

Multiphysics Simulation of Piezoelectric Cantilever Beam: Application in Automobile

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Abstract: This paper present a modeling and simulation of piezoelectric microgenerator applied in the automobile. The overall system (piezoelectric transducer and energy harvesting circuit) is designed with Simscape tool of Matlab/Simulink software, which allows a multiphysics modeling. The software drives the electromechanical behavior of the transducer which, overcomes the establishment of an equivalent circuit model. The micro-generator sizing is based on real vibration data detected in the automobile. The piezo stack component is used to evaluate the output performances of the piezoelectric transducer. Simulated results are validated experimentally by using the QuickPack actuators parameters. The maximum power delivered by the transducer is then used to evaluate the performance of a sensor node in a star topology network. The results show that the sensor node can sense and transmit data with a maximum size of 451 bits when measurements must be taken every 15 minutes. The model is then used to assess the contribution of the nonlinear treatment of the piezoelectric voltage called Synchronized Switch Harvesting on Inductor (SSHI). Specifically, an improvement of the recovered power of 18.9% is achieved by applying the SSHI technique; allowing an improvement in the size of the data by 13.3%. The proposed simulation technique can be used for the design of such micro-generators.

Key words: QuickPack actuators, multiphysics modeling, piezo stack, sims cape tool, star topology network, SSHI

1. Introduction

In the recent years, green and smart city concepts concern both industrialized countries and developing countries. The first concept is limited by two main problems which are the exhaustion of natural reserves and environmental impacts such as CO₂ emissions. The main alternative considered so far is the development of renewable energy, free and available from infinitely, research field known as energy harvesting. Specifically, energy harvesting gathers freely available energy from the environment, such as vibrations [1], light [2], radio waves [3], human activities [4], heat [5] or the wind [6], to power low-voltage and low-power-consumption electrical systems. The choice of primary energy source depends on the environment in which it is located. The block diagram of an Energy Harvesting System (EHS) has three main parts shown in Fig. 1.

- The transducer is the most important part of the chain. It is used to convert primary energy into AC electrical energy.
- Energy Harvesting Circuit (EHC) allows formatting the recovered energy. Its most essential function is the AC/DC conversion.
- The storage element that can be a battery, a capacitor or a super capacitor is used to store the recovered energy.



Fig. 1 Block diagram of an EHS.

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As shown in Fig. 1, the design of an EHS requires taking into account the multi-physical behavior of the transducer. To size the EHC, most designers establish electric models of the transducer [7, 8], for simulation of the overall behavior of the EHS. However, most of the proposed models are based on simplifying assumptions. These assumptions introduce some differences between experimental and simulated results. In this work, we use the Simscape tool of Matlab software to simulate the EHS without establishing an electric model. The case of vibrations in an automobile is considered since automobiles may include sensors for obtaining information regarding various physical parameters [9]. Typically, these sensors are powered by chemical batteries, which must either be replaced or recharged when they become exhausted. This maintenance related to the change of the battery can be costly in the case of sensors located in inaccessible locations such as the tire pressure monitoring sensors. Therefore, powering these distributed sensors from vibrational's energy becomes attractive. In previous work [1, 9], the designers are limited to the minimal performances of EHS when applied to the automobile. In this work, the simulation technique is used to quantify optimizations improvement proposed for such EHS.

Since the design of vibration energy harvesters is highly dependent upon the characteristics of the environmental vibrations present in the intended application [10], the spectrum of vibrations in an automobile is first studied in section 2. In section 3, the choice of the geometry of the transducer is made, and a simulation of its output performances, compared with the experimental results is proposed. In section 4, the power delivered by the transducer is then used to evaluate the performance of an autonomous sensor node based on the recovered energy. An improvement of the size of the collected data is also proposed by optimizing the performance of the micro generator. The used optimization technique is the SSHI technique which is known to increase the electrical output characteristics of the piezoelectric micro generators. The work ends in section 5 with a conclusion in which, few prospects for improving are introduced.

2. Detected Vibrations in the Test Automobile

2.1 Measurement Equipment

ACC103 laboratory accelerometer manufactured by Omega [11] is used to measure vibrations in the automobile. It has 10 mV/g output and can measure vibration up to 500 g. The AC signals were recorded with an oscilloscope of Hantek Electronic (DSO8060). The embedded Fast Fourier Transform (FFT) software was used for data analysis. The measurement setup is shown in Fig. 2.

2.2 Detected Vibration

A Kia Spectra brand automobile which has run about 126,000 km is used. The accelerometer is located on the engine of the automobile. Two series of measurements are made when the engine was running at 2000 rpm.

A plot of mean acceleration versus frequency is given in Fig. 3. A maximum acceleration is observed on the z-axis. More precisely, it is shown a peak of



Fig. 1 Vibration measurement equipment.



Fig. 2 Acceleration versus frequency.

acceleration magnitude of 1.3 m/s^2 around 40 Hz for both measurements.

3. Transducer Modeling and Simulation

3.1 Selected Transducer

Several transducers architecture were studied to obtain the best electromechanical coupling. The most common structure is based on the use of a free cantilever beam [12]. This geometry allows a resonator operating at low frequency without using important dimensions. Fig. 4 shows the geometry of the cantilever beam, which consists of three main parts. The cantilever beam is used to amplify the relative displacement of the seismic mass to the displacement



Fig. 4 Cantilever piezoelectric beam [12].

amplitude of the vibration source. The seismic mass increases the mechanical stress applied to the piezoelectric material, thus producing a high output power. The piezoelectric layers, which is the active part of the structure, is used to convert mechanical vibrations into electrical energy.

3.2 Transducer Modelling

For a cantilever structure, the natural frequency is given by [13, 14]:

$$f_R = \frac{1}{4\pi} \sqrt{\frac{EWT^3}{\left(m + \frac{33}{140}m_b\right)L^3}}$$
(1)

where *L*, *W*, *T* and *E*, are length, width, and thickness of the cantilever beam and its elastic modulus respectively. m_b is the mass of the beam defined as:

$$m_b = \rho L W T \tag{2}$$

 ρ is the density of the used material. Among the commonly used transducers, QuickPack actuator manufactured by Mide Technology [15] are the most popular and have been recently used as a piezoelectric micro-generator for applications in vehicles [1, 9, 16]. In this work, the piezoelectric composite QP20W from MIDE company with dimensions 45.974 mm × 33.02 mm × 0.76 mm is used as a piezoelectric transducer. The other necessary parameter's values of the QP20W QuickPack actuator are given in Table 1.

The first step in the design is the determination of the seismic mass that achieves optimum performance. Fig. 5 represents the relationship between the resonance frequency of the piezoelectric composite and the seismic mass. The targeted resonant frequency (40 Hz) is achieved for a seismic mass of 36 mg.

Parameters	Designation	Values
Е	Young Modulus	67 Gpa
F _b	Blocking Force	0.3058 N (1.1 ozf)
V ₀	Test voltage	40 V
δ	Displacement at V_0	0.4318 mm (0.017 in)
C _P	Piezo Capacitance	145 nF
Q_m	Mechanical quality factor	80

Table 1 QP20W Mide actuator properties [15].



Fig. 3 Resonant frequency versus seismic mass.

To simulate the behavior of the composite beam, the Simscape tool of Matlab is used. It is a tool that offers an acausal approach of modelling and allows modelling by assembling the components. The software directly supports the physical behaviour of the components allowing modelling a system without having to write the differential equation that characterizes his behavior. The piezo stack composite (Fig. 6) is used to simulate the performance of the transducer [17].



Fig. 4 Piezo stack composite and parametrization.

The piezo stack block represents the electrical and forces characteristics of a piezoelectric stacked actuator using the constitutive equations of piezoelectricity developed in [18, 19].

$$\begin{cases} S = s^E T + dE \\ D = dT + \varepsilon^T E \end{cases}$$
(3)

where: *S*, *T*, *E*, *D*, S^E , *d* and *S*, *T*, *E*, *D*, s^E , *d* and ε^T are the strain tensor, the stress tensor, the electric field vector, the electric displacement vector, the elastic compliance matrix, the piezoelectric compliance matrix and the permittivity respectively.

When the cantilever beam is subjected to an inertial force $F_0 = m_{eq}A$, (Fig. 7), caused by a constant acceleration A, the derived static deflection z is given by:

$$z = \frac{F_0}{k} \tag{4}$$

where $m_{eq} = m + \frac{33}{140}m_b$ is the equivalent mass and k is the bending spring constant.

However, in the case of a harmonic force of amplitude F_0 at the beam resonance frequency, the amplitude of the deflection is increased by the mechanical quality Q_m factor as [20]:

$$z = \frac{Q_m m_{eq} A}{k} \tag{5}$$

Thus, the amplitude of the force acting on the end of the beam is defined by:

$$F = Q_m \left(m + \frac{33}{140} m_b \right) A \tag{6}$$

The schematic simulation is shown in Fig. 8. It includes the composite that is excited by a sinusoidal force at 40 Hz. The input signal is designed in Simulink then converted by Simulink-to-Physical



Fig. 7 Static deflection of the piezoelectric cantilever beam.



Fig. 5 Schematic simulation of transducer.

Signal (S-PS) block into force signal. The generated force signal is then connected to the first mechanical port of the piezo stack composite as shown in Fig. 8.

3.2 Simulated and Experimental Results

To validate the Simscape model of the transducer, a comparison is made between the experimental results and the simulation result. The experimental device is the same used in Ref. [16]; it is shown in Figure 9 and U8556001 includes Vibration Generator а manufactured by 3B Scientific. This device is used for generating mechanical waves to study oscillations and resonance with a frequency range of 0 to 20 kHz. The vibration generator is powered by an FG 100 Function generator, also manufactured by 3B Scientific. The equipment gives several outputs; sine wave, a triangular wave, and a square wave voltages with adjustable amplitude and frequency. The frequency range is 1 Hz to 100 kHz. The various measured signals are recorded in a Hantek Electronic (DSO8060) oscilloscope. The used piezoelectric composite (QP20W) is also shows in Fig. 9.

Fig. 10 shows the waveforms of the open circuit voltage delivered by the transducer.

In Fig. 10(a), a comparison between the simulated voltage and the voltage obtained with the experimental device is made. The magnitude of the input force is 0.224 N corresponding to an 1.3 m/s^2 input acceleration according to Eq. (6). The simulation time is 20 s. An alternating voltage of amplitude 1.28 V is obtained by simulation while with the experimental device, the voltage amplitude is 1.14 V. A slight

distortion is observed on the experimental signal; this is due to an imperfect fixing of the composite on the



Fig. 6 Photo of the experimental setup.





Fig. 7 Open circuit voltage of the transducer.

vibrating plate. Fig. 10(b) shows the voltage waveform taken directly from the engine of the automobile. The results indicate an alternating voltage of amplitude of 1.18 V which is quite close to the results obtained by simulation, and with the experimental device. Moreover, these results are quite close to those obtained in works [1, 9], in which the alternating voltages of the used transducers were 1.5 V and 1.1 V respectively.

A good agreement is also found between simulated and experimentally recovered power (Fig. 11). A maximum experimental power of 130.8 μ W is achieved for optimal load resistance equal to 27 k Ω while a maximum power of 140.3 μ W is reached with the simulated results when the load resistance is 25 k Ω .

Assuming that all the recovered power is dedicated to the operation of a wireless sensor for measurements in smarts automobile [21], an assessment of the autonomous node's performance is proposed in the next section.

4. Application: Autonomous WSN Based on the Recovered Energy

Automobiles have more and more sensors, whose role is to provide at particular moments information about his condition (temperature, speed, ultrasonic sensors, etc. [9]). Since the insertion of these microsystems, the function of the battery is no longer just the start. Because it has become equally important



Fig. 8 Simulated and experimental recovered power.

to power the various sensors of the automobile. The increasing number of these sensors then results in frequent maintenance operations which can either be recharging or replacing the battery. In this section, the electrical output characteristics of the piezoelectric micro generator are used to evaluate the performance of a sensor node fed by the recovered energy. A model of consumption of a wireless sensor node is first proposed; the model is then used to evaluate the performance of the node powered by the recovered energy.

4.1 Wireless Sensor Node Energy Model

The general architecture of a wireless sensor node is shown in Fig. 12 [22]. Each sensor consists of three main units that must be powered by the recovered energy: the sensing unit, the processing unit, and the communication unit.

Energy consumption in the different modules of a sensor node is linked to the activity of the node in the network [23]. The activity of a node depends on the topology of the network. There are three main topologies: star, mesh and cluster head. The star topology is the most appropriate for small coverage areas as would be the case for an automobile [24].

As shown in Fig. 13, the star topology network consists of a central node called sink of the network and multiple wireless sensor nodes. In this topology, all sensors nodes send their data directly to the sink.







Fig. 13 Star topology network.

Taking into account our previous research [23], the dissipation sources of energy in a node will be:

- energy for data capture $E_{sens}(b)$,
- energy for data recording $E_{rec}(b)$,
- energy for data processing $E_{proc}(b)$,
- energy for the transmission of the data $E_{tx}(b)$,
- energy dissipated during the transition between the different states of the system (standby, active, sleep) *E_{trans}*.

where b is the size of the processed data. These various quantities are defined in [23] as:

$$\begin{cases} E_{\text{sens}} = b. V_{\text{sup}}. I_{\text{sens}}. T_{\text{sens}} \\ E_{\text{rec}} = \frac{bV_{\text{sup}}}{8} (I_{\text{read}}. T_{\text{read}} + I_{\text{write}}. T_{\text{write}}) \\ E_{\text{proc}} = bNCV_{\text{sup}}^2 + bV_{\text{sup}} \left(I_0 e^{\frac{V_{\text{sup}}}{n_P V_t}} \right) \left(\frac{N}{f} \right) \\ E_{tx} = bE_{elec} + b\varepsilon_{fs}. d^n \\ E_{\text{trans}} = T_A V_{\text{sup}} [\alpha_N I_A + (1 - \alpha_N) I_S] \end{cases}$$
(7)

 α_N is the duty cycle for the sensor node. It is defined in [25] as:

$$\alpha_N = \frac{T_{\text{tranON}} + T_A + T_{\text{tranOFF}}}{T_{\text{tranON}} + T_A + T_{\text{tranOFF}} + T_S}$$
(8)

The definitions and values of the various parameters used to estimate the energy requirement of the node are given in Table 2. All these values are originated from [23, 26].

4.2 Performance Evaluation of the Node Powered by the Recovered Energy

Assuming that all the recovered power (P_{max}) is dedicated to the operation of the node, the available energy during an operating cycle E_{avai} is defined by:

$$E_{\text{avai}} = P_{\max} \sum_{i} T_i \tag{9}$$

where *i* is the time duration of each of the steps performed to measure the physical quantity. The condition for supplying the sensor node by the energy recovered is defined by:

$$E_{\text{avai}} \ge E_{\text{node}}$$
 (10)

where:

 $E_{\text{node}} = E_{\text{sens}} + E_{\text{rec}} + E_{\text{proc}} + E_{tx} + E_{\text{trans}}$ (11) Assuming that the sleep time of the node is variable with $T_s = kT_A$, the performance of the node as a function of the recovered energy and the type of measured physical quantity are shown in Fig. 14.

- $k = 6 \times 10^4$ takes into account applications where measurements should be made every minute. The curve shows that we would not have enough energy for such applications because the energy recovered remains below the energy needs of the node.
- k = 3×10⁵ represents the case where the physical phenomenon must be controlled every 5 min. The recovered energy remains insufficient to power the node.
- $k = 6 \times 10^5$ represents the applications in which measurements must be taken every 10 minutes.
- k = 9×10⁵ studied the case of the applications where measurements must be taken every 15 min; the maximum packet size in this case is 401 bits.

4.3 Improving the Performance of the Node by Optimization of the Recovery System

The ability to simulate the electromechanical behavior of the transducer can now be used to quantify any optimization improvements. In the piezoelectric transducers field, most of the researches focus on the proposals of the methods that allow amplifying the voltage and the maximum energy that can be transferred to the load. Most of these techniques are



Fig. 9 Node performance versus sleep time.

based on non-linear treatments. In this work, we consider the Synchronized Switch Harvesting on Inductor (SSHI) method [27, 28]. The method is based on the switching of an inductor in parallel with the piezoelectric micro-generator like shown in Fig. 15. Furthermore, most of the previous works on the piezoelectric energy harvester are limited to the minimum performance of such systems when applied to automobiles [1, 9, 23]. The contribution of the SSHI amplification for such micro-generator is then quantified in this work.

The SSHI technique involves the addition of a switching device in parallel with the piezoelectric element. Switching is done at the time for which the displacement of the vibrating structure is maximum, at

Table 2Parameter values used to estimate energyconsumption of sensor node.

Symbol	Description	Value
b	Transmit pacquet size	
V _{sup}	Supply Voltage to sensor	2.7 V
Isens	Current sensing activity	25 mA
T _{sens}	Time duration: sensor node sensing	0.5 ms
Iread	Current: flash reading 1 byte data	6.2 mA
T _{read}	Time duration: flash reading	565 μs
I _{write}	Current: flash writing 1 byte data	18.4 mA
T _{write}	Time duration: flash writing	12.9 mS
E_{elec}	Energy dissipation: electronics	50 nJ/bit
ε _{amp}	Energy dissipation: power amplifier	100 pJ/bit/m ²
N	Number of clock cycles per task	0.97×10^{6}
С	Avg. capacitance switch per cycle	22 pF
I_0	Leakage Current	1.196 mA [10]
<i>n</i> _P	Constant: depending on the processor	21.26
f	Sensor frequency	191.42 MHz
V_t	Thermal voltage	0.2 V
d	Sink-node distance	1 m
п	distance based path loss exponent	2
T_A	Active time	1 ms
I_A	Current: wake up mode	8 mA
Is	Current: sleeping mode	1 µA
T _{tranON}	Time duration: sleep-idle	2450 µs
T _{tranOFF}	Time duration: idle-sleep	250 µs
Ts	Sleeping time	ms



Fig. 15 Piezoelectric beam with SSHI processing.

these times the voltage of the piezoelectric generator is also at its peak. Once the switch is closed, the system consisting of the piezo capacitance and the inductor forms a pseudo-periodic oscillating system. The period T_{os} is defined by:

$$T_{\rm os} = 2\pi \sqrt{LC_P} \tag{12}$$

The closing time t_{on} of the switches is given as half the pseudo period [28]:

$$t_{\rm on} = \frac{T_{\rm os}}{2} = \pi \sqrt{LC_P} \tag{13}$$

The quantification of the simulated performance of the transducer coupled to SSHI module is shown in Fig. 16.

Simulation results show an amplification of the open circuit voltage of the micro-generator of 1.82 times that obtained with the standard circuit. 18.9% improvement of the recovered energy compared to the standard circuit is also reached. This improvement in the capacities of the micro generator allows the sensor node to reach the performance shown in Fig. 17.

- for physical phenomena to be controlled every 10 min, data of a size of 31 bits can now be processed.
- for physical phenomena to be controlled every 15 min, data up to 511 bits can be processed; this improves the capabilities of the node by 13.3%.

5. Conclusion

In this work, a new method for simulating piezoelectric transducers has been proposed. The method avoids the establishment of an equivalent



Fig. 10 Optimized performances of the transducer.



Fig. 11 Node performance after optimization of the recovery system.

electrical model as in most of existing works. Induced vibrations in the automobile are considered as cases of study. For this, the spectrum of the detected vibrations have been studied, and the measurements show a maximum acceleration of 1.3 m/s^2 at a frequency around 40 Hz. A multiphysics simulation taking into account the properties of the detected vibrations and that of the used piezoelectric transducer is then made. The Simscape tool of Matlab software was used, and the simulated results were validated experimentally. The experimental open circuit test of the transducer shows 1.14 V magnitude when 1.28 V is observed in the simulated results. 130.8 μW on 27 $k\Omega$ load resistance is reached experimentally when simulation results give 140 μW on 25 $k\Omega$ load resistance. The simulation method can be used to quantify the maximum recoverable power of any other application when all available proposed optimizations are taken into account.

The induced vibrations in the automobile are then used as an alternative source for sensor nodes incorporated in automobiles. The performances of the slave node to the recovered energy are evaluated, and it results that for physical phenomena controlling every 15 min, the node can process data with a size of 451 bits. An optimization of the power delivered by the transducer of 18.9% through SSHI technique allows considering an optimization of the performance of the node of 13.3%.

The simulation method proposed in this work can be used to quantify the maximum recoverable power of any other application when all possible proposed optimizations are taken into account.

References

- [1] A. Mouapi, N. Hakem, G. Y. Delisle and N. Kandil, A novel piezoelectric micro-generator to power Wireless Sensors Networks in vehicles, in: *IEEE on Environment and Electrical Engineering (EEEIC)*, Rome, 2015, pp. 1089-1092.
- [2] L. M. Fraas, W. E. Daniels and J. Muhs, Infrared photovoltaics for combined solar lighting and electricity

for buildings, in: *Proceedings of 17th European Photovoltaic Solar Energy Conference*, 2001

- [3] J. O. McSpadden, Lu Fan and Kai Chang, Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna, *IEEE Transactions on Microwave Theory and Techniques* 46 (12) (1998) 2053-2060.
- [4] Y. Chuo, M. Marzencki, B. Hung, C. Jaggernauth, K. Tavakolian, P. Lin and B. Kaminska, Mechanically flexible wireless multisensor platform for human physical activity and vitals monitoring, *IEEE Transactions on Biomedical Circuits and Systems* 4 (5) (2010) 281-294.
- [5] A. Jacquot, G. Chen, H. Scherrer, A. Dauscher and B. Lenoir, Improvements of on-membrane method for thin film thermal conductivity and emissivity measurements, *Sensors and Actuators A: Physical* 117 (2) (2005) 203-210.
- [6] Y. K. Tan and S. K. Panda, Self-autonomous wireless sensor nodes with wind energy harvesting for remote sensing of wind-driven wildfire spread, *IEEE Transactions on Instrumentation and Measurement* 60 (4) (2011) 1367-1377.
- [7] G. K. Ottman, H. F. Hofmann, A. C. Bhatt and G. A. Lesieutre, Adaptive piezoelectric energy harvesting circuit for wireless remote power supply, *IEEE Transactions on Power Electronics* 17 (5) (2002) 669-676.
- [8] Y. C. Shu and I. C. Lien, Analysis of power output for piezoelectric energy harvesting systems, *Smart Materials* and Structures 15 (6) (2006) 1499-1512.
- [9] Z. Qingyuan, G. Mingjie and H. Yuanqin, Vibration energy harvesting in automobiles to power wireless sensors, in: *IEEE International Conference on Information and Automation*, 6-8 June 2012, pp. 349-354.
- [10] C. B. Williams and R. B. Yates, Analysis of A micro-electric generator for microsystems, *Sensors and Actuators A: Physical* 52 (1) (1996) 8-11.
- [11] ACC 103 Dataheet, available online at: http://www.omega.com/pressure/pdf/ACC103.pdf.
- [12] S. Roundy and P. K. Wright, A piezoelectric vibration based generator for wireless electronics, *Smart Materials* and Structures 13 (5) (2004) 1131.
- [13] H. Yu, J. Zhou, L. Deng and Z. Wen, A vibration-based MEMS piezoelectric energy harvester and power conditioning circuit, *Sensor* 14 (2) (2014) 3323-3341.
- [14] S. Kok, R. Aminur and F. Mohd, Design considerations of MEMS based piezoelectric cantilever for harvesting energy, in: *IEEE Conference on Applied Electromagnetics*, 2012, pp. 238-242.
- [15] QuickPack actuator datasheet available, available online at: http://www.mouser.com/ds/2/606/QuickPack-actuator-se nsor-datasheet-220082.pdf.
- [16] A. Mouapi, N. Hakem, N. Kandil and G. V. Kamani, Energy harvesting design for autonomous wireless sensors

network applied to trains, in: *IEEE International Ultrasonics Symposium (IUS)*, Tours, 18-21 Sep. 2016, pp. 1-4.

- [17] Model electrical and force characteristics of piezoelectric stacked actuator, available online at: http://www.mathworks.com/help/physmod/elec/ref/piezo stack.html.
- [18] J. G. Smits and A. Ballato, Dynamics behavior of piezoelectric bimorphs, in: *IEEE Ultrasonics Symposium*, Oct. 1993, pp. 463-465.
- [19] J. G. Smits and W. S. Choi, The constituent equations of piezoelectric heterogeneous bimorphs, in: *IEEE Symposium on Ultrasonics*, Honolulu, HI, 4-7 Dec. 1990, pp. 1275-1278.
- [20] S. S. Rao, Harmonically excited vibrations, in: *Mechanical Vibrations* (3rd ed.), Adison-Wesley, Boston, USA, 1995, pp. 200-262.
- [21] L. Zuo, B. Scully, J. Shestani and Y. Zhou, Design and characterization of an electromagnetic energy harvester for vehicle suspensions, *Smart Materials and Structures* 19 (4) (2010) 045003.
- [22] I. F. Akyildiz, Weilian Su, Y. Sankarasubramaniam and E. Cayirci, A survey on sensor networks, *IEEE Communications Magazine* 40 (8) (2002) 102-114.
- [23] A. Mouapi, N. Hakem and G. Y. Delisle, Autonomous wireless sensors network based on piezoelectric energy harvesting, *Open Journal of Antennas and Propagation* 4 (3) (2016) 138-157.
- [24] A. Shrestha and L. Xing, A performance comparison of different topologies for wireless sensor networks, in: *IEEE Conference on Technologies for Homeland Security*, Woburn, MA, 2007, pp. 280-285.
- [25] M. J. Miller and N. H. Vaidya, A MAC protocol to reduce sensor network energy consumption using a wakeup radio, *IEEE Transactions on Mobile Computing* 4 (3) (2005) 228-242.
- [26] M. N. Halgamuge, M. Zukerman, K. Ramamohanarao, and H. L. Vu, An estimation of sensor energy consumption, *Progress In Electromagnetics Research B* 12 (2009) 259-295.
- [27] M. Lallart, L. Garbuio, L. Petit, C. Richard and D. Guyomar, Double synchronized switch harvesting (DSSH): A new energy harvesting scheme for efficient energy extraction, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 55 (10) (2008) 2119-2130.
- [28] M. Lallart and D. Guyomar, An optimized self-powered switching circuit for non-linear energy harvesting with low voltage output, *Smart Materials and Structures*17 (3) (2008) 035030.