Modeling and Simulation of Piezoelectric Energy Harvesting

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Abstract—**Energy harvesting has received growing attention over the last decade. The research motivation in this field is due to the reduced power requirement of small electronic components, such as the wireless sensor networks used in structural health monitoring applications. The ultimate goal in this research field is to power such small electronic devices by using the vibration energy available in their environment. If this can be achieved, the requirement of an external power source as well as the maintenance requirement for periodic battery replacement can be minimized. In this paper, the modeling, simulation and experimental results of the piezoelectric energy harvesting using LabVIEW and Matlab are presented. This paper describes a dynamic model to simulate piezoelectric harvester and to identify model parameters with real time measurements and standard laboratory equipment.**

Index Terms— **power harvesting, mechanical vibration, piezoelectric materials, modeling and simulation**

I. Introduction

From literature, the idea to develop lumped dynamic model of vibration-to-electricity conversion first appeared in a journal article by Williams and Yates [1]-[3] in 1996. They described the basic transduction mechanisms that can be used for this purpose and provided a lumped-parameter base excitation model to simulate the electrical power output for electromagnetic energy harvesting. As stated by Williams and Yates [2], the three basic vibration-to-electric energy conversion mechanisms are the electromagnetic [2]-[4], electrostatic [5],[6] and piezoelectric [7],[8] transductions.

Over the last decade, several articles have reported to use these transduction mechanisms for low power generation from ambient vibrations. Piezoelectric transduction has received the greatest attention especially in the last few years. Piezoelectricity is a form of coupling between the mechanical and electrical behaviors of certain materials. The materials exhibiting the piezoelectric effect are called the piezoelectric materials. The piezoelectric effect is usually divided into two types as the direct and the converse of piezoelectric effects.

In the simplest terms, when a piezoelectric materials is squeezed (mechanically strained) electric charges collects at the electrodes located on its surface. This called the direct piezoelectric effect and it was first demonstrated by the Currie brothers in 1880[1]. If the same material is subjected to a voltage drop (i.e. an electrical potential difference applied across its electrodes), it deforms mechanically. This is called the converse piezoelectric effect and it was deduced mathematically (after the discovery of the direct piezoelectric effect) from the fundamental principles of thermodynamics by Gabriel Lippmann in 1881 and then confirmed experimentally by the Curie brothers. Piezoelectric sensors are used in a variety of applications to convert mechanical energy to electrical energy such as: pressure-sensing applications, detecting imbalances of rotating machine parts, ultrasonic level measurement, flow rate measurement, sound transmitters (buzzers), sound receivers (microphones), …etc [4].

This paper is organized as follows. Section I presents the literature work and research motivations in piezoelectric energy harvesting. Section II describes the generic dynamic model for piezoelectric energy harvester. Simulation and experimental results are presented and discussed in Section III. Finally, conclusion is drawn in Section IV.

II. Generic model of piezoelectric energy harvester

Mechanical energy can be found almost anywhere that wireless sensor networks (WSN) may potentially be deployed [2], which makes converting mechanical energy from ambient vibration into electrical energy an attractive approach for powering wireless sensors. The source of mechanical energy can be a moving human body or a vibrating structure. The frequency of the mechanical excitation depends on the source: less than 10 Hz for human movements and over 30 Hz for machinery vibrations [9]. Such devices are known as kinetic energy harvesters or vibration based power generators [10]. From dynamic point, the piezoelectric can be equivalent as a damped mass-spring mechanical system by a linear time-invariant second order differential equation, as shown in figure 1, and the equation can be written as in (1)[5], [11]-[12]:

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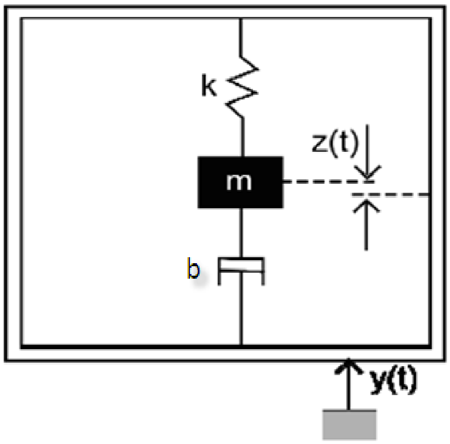

Fig.1. Generic model of piezoelectric energy harvester [2]

Where m, b, k are effective mass, damping coefficient, structure stiffness respectively. It is assumed that the mass of the vibration source is much greater than the mass of seismic mass in the generator and the vibration source is unaffected by the movement of the generator. Then the differential equation of the movement of the mass with respect to the generator housing from the dynamic forces on the mass can be derived as follows[13]-[16]

$$m.\frac{d^2 z(t)}{dt^2} + b.\frac{dz(t)}{d(t)} + k.z(t) = -m.\frac{d^2 y(t)}{dt^2} \quad (1)$$

Rewritten (1) in the form of Laplace transform as

$$m.s^2.z(s) + b.s.z(s) + k.z(s) = -m.a(s) \quad (2)$$

$$a(t) = \frac{d^2 y(t)}{dt^2} \quad (3)$$

Where *a(t)* is acceleration of the vibration. The transfer function of vibration micro generation is

$$\frac{z(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{\omega_r}{Q}s + \omega_r^2} \quad (4)$$

Where resonant frequency and quality factor are given by [15]

$$\omega_r = \sqrt{\frac{k}{m}}, Q = \frac{\sqrt{km}}{b} \quad (5)$$

Equivalent electrical circuit can be represented as shown in Fig.2.

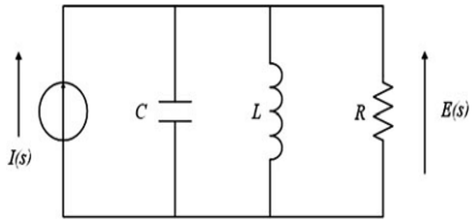

Fig. 2. Equivalent circuit of kinetic energy harvesters [17]

By comparing between the equation of an equivalent electrical circuit and kinetic energy harvester can be found

$$-m.a(s) = s.z(s)\left(ms + b + \frac{k}{s}\right) \quad (6)$$

Equivalent electrical circuit equation can be rewrite as

$$-I(s) = E(s)\left(sc + \frac{1}{R} + \frac{1}{sL}\right) \quad (7)$$

Where,

$$I(s) = m.a(s), E(s) = s.Z(s), C = m, R = \frac{1}{b}, L = \frac{1}{k}$$

From equation (7); the equivalent circuit is a parallel resonance circuit as shown in Fig. 2.

III. Experimental results

In this section, the proposed system used for real-time measurements is shown in Fig. 3. The main core of the setup includes National Instruments simulation and real time measurements tool LabVIEW which is used to simulate and measure the real data from the piezoelectric energy harvesting system through a compact data acquisition system (cDAQ-NI 9188). Figure 4 represents the frequency spectrum of the generated signal from the energy harvester. In Fig. 5; LabVIEW real time measurements represents output signal voltage and the center frequency of oscillation for measurements at different output voltage, the output of the measurements file transferred to excel sheet to draw the output using MATLAB. Figure 6 shows the real time measurements of piezoelectric energy harvesting. Experiments used to measure the relation between the frequency of the mini shaker and the output voltage of the harvester. The resonance frequency is 120 Hz at which the maximum peak-peak occurs.

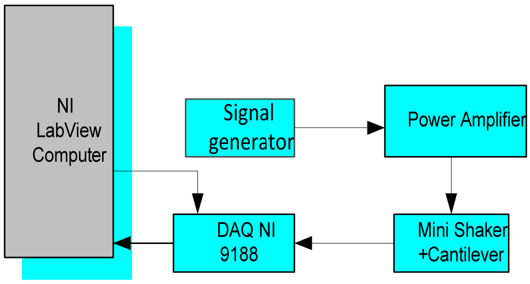

Fig. 3. Experimental setup

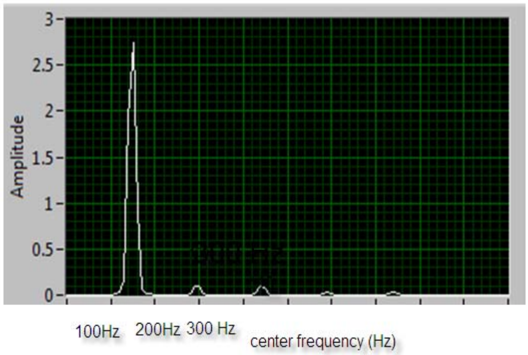

Fig. 4. Real time measurements of the frequency spectrum

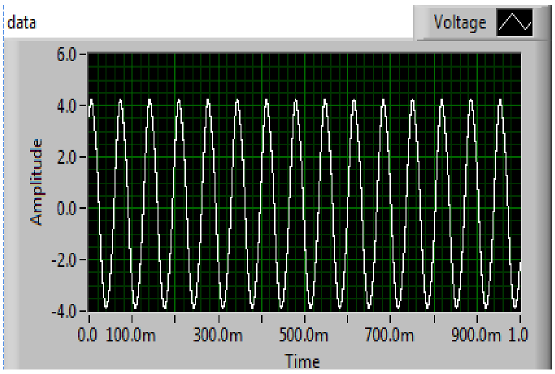

Fig. 5. Output voltage of energy harvesting peak to peak

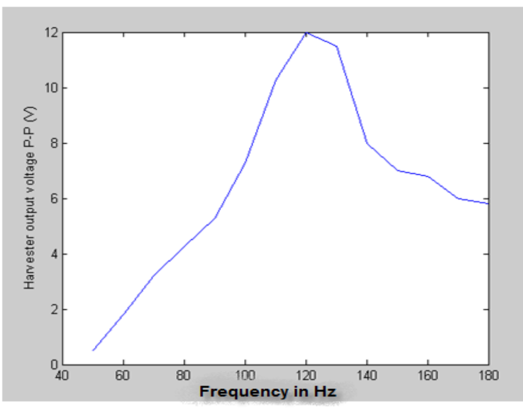

Fig. 6. Output voltage of Harvester Vs frequency

IV. Conclusion

This paper describes a reliable dynamic model to simulate piezoelectric energy harvester. The experimental results validate the dynamic model. The real time measurements show the relation between the acceleration and both output voltage and the resonant frequency of the energy harvester. A procedure for identifying model parameters is applied using simple measurements and standard laboratory equipment.

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