831. Experimental analysis of power harvesting on vehicle vibration using smart piezoelectric materials

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Abstract. In this paper the experimental analysis for power harvesting from mechanical vibration on a vehicle has been studied by using QuickPack smart materials with piezoelectric effect. The finite element ANSYS method (ANSYS FEM) was applied to explore the required mechanical structure, modal and harmonic analysis, and electrical feature, i.e., output voltage, admittance. The experimental platform consists of a shocker and a lever, which simulated a periodical oscillation on vehicle vibration, for evaluating conversion efficiency from mechanical energy to electrical energy. During loading experiments of power generation, the electromechanical coupling characteristics of smart materials were investigated via a proposed testing circuit. Also, various electrical output loadings were specified within resistance of 5~3000 kΩ. Through the experiment analysis, the power harvesting test with a buck converter at the output terminal was processed to obtain the spectrum analysis of output voltage within the vibrating frequencies below 200 Hz, controlled by the electromagnetic shaker. Based on the comparison between ANSYS FEM and spectrum analysis, the optimal results of mechanical oscillating quantities have been verified by the maximum output voltage for the QuickPack NQ45N material. Hence, the optimum power harvesting of the smart material has the maximum output power of 0.18 mW at 26-Hz-vibration on a vehicle.

Keywords: vehicle vibration, piezoelectric effect, power harvesting, FEM analysis, admittance.

1. Introduction

Most structural vibrations could be harvested as one of renewable and distributed energy to refill all electrical storage devices. These kinds of applications are based on the smart materials with piezoelectric effect [1]. A new power generation has an important tendency toward energy harvesting from mechanical vibrations through piezoelectric materials. Conventionally, the smart piezoelectric material system, involving piezoelectric materials, actuators, sensors, and a control system, is able to respond quickly for the variety of external conditions, e.g., pressure, stress, or deformation. A lot of similar research issues have been developed due to such rapid response to electromechanical conversion. Chandrakasan, et al [2] studied a power generation for distributed micro-sensor systems by using piezoelectric materials. Davis and Lesieutre [3] designed a tunable shaker as the mechanical source to provide vibrations for piezoelectric energy harvesting. Kymissis, et al [4] developed a lighting shoe with a piezoelectric membrane adhered to pads. Umeda, et al [5, 6] through a free-fall ball impacting on a piezoelectric plate, the proper equivalent circuit model has been constructed to explain the energy conversion between mechanical impact energy and electrical energy. Mitsos, et al [7] discussed the consideration of a portable power generation in piezoelectric materials. Poulin, et al [8] compared the efficiency and power density of electrical generation for portable devices by an electromagnetic and a piezoelectric system. Kimura [9] earned the U.S patent for rectifier voltage signals via vibrating energy from a piezoelectric thin film located the central plate. Shu and Lien [10, 11] performed a theoretical analysis and criteria for piezoelectric energy harvesting systems with better power output. Ottman, et al [12, 13] investigated an adaptive piezoelectric energy harvesting circuit with a step-down converter applied to a wireless portable power source.

This paper presents an ANSYS simulated and experimental analysis for the power harvesting of QuickPack smart materials in loading testing circuit and output performance with a buck converter, rather in equivalent-circuit models and theoretical-impedance characteristics. QuickPack QP40N materials are developed from Defense Advanced Research Projects Agency (DARPA), U. S. A., and commercially marketed by Mide Technology Corporation, which is a long compound bimorph actuator consisted of piezoelectric ceramics, epoxy matrix, Kapton polyimide film and electrodes, its appearance as shown in Fig. 1(a). The QuickPack QP40N material has the dimension in 100.6 mm × 25.4 mm × 0.76 mm and the weight of 9.52 g. Fig. 1(b) displays the apparatus of the QuickPack QP40N material including the interval between piezoelectric fibers in epoxy matrix and the structural pattern of interdigitated electrodes on Kapton film. Hence, it keeps an excellent flexibility and high quality d_{33} piezoelectric coupling feature under electric field applications. QuickPack materials, nowadays, are expanded to a piezoelectric energy harvesting device as a charging system for batteries, beyond its original design for sensing and/or actuating purpose.

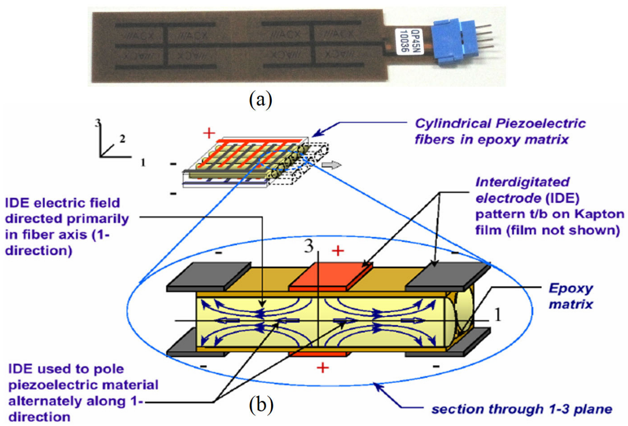


Fig. 1. (a) Appearance of QuickPack smart material (Model-NQ45N), (b) Apparatus of electrodes and electrical field applied on electromechanical coupling effects (adopted from Mide Technology Corporation)

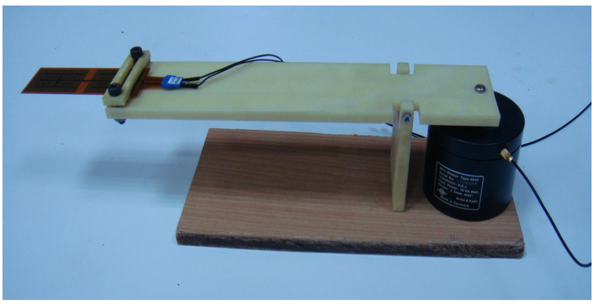


Fig. 2. Experimental platform of vehicle-vibration harvesting output power for the NQ45N smart material

The mechanism design of an experimental platform has a considerable element of the suspension system on a vehicle and the enlarged effect on vibrations from the body frame of an automobile as show in Fig. 2. Its whole size is limited to the dimension of

20 cm × 10 cm × 12 cm so that the future application on the vehicle could be possible. That is, it is an idea representative of a lever and an electromagnetic shaker (B&K 4810 MiniShaker) which offer a steady-state oscillating source periodically, like a running vehicle. QuickPack smart material absorbs an amplified vibration through a lever mechanism to convert the mechanical energy into the electrical energy. Because most useful mechanical-vibration frequencies for the renewable energy harvesting are below 200 Hz, the design concept would be adaptive for the major status of a distributed-vibration source, especially in the cycling vibration energy on a running car.

2. Simulations and experimental results

2.1. ANSYS simulation for natural modes, bending displacement and admittances

The proper finite modeling by the ANSYS software tool through the SOLID5 element for a combined structure of the lever and QuickPack NQ45N smart material was simulated in this study. At first, the meshing model, as shown in Fig. 3 (a) based on the different material properties of the lever and smart device with lead zirconate titanate (PZT) material parameters, was introduced to complete ANSYS modal analysis for their natural modes, as shown in Figs. 3(b) and 3(c). The two mode shapes in the seventh mode at 70 Hz and the eighth mode at 122 Hz are quite suitable for the feature of larger bending displacement. However, there is a damaged opportunity located at the middle cantilever structure of the QuickPack NQ45N material due to great bending resulted in stress concentration. According to ANSYS simulations, we decided to adopt the lower operating frequency of the seventh mode shape for the input voltage signal of the electromagnetic shaker.

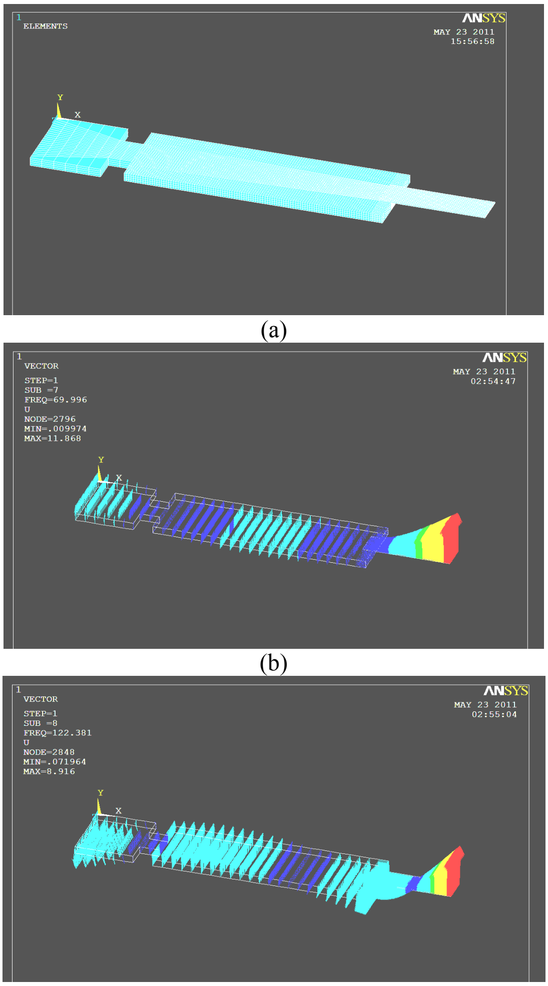
Further study through ANSYS harmonic analysis, the bending displacement is observed in frequency domain as shown in Fig. 4. Nearby 118 Hz, there was a huge amount of bending displacement where is a possible broken location for the QuickPack NQ45N material. Hence, there is a good reason to avoid this drawback and to operate the vibrating frequency at the lower bandwidth associated with the comparison of Fig. 3(b) and Fig. 4. Also, the admittance feature of the smart material is modified by the specific boundary condition as shown in the frequency spectrum of Fig. 4. The ANSYS admittance spectrum of harmonic modes at operating frequencies for the QuickPack NQ45N material is based on the Eq. (1) to calculate the admittance Y as [14]:

$$Y = \frac{1}{Z_c} = \frac{I}{V} = \frac{jQ\omega}{V} \tag{1}$$

where V, ω and Q are, respectively, the input voltage and scanning frequencies, and total electrical charges on the electrode of piezoelectric materials. Notation j is $\sqrt{-1}$ and the impedance Z_c is the reciprocal of admittance Y. Through the calculation of Eq. (1), admittance characteristics versus vibrating frequencies for the QuickPack NQ45N material are illustrated in Fig. 5. Obviously, there are resonant frequencies due to electromechanical coupling at 28 Hz and 146 Hz, respectively.

2.2. Loading circuit test of power harvesting

Before loading circuit test, the maximum open-circuit voltage should be obtained at output terminals with free loading because it stands for the optimal mechanical oscillating frequencies for the QuickPack NQ45N material. According to the spectrum scanning between 0 and 200 Hz vibrations, the maximum open-circuit voltage of 40 V_{pp} and 65 V_{pp} were gathered at 26 Hz and 150 Hz, respectively. Also, the effect of structural resonance on the QuickPack NQ45N material and the lever results in an ideally sinusoidal wave form for the output voltage. The sinusoidal wave represents lot of harmonic vibration components which have the potential energy concentration. Furthermore, the phenomena of harmonic vibration would be obviously appeared the output efficiency of converse piezoelectric effect on the QuickPack NQ45N material. Therefore, the portable power harvesting system for vibration could be implemented when a proper resonance structure acted on the smart material with maximum output voltage and optimal output power. During loading testing of the QuickPack NQ45N material, a series of energy conversion between vibrating energy and electrical power were proceeding as the optimal power harvesting by using the full-bridge rectifier, a capacitor filter, and a variable resistor, as shown in Fig. 6(a). At the constant driving frequency of 26 Hz with a controlled input voltage into the oscillating shaker, the output-power characteristics with tunable loading resistance from 5 kΩ to 3000 kΩ were measured as shown in Fig. 6(b). To observe the loading curve, the maximum output power points out the optimal loading resistance about 500 kΩ in which generated near 0.113 mW power.



(a)

(b)

(c)

Fig. 3. (a) Modeling smart materials by ANSYS software, (b) seventh natural mode (at 70 Hz), and (c) eighth mode (at 122 Hz) by ANSYS modal analysis

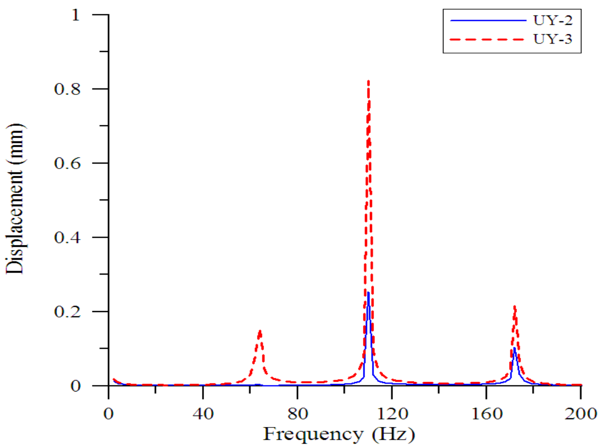


Fig. 4. Optimum analysis of bending displacement in relation to vibrating frequencies for the QuickPack NQ45N smart material through ANSYS simulation (Harmonic analysis)

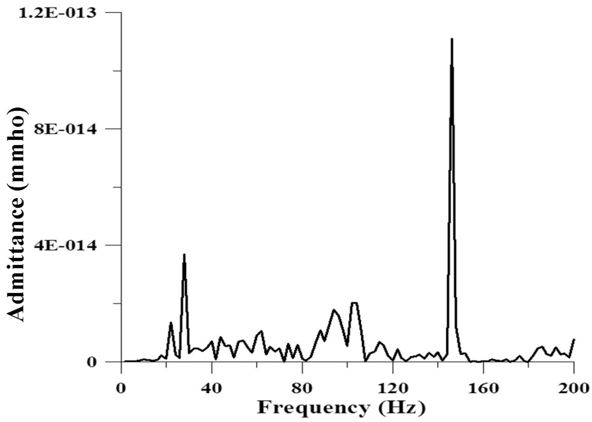
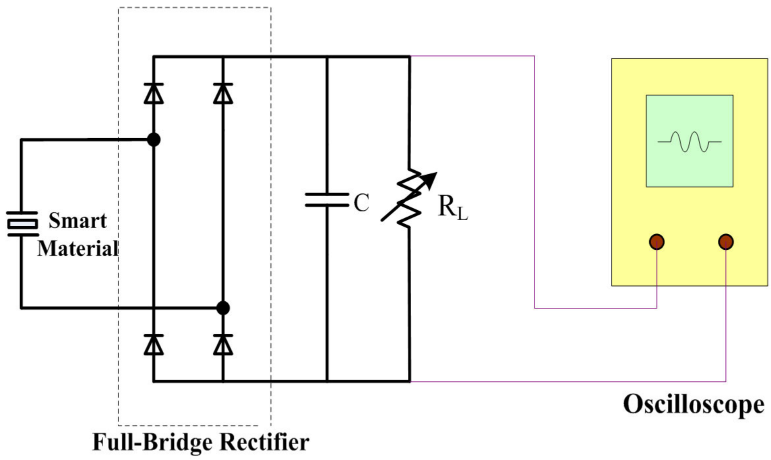


Fig. 5. Characteristic analysis of admittance versus vibrating frequencies for the QuickPack NQ45N smart material through ANSYS software

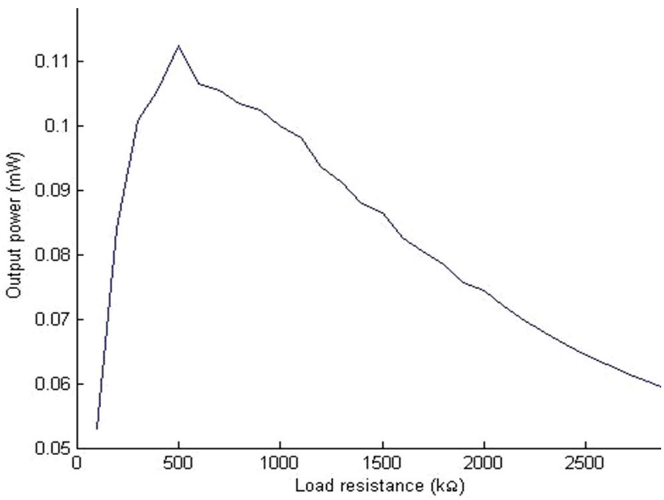
2.3. Output characteristics of harvesting with simulations and through a buck-converter circuit

Applying a shaker to generate periodical impact energy for the QuickPack NQ45N smart material, the fundamental concept of ANSYS harmonic simulation and experimental platform was used to evaluate the energy converting efficiency. It is a transformation from mechanical energy on a vehicle, like engine vibrations or motor oscillations, into electrical energy harvesting after the bridge rectifier and filter circuit, such as output voltage as shown in Fig. 7. There are obvious voltage peaks at stimulated frequencies of 16 Hz, 28 Hz and 164 Hz, respectively. To compare the results of simulation through experiments, the acceptable error percentages of 12 % and 2.5 % were occurred at the frequencies of 25 Hz and 160 Hz. One of possible explanations could be lack of damping factor in the ANSYS model and of the nonlinear structure consideration.

An adaptive piezoelectric harvesting circuit for vehicle power supply using a buck converter in discontinuous conduction mode was implemented as it is very similar to the practical situation during vehicle operation. The testing circuit of harvesting output power consists of a full-bridge rectifier, a capacitance filter, a buck converter with a DSP controlled power transistor chip, and loading resistor, as shown in Fig. 8(a). The experimental parameters, including the constant frequency of 26 Hz for the shaker voltage input of 1.4 V_{pp}, the loading resistance of 20 kΩ, and the adjustable duty cycle from 10 % to 95 % tuned by the buck converter circuit, were setup as measured factors for the QuickPack NQ45N material. Hence Fig. 8(b) presents the characteristic of harvesting output power in relation to the duty cycle. It is a transformed form of the input voltage for a vibrating shaker and of the output voltage through the NQ45N material, which is replaced by the duty cycle of the power transistor controlled by the PWM signals from the DSP chip inside the buck converter. On the basis of the evidence we deduced that the smart material has the optimum operating conditions for maximum output power when the specific mechanical vibration and loading resistance could be tunable by the proper duty cycle of a buck-converter circuit. To achieve the maximum output power, the 90 % duty cycle of the power transistor applied to the experimental mechanism could obtain the 0.18 mW power as shown in Fig. 8(b), in which is much better than that of a conventional rectifier circuit only as shown in Fig. 6(b).



(a)



(b)

Fig. 6. (a) Testing circuit for loading output, and
(b) output power characteristic with various loading resistance

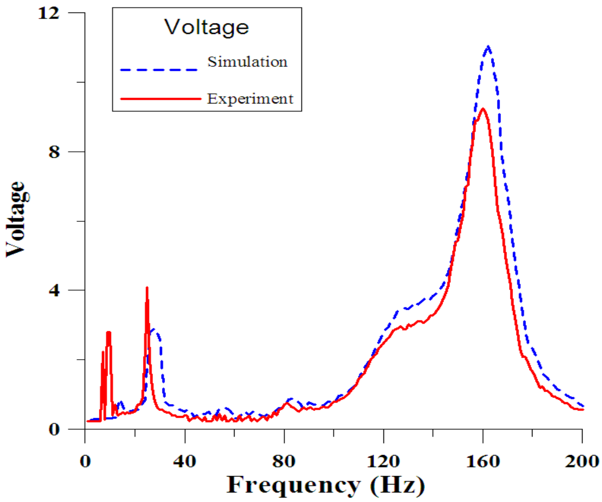
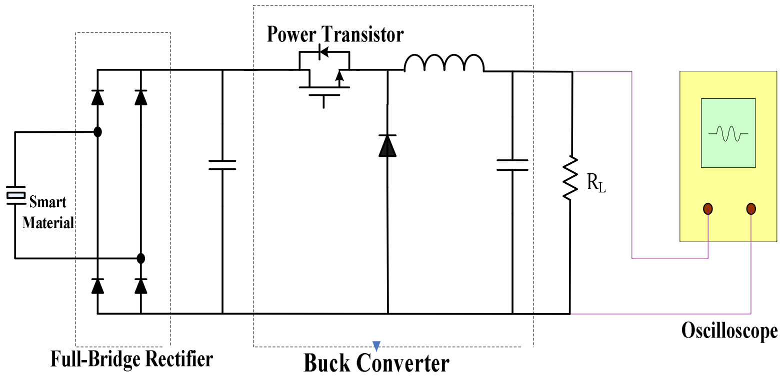
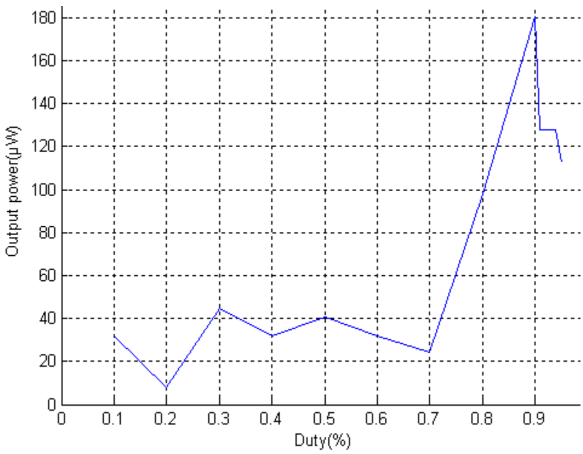


Fig. 7. Characteristic comparison of output voltage versus vibrating frequencies for the NQ45N smart material through the ANSYS harmonic simulation and experiment



(a)



(b)

Fig. 8. (a) Testing circuit of harvesting output power based on a buck converter for the QuickPack NQ45N material, and (b) characteristic of harvesting output power

3. Conclusions

The operating frequency of maximum output power for the smart piezoelectric material stacked up electrodes between epoxy matrixes is the much lower than their structural resonant frequency. There is an apparent proof of the power harvesting for vibration on a simulated running vehicle in this study. The power generation system of the QuickPack NQ45N material has an optimal operating point and electrical converting parameters. Through the comparison of simulation and experiment, we believe that mechanical fluctuations from the body frame of a vehicle could be harvested as the renewable energy to supplement the electrical consumption, rather than a recharging wire of the battery on a vehicle. According to the buck-converter circuit design for electric charge output of QuickPack materials, the future application in relation to the practical purpose on a running automobile is expectable for various smart materials because of their quick converting response from vibration to electrical power supply.

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