for sensor operation, and 0.01 mJ for microcontroller energy). In average, therefore, the considered harvester might be able to generate the energy required for a significant data transmission when the PGA is larger than 0.20*g* and the strong motion phase duration is larger than 10 s. Because of the uncertainty level, however, the minimum required energy might be not generated in some cases adopting this device. The use of an array of harvesters is a simple way to increment the chances of generating a sufficient amount of energy from an earthquake (Tomicek et al., 2013).

5 ENERGY HARVESTING-BASED WIRELESS SENSING IN SEISMIC AREAS

A possible implementation of earthquake-powered wireless sensor nodes for post-seismic assessment of structures and emergency management is devised in Figure 4. Generally, the urban areas comprise strategic and ordinary structures. Strategic structures are those structures that are essential for post-seismic emergency management. Because of their importance, these structures should be equipped with continuous dynamic monitoring systems and backup energy generators. Hence, the aftershock assessment based on experimental data should be always ensured for strategic structures. It is highlighted that the sensor networks of strategic structures can be designed using standard technologies.

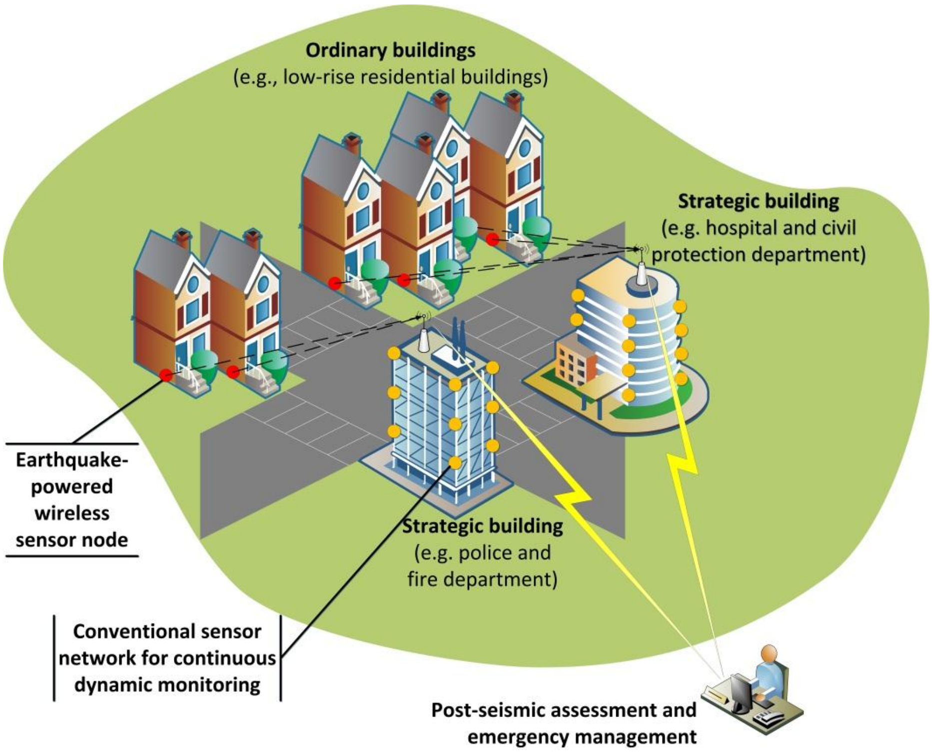

Figure 4 Smart monitoring strategy for post-seismic assessment and emergency management.

On the other hand, ordinary structures cover the largest part of urban areas, the most representative examples being low-rise residential buildings. The lack of a continuous monitoring system on ordinary buildings complicates the post-seismic assessment of largest part of the built environment and makes difficult the organization of emergency operations. While the installation of a continuous dynamic monitoring system for each ordinary structure is too prohibitive and unrealistic, the placement of one or few earthquake-powered wireless nodes would be a more feasible and cheap option. Each smart wireless node should be designed to perform a single (static) measurement after an earthquake, so as to consume a minimum amount of electrical energy. For instance, such measure can be the residual displacement because it is able to provide a preliminary overview about the extent of the damage due to an earthquake and can support informed decisions about usability and repairability (Yazgan and Dazio, 2011). Moreover, information about the spatial distribution of damaged buildings can facilitate the preliminary identification of roads that can be inaccessible for emergency operations because of the presence of debris. Hence, the proposed smart monitoring strategy works as follows. First, the measurements performed by the earthquake-powered sensor nodes are transmitted to the nearest collecting point by means of the wireless technology after the seismic event. Then, the data collected from a cluster of buildings are transmitted to support post-seismic assessment and emergency management. Candidate collecting points can be the nearest strategic buildings or the closest utility poles.

6 CONCLUSIONS

This paper has proposed a computational approach based on the random vibrations theory for the analysis of piezoelectric energy harvesters under modulated and filtered white Gaussian noise. Numerical results for seismic energy harvesting applications are discussed and a possible strategy to enhance the resilience of urban areas by means of smart wireless sensor nodes is illustrated. This contribution should be considered as a first step towards the understanding of the feasibility of earthquake-powered sensing systems, and a long deal of researches is still needed in this regard. Within this framework, the authors are also exploring alternative technological solutions to generate a larger amount of energy.

7 ACKNOWLEDGEMENTS

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