Electromechanical modelling and experimental analysis of a compression-based piezoelectric vibration energy harvester

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Over the past few decades, wireless sensor networks have been widely used in the field of structure health monitoring of civil, mechanical and aerospace systems. Currently, most wireless sensor networks are battery-powered and it is costly and unsustainable for maintenance because of the requirement for frequent battery replacements. As an attempt to address such issue, this paper theoretically and experimentally studies a compression-based piezoelectric energy harvester using a multilayer stack configuration, which is suitable for civil infrastructure system applications where large compressive loads occur, such as heavily vehicular loading acting on pavements. In this paper, we firstly present analytical and numerical modelling of the piezoelectric multilayer stack under axial compressive loading, which is based on the linear theory of piezoelectricity. A two-degree-of-freedom (2DOF) electromechanical model, considering both the mechanical and electrical aspects of the proposed harvester, was developed to characterize the harvested electrical power under the external electrical load. Exact closed-form expressions of the electromechanical models have been derived to analyze the mechanical and electrical properties of the proposed harvester. The theoretical analyses are validated through several experiments for a test prototype under harmonic excitations. The test results exhibit very good agreement with the analytical analyses and numerical simulations for a range of resistive loads and input excitation levels.

Keywords: Vibration Energy Harvesting; Piezoelectric; 2DOF Electromechanical Model; Large-force; Low-frequency

1. Introduction

Because of the advantages over existing wired technologies, wireless sensors and sensor networks have become ubiquitous in the field of civil structure health monitoring in recent years. Currently, the wireless sensors network is battery-powered and it is not only costly for maintenance but the requirement for frequent battery replacements raises serious reliability and sustainability issues in practice. The task of replacing battery

sometimes can become extremely difficult, especially in case of structural health monitoring applications, where there are hundreds and thousands of sensors that are often installed during construction stages. For these sensors, if it is not impossible, for the least it is impractical to gain access, remove protection and replace batteries. The disposal of large quantities of batteries may also lead to serious environmental hazards. Although the power requirement of a single wireless node is quite low (normal lower than hundreds of μW), the wireless sensor network required significant power supply since the number of the sensor nodes and the computational demands have drastically increased due to advanced algorithms to enable performance of structural health monitoring [1], especially for large-scale civil infrastructures. So it is of great necessity to seek alternative power sources for the sensor networks. Due to the low-power consumption requirements of an individual wireless sensor, a possible solution to this problem is the technologies that enable harvesting ambient vibration mechanical energy to power wireless sensor networks [1,2].

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Obtaining power from ambient vibration sources is generally known as vibration energy harvesting, or vibration energy scavenging. Several methods, such as electromagnetic induction, electrostatic generation, and piezoelectric generation, can be utilized to harvest electrical energy from external vibrations [3]. While each of the aforementioned methods can generate a useful amount of energy, piezoelectric materials have received more attentions especially in the recent years due to their ability to directly convert applied strain energy into usable electrical energy, as well as its large power density, and ease of application [4-6]. Comparing to energy harvesting for large-scale alternative energy generation using wind turbines and solar cells is mature technology, the development of energy harvesting technology by using piezoelectric devices on a scale appropriate for small, low-power, embedded wireless sensing

systems is still in its developmental stage, particularly for application of structural health monitoring sensing system. In 2002, Elvin et al. proposed a self-powered damage detection sensor using piezoelectric patches [7]. A piezoelectric harvester in cantilever beam configuration is utilized to convert the applied load into electricity and provide a power for the sensors in order to measure the strain and to send the results to a moving cart. In 2006, Discenzo et al. developed a prototype self-powered sensor node that performs sensing, local processing, and telemeters the results to a central node for pump condition monitoring applications [8]. The device was mounted on an oil pump, and a cantilever piezoelectric beam tuned to the excitation frequency was embedded with the sensor node to scavenge energy from the pump vibration. The test results showed that the output power could reach to 40mW. In 2008, Lallart et al. proposed a self-powered wireless structural health monitoring system [9]. A piezoelectric harvester based on the beam structure, using the synchronized switch harvesting method, was utilized to convert ambient mechanical energy into electricity and powered the structure health monitoring system. In 2011, Kim et al. investigated the possibility of harvesting energy from bridges by converting the potential energy of vibrating bridge systems into electrical energy using a cantilever piezoelectric harvester, and got some good results [10]. Of the published results that focus on using piezoelectric harvesters scavenging electricity for the wireless sensor networks, most of them have focused on harvesting energy using cantilever beams configuration [11-13]. However, the cantilever beam cannot sustain large force, and in large force vibration environments, such as the large compressive loadings induced by the heavy trucks on the pavement, the piezoelectric harvester in cantilever beam configuration would be more frangible and breakable.

In this paper, a compression-based piezoelectric harvester was developed to scavenge energy from surrounding vibrations in order to provide power for the wireless

sensor networks. The piezoelectric material used in this novel harvester is constructed in multilayer stack configuration that is robust and suitable for large force vibrations existing in the civil infrastructure system applications. In comparison with the monolithic configuration, the stack structure can reduce the voltage output and the matching resistive load of the harvester to a more manageable level [14], therefore the piezoelectric stack is selected in this research to scavenge vibration energy. By now, the development of models for cantilevered piezoelectric harvester has attracted a great deal of attentions from researchers. And there are already many models available to evaluate the harvested power of cantilevered harvester [15-17]. Roundy et al. [18], Aldraihem and Baz [19] have ~~done~~uconducted ~~some~~ studies on the multiple-DOF models of cantilevered piezoelectric harvesters. Tang and Yang [20] presented a novel multiple-DOF harvesting model of the cantilevered piezoelectric harvester. Wu et al. [21] presented a nonlinear 2-DOF model of the cantilevered piezoelectric harvester to enhance the performance of piezoelectric energy harvesters. However, to date, there is limited research reported on the development of stack configuration based piezoelectric harvesters. Keawboonchuay and Engel [~~18~~22,~~19~~23], Platt et al. [14, ~~20~~24], Feenstra et al. [~~21~~25] have done some feasibility investigations on the piezoelectric harvester in stack configuration, however comprehensive research on the piezoelectric harvester constructing in multilayer stack configuration is still limited. Moreover, a piezoelectric harvester system contains two fundamental elements: the mechanical part that generates electrical energy, and an electrical circuit that converts and rectifies the generated energy in a form of an alternating voltage, into a constant voltage. The efficiency of the energy harvester design depends not only on the piezoelectric harvester itself but also on its integration with the electrical circuit. Therefore, an electromechanical model which considers both the mechanical and electrical aspects of the proposed harvester is

of great importance to optimize the design as well as for understanding the behavior of the piezoelectric harvester.

In this paper, we will firstly investigate the longitudinal mode of the piezoelectric stack for the aim of finding the inter-medium force that will be used to convert vibration energy into electrical energy. Then, the electromechanical model of the proposed compression-based piezoelectric stack harvester will be presented to investigate the ability of harvesting electrical power and analyse the electrical properties of the harvester. Finally, we will present a series of tests conducted to verify the theoretical findings. Test results strongly verify the validity of the proposed theoretical analysis and show that the harvester can generate a maximum 200 mW electrical power under the harmonic excitation with 1360 N amplitude and 6 Hz frequency. Also, the harvested electrical power is proportional to the level of external excitation.

2. Electromechanical models

2.1 Electrical characteristics of the piezoelectric wafer-stack

The vibration energy harvester proposed in this paper employs piezoelectric multilayer stack in order to endure large compressive loads that exist in the field of civil infrastructure systems application. In practice, the proposed harvester can be embedded into the civil building, roads and highways to harvest electrical energy, just like the energy harvesting system shown in INNOWATTECH LTD.'s patent [26]. When subjected to an external force, the piezoelectric stack will produce an electric charge and convert external kinetic energy into electricity. Therefore, the piezoelectric stack is the media to convert kinetic energy to electrical energy and it is necessary to investigate the electrical reaction of the stack under external excitation before developing an accurate model to present a piezoelectric harvester. Figure 1 shows the sketch of the

piezoelectric stack under applying external force. The force, F(t), used in this analysis is a harmonic excitation in order to simplify the analysis. The rubber, as shown in Figure 1, is used to protect the wafer-stack from damage under external large force due to the brittleness of piezoelectric materials.

According to the IEEE Standard on Piezoelectricity: under the external force, giving by the strain S, stress T, electric field E, and electric displacement D, the constitutive relations of the piezoelectric energy harvesting device are typically defined by:

$$\begin{bmatrix} T_3 \\ D_3 \end{bmatrix} = \begin{bmatrix} c_3^E & -e_{33} \\ e_{33} & \varepsilon_{33}^s \end{bmatrix} \begin{bmatrix} S_3 \\ E_3 \end{bmatrix} \tag{1}$$

where the e_{33} is the piezoelectric coefficient, c_3^E is the elastic stiffness constant under a constant electric field, and ε_{33}^s is the dielectric constant under constant strain. Note that the subscripts of the state variables show that all constitutive qualities are generated and applied on the thickness direction of the piezoelectric material.

Figure 2 shows the electrical characteristics of the piezoelectric stack, and it needs to point out that the polarization direction of each wafer is opposite to each other. For the configuration as shown in Figure 2, the constitutive equations of the piezoelectric wafer-stack can be written as:

$$S_3 = x_p / h, \qquad E_3 = V_p / h\,, \qquad T_3 = F/A, \qquad D_3 = Q/A \tag{2}$$

where x_p is the strain of the piezoelectric wafer-stack under the external force; V_p is the output voltage of the wafer-stack; Q is the electric charge; A is the cross-section area of the wafer-stack, and h is the length of the wafer-stack. To simplify the analysis, we assume the length of the stack is equal to the entire thickness of all the piezoelectric wafers (h=nt) with identical dimension, where n and t are the number and thickness of a

single piezoelectric wafer, respectively. According to the relationship in Equation (2), the constitutive equations of the piezoelectric wafer-stack from Equation (1) can be rewritten as:

$$\begin{bmatrix} F \\ Q \end{bmatrix} = \begin{bmatrix} k_p & -N \\ N & C_P \end{bmatrix} \begin{bmatrix} x_p \\ V_p \end{bmatrix} \tag{3}$$

It can be found from Equation (3) that the V_p is generated by the external force. The force applied to the piezoelectric disc without any electrical input can produce deformation x_p, the relationship of which is regarded as the elastic coefficient k_p of the mechanical characteristic. Piezoelectricity also possesses an electrical property between the voltage and the electric charge, which can be modeled as a capacitor C_p. The electromechanical conversion coefficient N is defined as the electromechanical coupling coefficient. Based on Equation (3), there is a critical force which is actually used to generate electrical voltage. This critical force can be denoted as F_e and written as:

$$F_e = NV_p \tag{4}$$

Equation (4) gives an explicit relationship of vibration force and output voltage, which will be used to build the electromechanical model of the piezoelectric harvester.

2.2 2DOF electromechanical model without a rectifier circuit

Considering the mechanical and electrical characteristics of the rubber and piezoelectric stack under the external force, the electromechanical model without a rectified circuit of the proposed harvester is illustrated in Figure 3. As shown in Figure 3, $F(t)$ is the excitation force. Parameters, m_r, c_r, and k_r, are used to represent the mass, damping and elastic coefficient of the rubber layer, respectively. Parameters, m_p and k_p, are used to represent the mass and elastic coefficients of the piezoelectric wafer-stack, respectively.

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Parameters, c_h and k_h, are used to represent the mechanical damping and elastic coefficients of the mechanical structure of the harvester, respectively. Parameters, x_r and x_p, are used to represent the deformation of the rubber layer and piezoelectric wafer-stack under the external force, respectively. Parameter, C_p, is used to represent the clamped capacitance of the piezoelectric wafer-stack, and R_p is the piezoelectric leakage resistance and used to represent the electric loss property of the piezoelectric wafer-stack. R_l is used to represent the external electrical load. I and V_p are used to represent the output current and voltage of the harvester. F_e is used to link the mechanical parts and electrical parts of the model and convert mechanical energy into electrical energy. The governing equations of the model can be written as:

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$$\begin{cases} m_r\ddot{y} + c_r\dot{y} + k_r y = F(t) - m_r\ddot{x}_p \\ m_p\ddot{x}_p + c_h\dot{x}_p + k_h x_p + k_p x_p + F_e = F(t) - m_r\ddot{x}_p - m_r\ddot{y} \\ -N\dot{x}_p + C_p\dot{V}_p + \dfrac{V_P}{R} = 0 \end{cases} \tag{5}$$

where y is defined as $y = x_r - x_p$; ~~x_r and x_p are the deformation of the rubber and piezoelectric wafer stack under the external force, respectively; m_r, c_r, and k_r are the mass, damping and elastic coefficient of the rubber, respectively; m_p and k_p are the mass and elastic coefficients of the piezoelectric wafer stack, respectively; c_h and k_h are the mechanical damping and elastic coefficients of the harvester, respectively;~~ $\frac{V_P}{R}$, i.e. I, is the current output of the harvester; ~~C_p is the clamped capacitance of the piezoelectric wafer-stack; R_p is the piezoelectric leakage resistance and used to represent the electric loss property of the piezoelectric wafer-stack; R_l is the external electrical load;~~ R is the equivalent resistance of two parallel resistances R_p and R_l. In general, the R_p is much higher than the load resistance, so that $R \approx R_l$.

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Transforming Equation (5) into the frequency domain and dividing the first equation by m_r, the second equation by m_p and the third equation by C_p, obtain:

$$\begin{cases} (-\omega^2 + 2\zeta_1\omega_1\omega j + \omega_1^2)Y(\omega) - \omega^2 X_p(\omega) = \dfrac{F(\omega)}{m_r} \\ \left[-(1+\mu)\omega^2 + 2\zeta_2\omega_2\omega j + \omega_2^2\right]X_p(\omega) - \mu\omega^2 Y(\omega) + \dfrac{NV_p(\omega)}{m_p} = \dfrac{F(\omega)}{m_p} \\ -\dfrac{\omega N j X_p(\omega)}{C_p} + (\omega j + \dfrac{1}{RC_p})V_p(\omega) = 0 \end{cases} \quad (6)$$

Here ω is the angular frequency of the exciting vibration; $Y_p(\omega)$, $X_p(\omega)$, $V_p(\omega)$ and $F(\omega)$ are the frequency counterparts of y, x_p, V_p and $F(t)$. Other parameters, i.e. ω_1, ω_2, ζ_1, ζ_2, μ, are defined as:

$$\omega_1 = \sqrt{\frac{k_r}{m_r}}, \quad \omega_2 = \sqrt{\frac{k_a}{m_p}}, \quad \zeta_1 = \frac{c_r}{2\sqrt{m_r k_r}}, \quad \zeta_2 = \frac{c_h}{2\sqrt{m_p k_a}}, \quad \mu = \frac{m_r}{m_p}, \quad k_a = k_p + k_h \quad (7)$$

Solving Equation (6), obtain:

$$X_p(\omega) = \frac{\dfrac{(\alpha^2 + 2\zeta_1\psi\alpha j)F(\omega)}{k_a(\alpha^2 - \psi^2 + 2\zeta_1\psi\alpha j)}}{1 - (1+\mu)\psi^2 + 2\zeta_2\psi j - \dfrac{\mu\psi^4}{\alpha^2 - \psi^2 + 2\zeta_1\psi\alpha j} + \dfrac{\beta\psi k_e^2 j}{1 + \beta\psi j}} \quad (8)$$

$$V_p(\omega) = \frac{\dfrac{(\alpha^2 + 2\zeta_1\psi\alpha j)F(\omega)}{N(\alpha^2 - \psi^2 + 2\zeta_1\psi\alpha j)}}{\left[1 - (1+\mu)\psi^2 + 2\zeta_2\psi j - \dfrac{\mu\psi^4}{\alpha^2 - \psi^2 + 2\zeta_1\psi\alpha j}\right]\dfrac{1 + \beta\psi j}{\beta\psi k_e^2 j} + 1} \quad (9)$$

where α and ψ are the normalized frequencies; β is the normalized electrical resistance; k_e is the alternative electromechanical coupling coefficient. Those dimensionless parameters can be calculated as:

$$\alpha = \frac{\omega_1}{\omega_2}, \qquad \psi = \frac{\omega}{\omega_2}, \qquad \beta = \omega_2 R C_p, \qquad k_e^2 = \frac{N^2}{C_p k_a} \tag{10}$$

Based on Equation (9), the voltage generated by the harvester can be rewritten as:

$$V_p(\omega) = \frac{F(\omega) k_e^2 \beta \psi \alpha}{N(A_3^2 + A_4^2)} \left[(A_3\alpha + 2A_4\zeta_1\psi) + (2A_3\zeta_1\psi - A_4\alpha) j \right] \tag{11}$$

where parameters A_3 and A_4 can be calculated as:

$$\begin{cases} A_3 = A_1\beta\psi + \left(\alpha^2 - \psi^2\right)\beta k_e^2\psi + A_2 \\ A_4 = A_2\beta\psi + 2\zeta_1\alpha\beta k_e^2\psi^2 - A_1 \end{cases} \tag{12}$$

In Equation (12), parameters A_1 and A_2 are defined as:

$$\begin{cases} A_1 = \alpha^2 - \psi^2 - (1+\mu)\alpha^2\psi^2 + \psi^4 - 4\zeta_1\zeta_2\psi^2\alpha \\ A_2 = 2\psi\left[\alpha(1-\psi^2 - \mu\psi^2)\zeta_1 + (\alpha^2 - \psi^2)\zeta_2\right] \end{cases} \tag{13}$$

Therefore, based on Equation (11), the electrical power generated by the harvester can be calculated as:

$$P = \frac{V_p \times V_p^*}{2R} = \frac{F(\omega)^2 k_e^4 \beta^2 \psi^2 \alpha^2 \left[(A_3\alpha + 2A_4\zeta_1\psi)^2 + (2A_3\zeta_1\psi - A_4\alpha)^2 \right]}{2N^2 (A_3^2 + A_4^2)^2 R} \tag{14}$$

In Equation (14), V_p^* is the complex conjugate of V_p. From the Equation (14), it can be concluded that the electrical power, generated by the presented piezoelectric stack harvester, depends on the external vibration characteristics (frequency ψ and amplitude $F(\omega)$), the mechanical ~~coefficients~~ properties of the system (such as the natural frequency ω_1 and ω_2, the mechanical damping factor ζ_1 and ζ_2, and the stiffness of the harvester k_a), and the electrical properties of the harvesting system (such as the

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normalized electrical load β, and the overall electromechanical coupling coefficient of the harvester k_e). Also, the value of parameters A_3, A_4 and β are all dependent on the electrical load R, therefore the value of the load has a great impact on the electrical power output of the harvester. It is of great need to find out the optimal external resistive load, on which the power generated by the harvester reaches its maximum value.

Based on the Equation (14), the optimal resistive load and the maximum electrical power generated by the harvester can be calculated as:

$$R_{opt} = \frac{A}{(A+\alpha^2 k_e^2 - \psi^2 k_e^2)C_p \omega} \text{ and } P_{\max} = \frac{F(\omega)^2 \alpha^4 k_e^4 C_p \omega}{4N^2 A(A+\alpha^2 k_e^2 - \psi^2 k_e^2)} \quad (15)$$

where $A = \alpha^2 - \psi^2 - (1+\mu)\alpha^2\psi^2 + \psi^4$

Normally, the nature frequency of the piezoelectric stack is very high (around 1.78e4 Hz in this design). Therefore, based on Equation (10), it is reasonable to assume that the normalized frequency ψ can be set to zero under low input frequency conditions (lower than 10 Hz). Under this assumption, the optimal electrical load and the maximum generated power can be rewritten as:

$$R_{opt} = \frac{1}{(1+k_e^2)C_p \omega} \text{ and } P_{\max} = \frac{F(\omega)^2 k_e^2 \omega}{4k_a(1+k_e^2)} \quad (16)$$

Equation (16) indicates that the maximum electrical power generated by the proposed piezoelectric harvester is proportional to the frequency of external excitation. A~~a~~nd the maximum harvested energy is proportional to the square of the force amplitude of external excitation. Therefore, it indicates that the proposed compression-based piezoelectric vibration harvester is a linear system, the output power of the harvester increases with the input excitation level. It can also be found that the

generated electrical power increases with the electromechanical coupling coefficient k_e. Equation (10) shows that the value of k_e is determined by the mechanical framework of the harvester and the properties of the selected piezoelectric materials. Therefore, careful selection of the piezoelectric material and optimal design of the mechanical structure are very important to obtain higher electromechanical coupling coefficient k_e resulting in optimal scavenging electrical energy under ambient vibration.

Meanwhile, Equation (16) shows that the optimal external resistive load for the maximum electrical power generation is not a constant value and changes with the parameters of the harvester, the properties of the piezoelectric material and the input frequency. The value of the optimal resistive load is inversely proportional to the input frequency and the capacitance of the piezoelectric material. For a weak electromechanical coupling coefficient k_e, the optimal electrical load can be simplified as $1/C_p\omega$.

3. Experimental testing

3.1 Experimental setup

The proposed piezoelectric harvester was designed and fabricated to verify the theoretical findings. The sketch of the test setup is shown in Figure 4, and Figure 5 gives the photo of the test system. As shown in Figure 4, the piezoelectric stacks are installed in a host-structure to form the harvester system. Table 1 gives the properties of the piezoelectric stack. Three stacks connected in parallel are used in this design to scavenge electrical energy. One side of the host-structure is fixed on the ground and another side is connected to the shake table which is used to input the vibration excitations. An outer-spring, as shown in Figure 4, was used to transfer shake table's motions into vibrational force and apply on the harvester. The stiffness of the outer-

spring has been tested and shown in Figure 6, and the spring stiffness is 34 N/mm. In the test, the shake table firstly compressed the outer-spring for 50mm as pre-load (i.e. 1700 N) on the piezoelectric harvester, and then reset to zero. Afterward, the shake table performs different harmonic motions with different amplitudes (i.e. 10 mm, 20 mm, 30 mm and 40 mm) and applies exciting harmonic mechanical loads with different amplitudes (i.e. 340 N, 680 N, 1020 N, and 1360 N) on the test prototype by using the outer-spring. The harvester generates electrical power when the exciting loads from the shake table apply on the piezoelectric stacks. Two series-connected rheostats, as shown in Figure 5, were chosen to serve as the electrical load of the harvester in order to investigate the relationship between the power output and the electrical resistance. Data acquisition system was used to record the output voltage signal applied on the electrical load.

3.2 Experimental results comparison and discussion

Figure 7 shows the actual exciting force applied on the piezoelectric harvester and the real-time output voltage of the harvester with 750 kΩ electrical load when the shake table performs 20mm/2Hz sinusoidal motion. It can be seen that the preloading force is 1700 N and the harmonic force applied on the harvester has 680 N amplitude and 2 Hz frequency when the shake table performs 20mm/2Hz sinusoidal motion. Under this harmonic force, the voltage generated by the piezoelectric harvester is an AC voltage with the same frequency of the external excitation. Also, as shown in Figure 7, there is a phase change between the excitation and the output voltage, which is caused by the response time of the outer-spring and energy harvesting system itself.

Under the same input shown in Figure 7, Figure 8 shows the real-time output voltages of the proposed piezoelectric stack harvester on different electrical loads, i.e. 292 kΩ, 480 kΩ and 750 kΩ. It can be seen that the voltage output of the harvester is an

AC voltage and its amplitude increases with the external resistance. Figure 8 indicates that the output voltage of the proposed piezoelectric stack harvester under vibrational excitation relates to external electrical loads.

Figure 9 and Figure 10 give the relationships between the amplitudes of the generated voltage/power with different external electrical loads under the applied excitation shown in Figure 7, i.e. 680N/2Hz excitation. Figure 9 indicates that the amplitude of the output voltage, within a certain range of external resistance, increases with the value of the external loads, and then trend to constant after the external resistance exceeding a certain value. And Figure 10 indicates that the power generated by the proposed harvester firstly increases with the value of external loads, and then trends to decrease after the external resistance exceeding a certain value. Based on the results of Figure 9 and Figure 10, it can be obtained that the electrical power generated by the compression-based piezoelectric harvester depends not only on the harvester itself but also on the external electrical load, and there is an optimal electrical load, on which the electrical power harvested by the harvester reaches maximum value under given exciting vibration environment.

Figure 11 and Figure 12 show the relationship between the output voltage/power and the external loads under the excitations with different force amplitudes, i.e. 340 N, 680 N, 1020 N and 1360 N, and fixed frequency, 2 Hz. It can be obtained that: (1) the electrical power generated by the harvester increases with the amplitudes of exciting forces, and the maximum harvested power increases, from 2mW to 45mW, when the exciting force amplitude increases from 340 N to 1360 N; (2) the optimal electrical load does not change its value with the exciting force amplitude under the fixed frequency.

Figure 13 and Figure 14 show the relationship between the output voltage/power and the external loads under the excitations with different frequency, i.e. 1 Hz, 2 Hz, 4

Hz and 6 Hz, and fixed force amplitude, 1360 N. It can be obtained that: (1) the electrical power generated by the harvester increases with the frequency of external excitation, and the maximum harvested power increases from 25 mW to 200 mW, when the exciting frequency increases from 1 Hz to 6 Hz; (2) the value of the optimal electrical load is inversely proportional to the input frequency of the excitation, and its value decreases from 1400 kΩ to 300 kΩ, when the exciting frequency increases from 1 Hz to 6 Hz.

For the aim of clearly showing the relationship between the harvested electrical energy with the external excitation, Figure 15 gives the relationship between the maximum power outputs with the input frequencies when the exciting force amplitude fixed on 1360 N, and Figure 16 gives the relationship between the maximum power outputs with the force amplitude when the frequency of the excitation fixed on 6 Hz. Based on the Figure 15 and Figure 16, it can be obtained that the electrical energy which can be harvested by the proposed harvester is proportional to the frequency of external harmonic excitation and is proportional to the square of the force amplitude of the harmonic excitation. Therefore, the proposed piezoelectric energy harvester is a linear system, the output power increases with the external excitation level in the considered frequency and force.

4. Conclusion

Feasibility of a compression-based piezoelectric multilayer stack energy harvester as a promising alternative power for wireless sensor networks in civil structure health monitoring applications is investigated in this paper. Investigation of energy harvesting of such system for large force vibration existing in civil structure applications carried out theoretically and experimentally. Based on the linear theory of piezoelectricity, this paper presents the theoretical analysis of the piezoelectric multilayer stack harvester.

The theoretical analysis which has been verified with a series of experimental results can be used to synthetically analyze the behavior of vibration-to-electricity of the compression-type piezoelectric stack harvesting system. The experimental results show that the proposed piezoelectric stack harvester can generate up to 200 mW electrical power under harmonic excitation and it is sufficient for powering most normal wireless sensors. Additionally, based on the theoretical analysis and experimental results, the following conclusions can be acquired:

(1) The electrical power scavenged by the proposed piezoelectric harvester depends not only on the harvester itself but also on the external electrical load. There is an optimal electrical load for a given exciting vibration, with which the electrical power harvested by the harvester reaches maximum value.

(2) The optimal electrical load is inversely proportional to exciting frequency, and the value of the optimal electrical load does not affected by the force amplitude of excitation. Under the same input frequency, the optimal electrical load keeps in a constant value for different force amplitudes.

(3) The proposed compression-based piezoelectric energy harvester is a linear system, the electrical energy which can be harvested by the proposed vibration harvester increases with the frequency and force amplitude of the harmonic excitation.

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Table 1. Characteristic properties of the piezoelectric stack

Material properties	Value	Stack properties	Value
Material type	PZT-8	Diameter (mm)	20
Coupling factors k_{33}	0.68	Height h_p (mm)	34
Piezoelectric constant d_{33} (pC/N)	280	Single wafer thickness t (mm)	0.85
Dielectric constants $\varepsilon_{33}/\varepsilon_0$	1000	Layer number	36
Young's modulus $YE_{33}(10^{10}$ N/m)	7.1	Mass m_p (g)	87
Curie point (◦C)	320	Capacitance C_p (μF)	0.12
Density (10^3 kg/m^3)	7.7	Natural frequency ω_n (10^9 N/m)	1.1

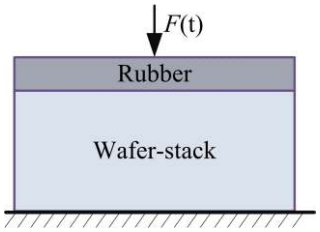

Figure 1. Construction of the piezoelectric stack

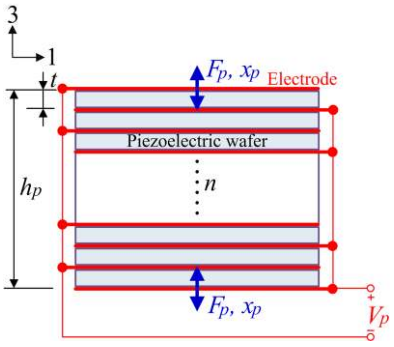

Figure 2. Longitudinal mode of the piezoelectric stack

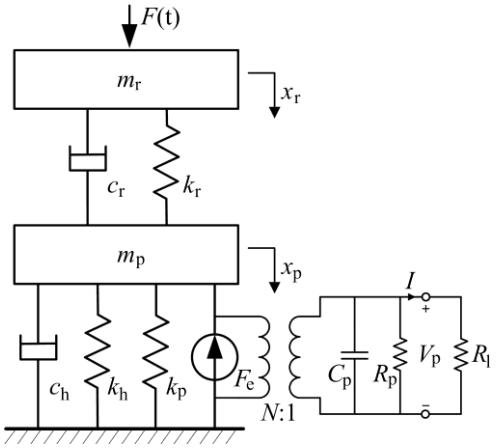

Figure 3. 2DOF electromechanical model of the proposed harvester

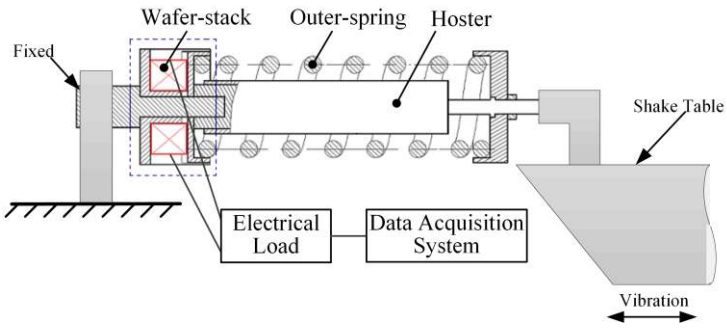

Figure 4. Sketch of the test setup

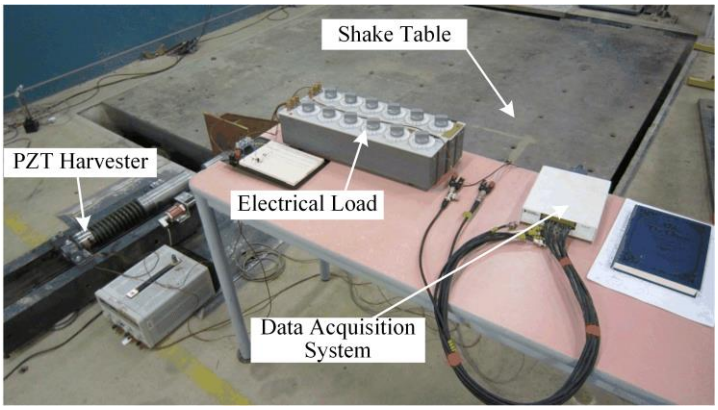

Figure 5. Photo of the test setup

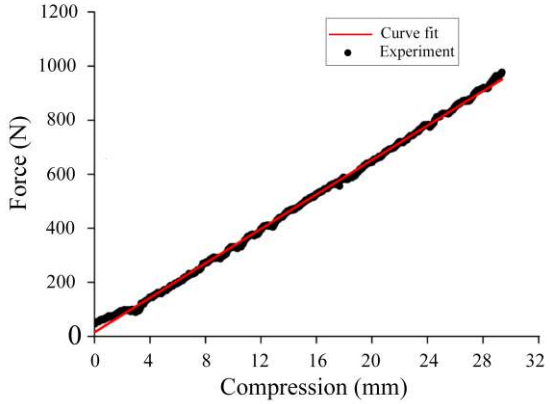

Figure 6. Spring stiffness static test from MTS machine

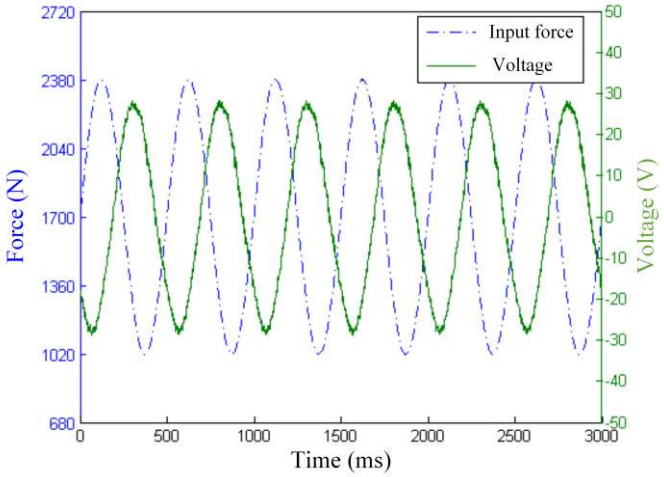

Figure 7. The applied force vs. output voltage under 20mm/2Hz motion

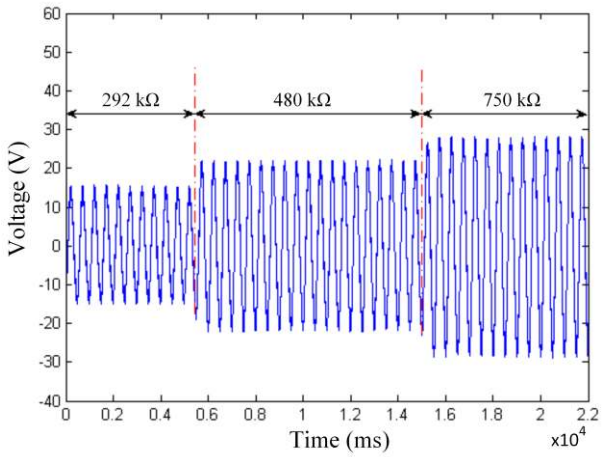

Figure 8. Output voltage under 680N/2Hz excitation

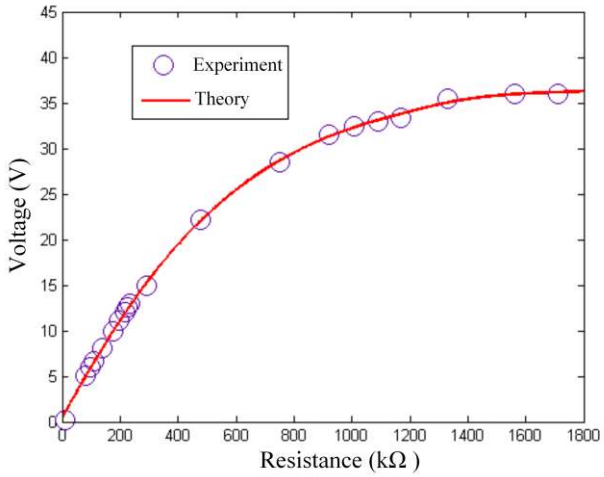

Figure 9. Output voltage vs. electrical loads under 680N/2Hz excitation

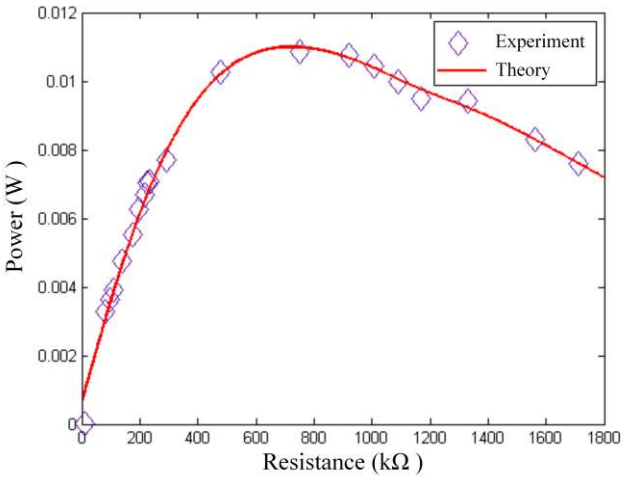

Figure 10. Output power vs. electrical loads under 680N/2Hz excitation

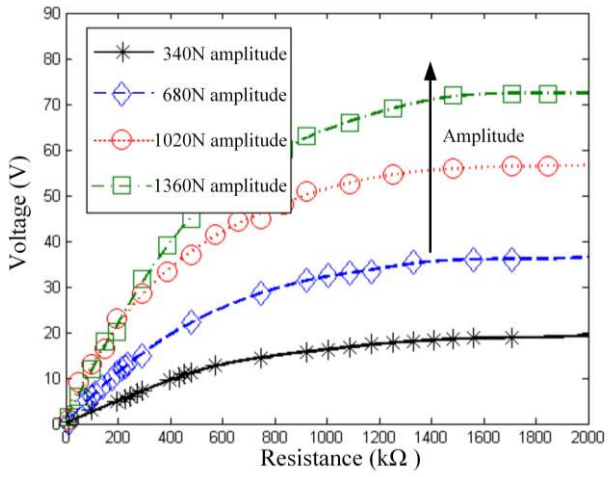

Figure 11. Output voltage comparison under different excitations with same frequency

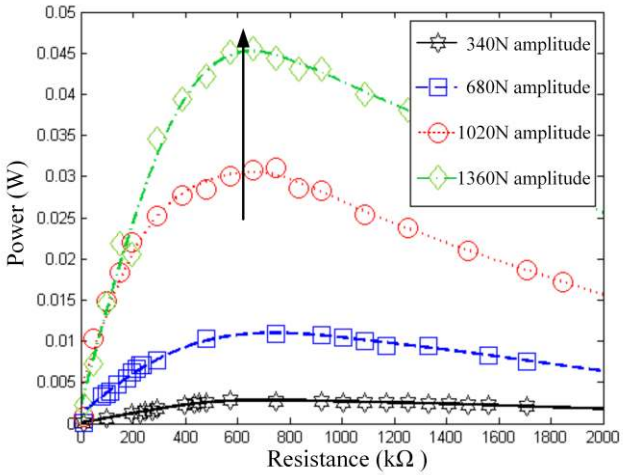

Figure 12. Harvested power comparison under different excitations with same frequency

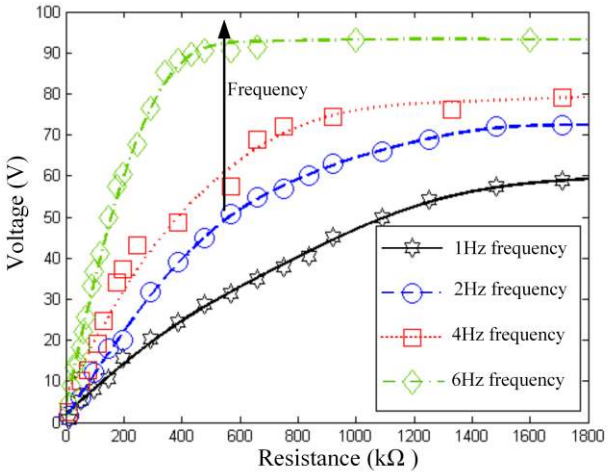

Figure 13. Output voltage comparison under different excitations with same force amplitude

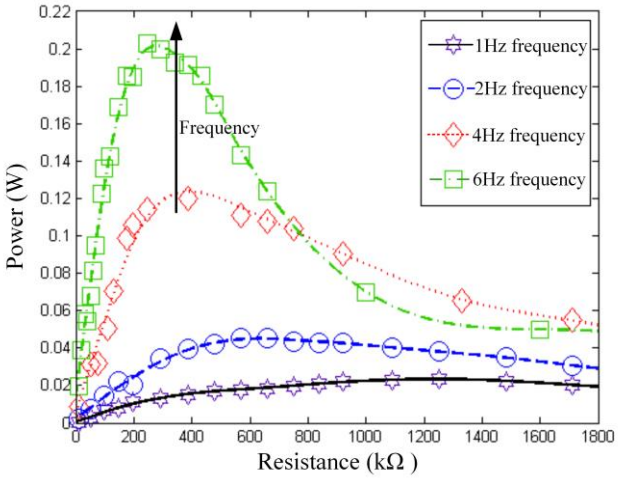

Figure 14. Harvested power comparison under different excitations with same force amplitude

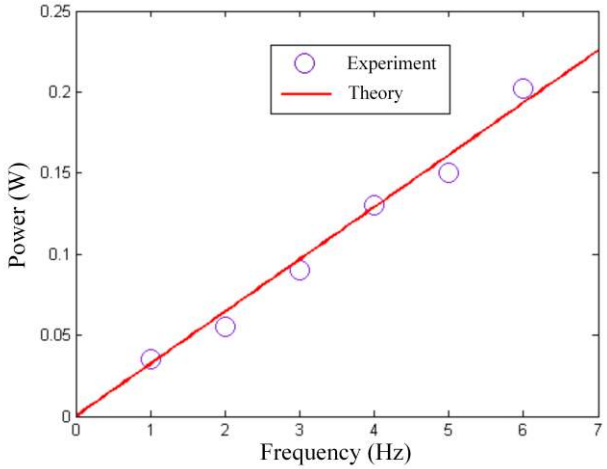

Figure 15. Maximum harvested power vs. exciting frequency

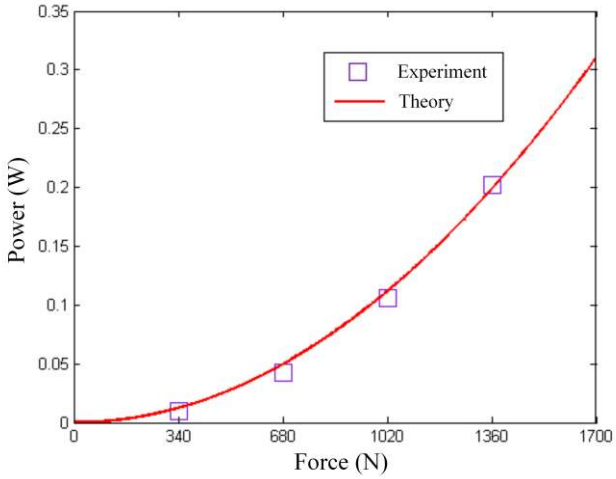

Figure 16. Maximum harvested power vs. exciting force amplitude