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Design and evaluation of an experimental system for monitoring the mechanical response of piezoelectric energy harvesters

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Abstract. Increasing interest in prognostics and health management has heightened the need for wireless sensor networks (WSN) with efficient power sources. Piezoelectric energy harvesters using Pb(Zr,Ti)O3 (PZT) are one of the candidate power sources for WSNs as they efficiently convert mechanical vibration energy into electrical energy. These types of devices are resonated at a specific frequency, which has a significant impact on the amount of energy harvested, by external vibration. Hence, precise prediction of mechanical deformation including modal analysis of piezoelectric devices is crucial for estimating the energy generated under specific conditions. In this study, an experimental vibrational system capable of controlling a wide range of frequencies and accelerations was designed to generate mechanical vibration for piezoelectric energy harvesters. In conjunction with MATLAB, the system automatically finds the resonance frequency of harvesters. A small accelerometer and non-contact laser displacement sensor are employed to investigate the mechanical deformation of harvesters. Mechanical deformation under various frequencies and accelerations were investigated and analyzed based on data from two types of sensors. The results verify that the proposed system can be employed to carry out vibration experiments for piezoelectric harvesters and measurement of their mechanical deformation.

Keywords: piezoelectric; beam shape; energy harvester; PZT; mechanical deformation

1. Introduction

Energy harvesting is defined as the capturing of energy from external sources, such as solar power, thermal gradient, wind energy, fluid flow, salinity gradient, mechanical vibration, and storing it for powering devices. Among these external power sources, solar power is considered the best for generating electricity as excellent power density is available in direct sunlight (Roundy *et al.* 2003). In low-light (or even no light) environments when solar power is inefficient however, piezoelectric energy harvesters, which use mechanical vibration energy, are considered to have sufficient potential (Shu and Lien 2016). Piezoelectric devices are widely used to convert vibrational energy into electrical energy. Power generation systems that use Pb(Zr,Ti)O_3 (PZT) have a simple structure and can be used without reliability issues for extended periods (Kim *et al.* 2011). However, because the device converts mechanical energy into electrical energy, collaborative research in both fields is essential. These collaborations include studies on how mechanical properties such as mass, spring, and damping coefficients are related to electrical properties such as resistance, inductance, and conductance (Roundy and Wright 2003). Impedance matching is critical to maximize the useful energy harvested on the load side of the alternating current (AC) electric potential energy generated by PZT (Liang and Liao 2012, Lee *et al.* 2016). However, to achieve such impedance matching, both the impedance of the electrical part of PZT and the mechanical part must be clearly understood. In particular, the mechanical deformation of PZT elements needs to be accurately modeled under various vibrating environments, as this information is critical for predicting and utilizing the generated power effectively. In fact, mechanical strain is an important parameter for piezoelectric cantilever analysis because electrical power is generated by mechanical strain and stress (Indrani and Nitin 2013). The more uniform is the strain distribution in a piezoelectric cantilever, the more electric potential energy the cantilever has (Guan *et al.* 2014, Avsar and Sahin 2016). Many studies have been conducted with the objective of achieving uniform strain distribution by changing the geometrical configuration of the cantilever. In addition, simulations or experimental studies involving piezoelectric energy harvester often use tip displacement as an important parameter, which directly affects the amount of energy harvested (Dong *et al.* 2006, Renato *et al.* 2014, Olyaie and Raxfar 2013). Thus, it is clear that knowledge of the mechanical deformation of piezoelectric cantilevers under vibration environments is important for designing and analyzing piezoelectric devices.

In this paper, a design for a system that can

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automatically characterize the vibration response, including the resonance frequency, of PZT devices is proposed. Further, the results of experimental investigation of the mechanical response of PZT under specific vibrational conditions using this system are discussed. In addition, the experimental results are compared with simulation results to verify the efficacy of simulation models.

2. Design of experimental set-up and measurement

Fig. 1 shows the proposed experimental system. It consists of a shaker that can be controlled through a computer program, an accelerometer that measures the vibration of the shaker and provides feedback to the system, and a laser displacement sensor that measures the mechanical displacement in all points of the PZT through a non-contact method. A sinusoidal input signal is generated through in the computer system to drive the vibration shaker (Modal shop, Shaker 2007E) and thereby vibrate the piezoelectric harvester to a desired state.

To generate the intended vibration, precise control of the input signal to the shaker is essential. However, because the experimental system uses a dial-type amplifier, it is difficult to manually adjust the input correctly. Therefore, control of the input is ensured vis the computer. The accelerometer (Dytran, 3225M24T) is fixed on the jig to measure the acceleration applied to the harvester. Because the shaker only vibrates in the vertical direction, a single-axis accelerometer is used, and the laser displacement sensor (Microtrak, LTS-250-04) is used to verify the acceleration. The resolution of the laser sensor is 0.076 μm, which is sufficient for measuring the fine movement of the base. To calculate the base acceleration, the measured values are all converted to the same units via the following equations

$$\mathrm{A} = \frac{dV}{dt} = \frac{d^2D}{dt^2} \tag{1}$$

$$\mathrm{A} = \mathrm{a}\sin(\omega \mathrm{t}) \tag{2}$$

$$\mathrm{V} = -\frac{\mathrm{a}}{\omega}\cos(\omega t) \tag{3}$$

$$\mathrm{D} = -\frac{\mathrm{a}}{\omega^2}\sin(\omega t) \tag{4}$$

where A, V, D, a, and ω are the acceleration, velocity, displacement, amplitude, and frequency, respectively.

The system and the piezoelectric energy harvester are controlled via the following process. First, the harvester is vibrated using an arbitrary excitation force at a specific frequency. Next, the accelerometer measures the acceleration at the base and the data are processed through the oscilloscope (Rigol, DS1074Z-S). The data are then collected and refined via regression analysis in MATLAB. Subsequently, the amplitude of the signal is suitably adjusted in consideration of the errors between the desired and the measured acceleration. This procedure is repeated until the desired amplitude is achieved. Then, after adjusting the amplitude through the accelerometer, the laser sensor is used to confirm the vibration of the base.

Fig. 2 shows the geometry of the harvester used in the experiment. The substrate of the harvester was made up of stainless steel material and partially covered with PZT. The silver layer functions as an electrode. One side of the harvester was bolted to the jig, and the other side remained free. In general, experiments are conducted at resonance frequency to obtain maximum power. To achieve this, the tip displacement during sweeping frequencies is measured to determine the actual resonant frequency of the harvester. Thus, we determined the resonance frequency of the piezoelectric harvester to be the frequency at which maximum displacement was indicated. The system automatically changes the frequency within a set range and records the voltage occurring in the harvester in terms of root mean square at each frequency; hence, the resonant frequency was easily determined. More specifically, using MATLAB, the frequency representing the highest value of the recorded voltage was obtained as the resonance frequency. Therefore, the system can automatically find the resonant frequency by selecting only the appropriate frequency range. The resonance frequency was verified by comparing the experimental results with simulation results.

One of objectives of this study is to confirm that the numerical model accurately simulates the mechanical deformation of the harvester in a vibration environment. To achieve this objective, the damping ratio of the actual piezoelectric energy harvester had to be considered. The actual damping ratio can be determined experimentally. Using logarithmic decrement, the damping ratio can also be calculated as follows

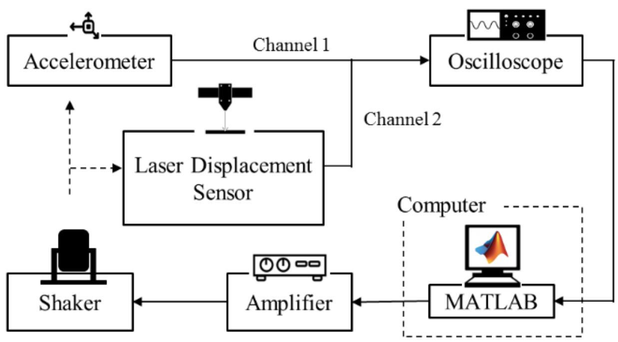


Fig. 1 Schematic of the proposed experimental system

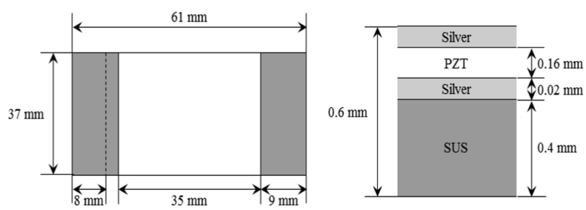


Fig. 2 Geometry of the unimorph piezoelectric harvester

$$\frac{1}{n}\ln\left(\frac{x(t)}{x(t+nT)}\right)=\frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \quad (5)$$

where x(t) is the amplitude of successive oscillations of the harvester, n is the number of oscillation peaks, ζ is the damping ratio, and T is the oscillation period.

3. Results and discussion

The accelerometer and the non-contact laser displacement sensor were used to verify that the jig with the PZT device was correctly vibrating with controlled acceleration by the shaker. The results in Table 1 show the acceleration, velocity, and displacement of the jig of the PZT device. There is no significant difference between the measurements from the two types of sensors. We surmise that the actual errors between the data from the two types of sensors may be due to the following causes. First, the base displacement in the vertical direction in our application is too small. For example, the vertical displacement of the base is theoretically about 21.7 µm at 1 g acceleration with a vibration frequency of 107 Hz. According to its specifications, the current instrument has an error of several micrometers. Another source of error in the data from the sensors is intrinsic noise. Both the data and the noise are approximated by regression analysis. Finally, the shaker does not produce vibrations entirely in the vertical direction, which is also an error factor. These error sources in our experimental system result in a negligibly small overall error. Therefore, the system is consistently controlled to provide the desired input and vibration.

Fig. 3 shows the RMS voltage occurring in the PZT device as a function of vibrational frequency. The voltages of the piezoelectric energy harvester were measured by the oscilloscope when the base of the harvester vibrated with accelerations of 1 G (9.8 m/s^2), 2 G, and 3 G at frequencies ranging from 90 to 150 Hz. Based on the RMS voltage, the resonant frequency was determined to be 107 Hz. Because at the resonant frequency, the tip displacement of the cantilever is much larger than the other frequencies around it, there is more strain and stress on the harvester, which leads to an AC voltage with a large amplitude. The amplitude of the AC voltage can be represented by the RMS value. Therefore, the peak shown in the graph can be confirmed as the resonance frequency. The graph also shows that the resonance frequency increases slightly as the base acceleration increases from 1 G to 3 G. In a linear system, the resonant frequency of the system does not vary with input. However, when the input is outside the specified range, the system can no longer be assumed to be a linear system. Because the resonant frequency of a nonlinear system does not remain constant even with constant input, there is a change in the resonant frequency (Stanton *et al.* 2010). The simulation and experiment are based on the results at 1 G. Fig. 4 shows the response of the harvester tip to impulse. The damping ratio was determined to be 0.008 considering 55 periods, based on Eq. (5).

To facilitate understanding of the deformation of the entire area, including the end point of the PZT device, Fig. 5 shows the measurement points on the PZT device. The measurement results were used to confirm the actual beam shape compared with the simulation result. At point 1, the vertical displacement of the jig is measured to confirm the base excitation. At point 9, the displacement of the tip of the device is measured. The displacement of each node of the device is confirmed based on the point at the corresponding equal interval between point 1 and point 9.

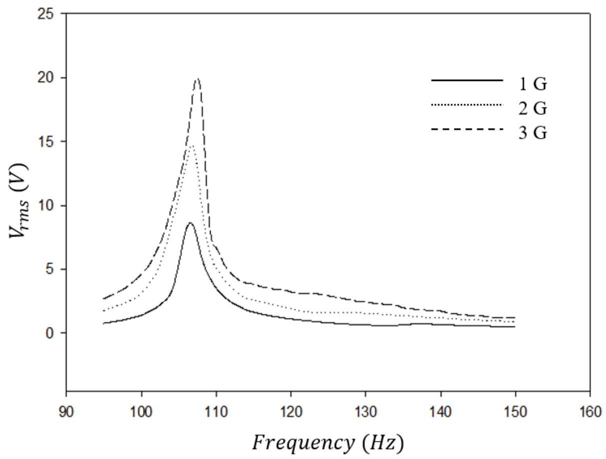


Fig. 3 Voltage of harvester as a function of vibrational frequency

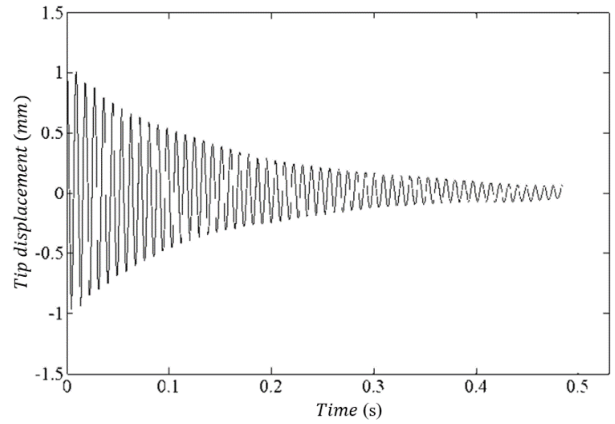


Fig. 4 Experimental result of harvester tip response to impulse

Table 1 Summary of measured and calculated results using two types sensors

	Accelerometer	Laser displacement sensor
Acceleration (g)	1.004	0.943
Velocity (m/s)	0.018	0.017
Displacement (µm)	32.43	30.52

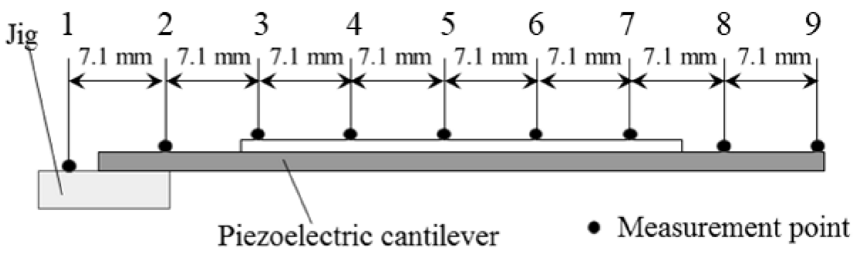
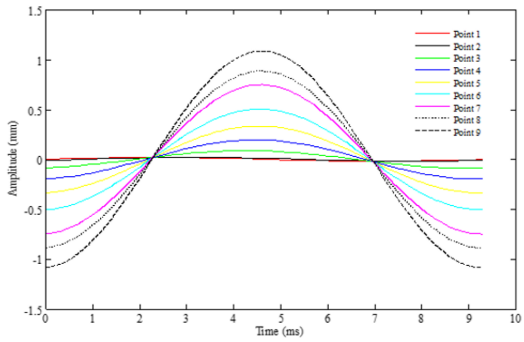
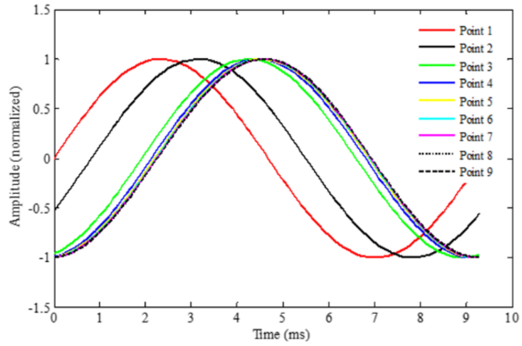


Fig. 5 Measurement points used to compare simulation results with experimental results

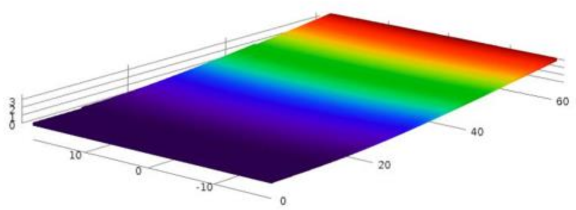


(a) Actual displacement

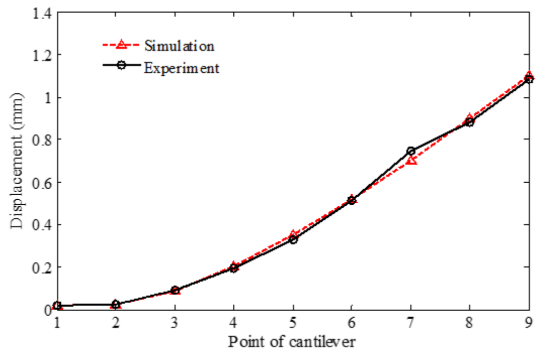


(b) Normalized displacement

Fig. 6 Displacement over time at each point based on the experiments



(a) Simulation result



(b) Comparison of simulation and experimental results

Fig. 7 Shape of piezoelectric cantilever using experimental method and simulation

Fig. 6(a) shows the displacements from the clamped end (point 1) to the free end (point 9) as a function of time. It can be seen that the magnitude of the vertical displacement of the beam continues to increase with the distance from the clamped end. As the distance from the clamped end increases, the displacement in the vertical direction becomes larger as the PZT device oscillates at the resonant frequency. This leads to more horizontal strain on the surface of the PZT device, resulting in more generated power.

There is a phase difference between the points of the device that must be considered in order to identify the beam shape. In the case of cantilever-type beam connected to the shaker, the time when each point of beam shown in Fig. 5 reaches its peak is all different due to the elasticity of the beam. This difference of time is phase difference. Thus, each displacement is measured when the free end of the cantilever is at its highest position and the phase of each point is based on the simulation results. However, because the vertical displacement difference between the free end and the clamped end very large, the phase difference is not described well in Fig. 6(a) for some points. The normalized graph of the displacement in Fig. 6(b) more clearly shows the phase difference that occurs between the points. In the graph, the phase of the clamped end is delayed by approximately 90 degrees compared to the phase of the free end. Because of this phase difference, when the base starts to descend from the zero point, the end (point 9) is at the highest position.

Table 2 Summary of results for confirming the actual shape of the piezoelectric cantilever

Point	Phase (degree)	Displacement (mm)	
		Simulation	Experiment
1	180	0.0217	0.0204
2	148.350	0.0260	0.0262
3	106.070	0.0893	0.0917
4	98.115	0.2036	0.1956
5	95.521	0.3506	0.3315
6	94.344	0.5194	0.5133
7	93.703	0.7018	0.7457
8	93.295	0.8980	0.8834
9	93.023	1.1006	1.0831

The experimental results of the vertical displacement at each point of the PZT device were compared with finite element method (FEM) simulation results. In the case of FEM simulation, the magnitude of the vertical displacement is directly dependent on the damping coefficient. Hence, the experimentally calculated coefficient was used in this simulation. Fig. 7(a) shows the beam shape when the end of the cantilever was at the highest position at the resonant frequency. Fig. 7(a) and 7(b) show the magnitude of the vertical displacement of each point for both the experiment and simulation. It can be seen that both results are virtually identical. The phases and the displacement obtained through simulation and measurement are summarized in Table 2. Thus, it is clear that using the designed experimental system, the vibration and morphological deformation characteristics of piezoelectric devices under a vibration environment can be investigated and understood.

4. Conclusions

This paper presented the design and evaluation of a proposed experimental vibrational system for investigating the mechanical response of piezoelectric energy harvesters. MATLAB was used to operate and control all equipment, with ability to precisely control the shaker being the most important part of the system. Although the frequency of the input is also an important factor, this study focused on amplitude, which is relatively difficult to control. The experimental verification using the two types of sensors indicates that the proposed system can be employed to carry out vibration experiments for piezoelectric harvesters and measurement of their mechanical deformation. Further, the negligible error found between the mechanical deformation simulation results and those obtained experimentally show that the simulation model is valid.

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