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# Double Peak Derived from Piezoelectric Coefficient Nonlinearity and Proposal for Self-Powered Systems

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**Abstract**: With the development of wireless sensor network (WSN) applications in intelligent monitoring, additional support for the low power consumption wireless nodes can be provided by piezoceramics that harvest vibrational energy. First, we describe the effects of stimulation variations on piezoceramics and the energy harvesting circuit set-up. Two types of piezoceramics were stimulated at different frequencies and amplitudes to obtain the power output characteristics. Then, the energy harvesting circuit was studied and coupled with the piezoceramics. A double peak phenomenon was found in energy harvesting using a hard piezoceramic which gave a direct proof that the nonlinearity of the piezo constant should be considered in application. Finally, energy storage and output were studied and analyzed. Electronic components for the WSN were recommended according to the output power and the application. The results will give an instruction for piezoceramic energy harvesting under various stress amplitudes on its implementation.

**Key words**: piezoelectric; energy harvesting; self-powered system; energy harvesting circuit; output optimization

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## 0 Introduction

In piezoceramics, the piezoelectric effect allows to harvest electricity energy from ambient vibrations to supply low-power consumption devices. Wireless sensor networks (WSN) for monitoring the status of the environment have advantages such as distributed sensing capabilities, ease of deployment, real-time processing, a small size, a low cost, and high reliability[1-2]. In long-term monitoring, the duration of monitoring is limited to the batteries' life span. A complete system has energy consuming elements such as sensing, communicating, and processing modules. With the development of integrated circuit and communication technologies, the required power consumption is decreasing. For example, compared with the former versions, Bluetooth 4.0 saves 90% of the energy while its transmission rate and distance increase. At the same time, energy extraction circuit[3-6], broadband technique[7-14] and various environmental vibration resource[15-16] in energy harvesting systems development augments the extraction percentage of energy, supplying more electricity for the devices. With the energy consumption decreasing, extraction energy increasing, and the power-management strategies optimizing, a self-powered system is developing rapidly.

To supply wireless sensor networks with a ubiquitous energy source, vibration can be turned into electricity using a piezoceramic. Lallart and Guyomar et al.[17-18] designed a self-powered structural health monitoring (SHM) system, including the autonomous wireless transmitter (AWT) and the autonomous wireless receiver

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(AWR), powered by a piezoceramic. Two pieces of piezoceramic were integrated into every module for energy harvesting. During health monitoring, data were transmitted to the base station. Hu et al.[19] studied the sandwich structure design based on piezoelectric nanogenerators and gave an illustration of photon detecting and environmental monitoring self-powered systems. These promising achievements urged more researchers to study self-powered systems.

Here, we primarily concentrate on the low-frequency energy harvesting where piezoceramic power output has been analyzed and a self-powered system design has been proposed. Energy harvesting experiments, wireless sensor networks and their design will be illustrated.

## 1 Energy Harvesting from Piezoceramic

### 1.1 Configuration of electro-mechanical conversion

There are two types of piezoelectricity: direct piezoelectricity and converse piezoelectricity. Direct piezoelectricity is that the piezoceramic generates electric charges on the electrode due to the applied mechanical forces. To simulate the stimulating vibrations, an experimental setup has been established to measure energy harvesting in the following section.

For a bulk piezoceramic used in this study, the lumped model is modeled as mass-spring-damper-piezo. Considering the boundary conditions, the constitutive equation for direct piezoelectricity is

$$\begin{cases} T_{33} = c_{33}^{E} S - e_{33} E \\ D_{33} = e_{33} S + \varepsilon_{33}^{S} E \end{cases} \tag{1}$$

where the superscripts "E, S" represent the constant electric field and constant strain, respectively and the subscript "33" represents the polarization direction coincides with the mechanical stress. $T_{33}$ is the mechanical stress, $D_{33}$ the electric displacement, $E$ the electric field, and $S$ the strain. The coefficient $c$ is the piezoceramic elastic coefficient; and the coefficients $e$ and $\varepsilon$ are the piezoelectric constant and the dielectric constant, respectively. The piezoelectric coefficient can be considered constant at low (frequency & energy) excitations, both electrical and mechanical. However, nonlinearity in the piezoelectric coefficient emerges at high excitations[12, 14, 20].

The output current, $I_o$, can be calculated with the displacement $u$, force factor $\alpha$, piezoceramic capacitance $C_0$, and $V$ the voltage across the piezoceramic.

$$I_o = \alpha \dot{u} - C_0 \frac{\mathrm{d}V}{\mathrm{d}t} \tag{2}$$

When the rectifier circuit reaches its steady-state, $I_o$ is the current going through the load. By integration of Eq. (2), the charge is

$$\int_0^{T_0/2} I_o \mathrm{d}t = \frac{V_L}{R_L} \cdot \frac{T_0}{2} \tag{3}$$

where $V_L$ is the voltage across the load, $R_L$ the load, and $T_0$ the period. Combining Eqs. (2,3), the rectified $V_L$ is a function of displacement amplitude $U_M$, excitation circular frequency $\omega$, given in Eq. (4)

$$V_L = \frac{2\alpha\omega R_L}{\pi + 2\omega R_L C_0} U_M \tag{4}$$

Considering

$$e_{33} = d_{33} c_{33}^{E},\ U_M = l c_{33}^{E} T_M A,\ \alpha = e_{33} A / l \tag{5}$$

the harvested power can be expressed as

$$P_{\text{harvest}} = \frac{V_L^2}{R_L} = \frac{4\omega^2 (c_{33}^{E})^6 R_L A^4}{(\pi + 2\omega C_0 R_L)^2} (d_{33} T_M)^2 \tag{6}$$

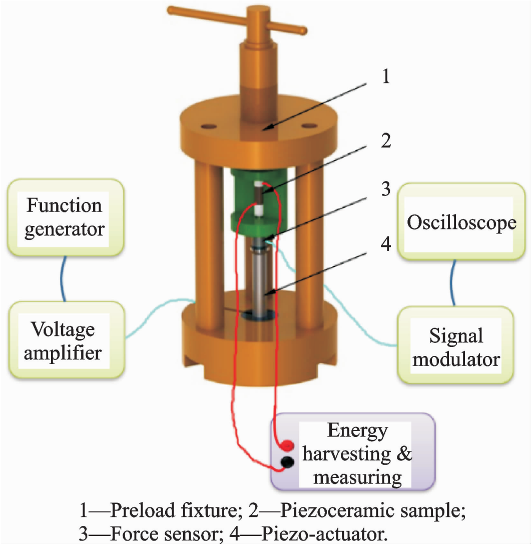
where $d_{33}$ is the piezoelectric charge constant, $l$ the thickness of a bulk piezoceramic, $A$ the cross sectional area of the piezoceramic, and $T_M$ the mechanical stress amplitude. It can be concluded that the harvested energy $E_s$, the piezoelectric charge coefficient, and the mechanical stress obey the following relation

$$E_s \propto (d_{33} \cdot T_M)^2 \tag{7}$$

### 1.2 Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup.

The fixture provides a preload force on the piezoceramic and holds the other instruments. The waveform generator (TFG1005 DDS, SUING) controls the voltage amplifier (XE-501-A,



1—Preload fixture; 2—Piezoceramic sample; 3—Force sensor; 4—Piezo-actuator.

Fig. 1 Piezoceramic energy harvesting experimental setup

Newpi, Ltd.) to drive the piezo-actuator (PSt-150/10/80VS15, Newpi, Ltd.). The force sensor (XFC200R, Measurement Specialties, Ltd and ARD154, Measurement Specialties, Ltd.) measures the applied force. The oscilloscope (SDS 2104, SIGLENT) monitors all the variations. The rectifier bridge and LTC3588 (Linear Technology Corporation) are used as the energy harvesting module that uses the data acquisition system (2638A, Fluke Corporation) to measure the current and voltage.

Two types of piezoceramic, p-43 and PMgN-51 (Weifang Jude Electronics Co., Ltd.), were used in the experiment. ∅6×5 mm conductive copper tapes were adhered to both sides of the silver electrodes, as shown in Fig. 2. The coefficients of the piezoceramics are shown in Table 1.

Fig. 2 Piezoceramic sample

**Table 1 Parameters of piezoceramic sample**

| Parameter/Sample | p-43 | PMgN-51 |
|---|---|---|
| $\varepsilon_{33}^{T}/\varepsilon_0$ | 1 700 | 3 800 |
| $d_{33}/(10^{-12}\,\mathrm{C/N})$ | 390 | 500 |
| $g_{33}/(10^{-3}\,\mathrm{V\cdot m/N})$ | 11.2 | 10.6 |
| $Q_m$ | 200 | 70 |

### 1.3 Experiment and results

#### 1.3.1 Full-bridge rectifier standard circuit

The standard energy harvesting circuit consists of a full-bridge rectifier circuit and a capacitor. The piezoceramic is connected in series. Measuring the electrical characteristics of the load, $R_L$, allows calculation of the output power, as shown in Fig. 3.

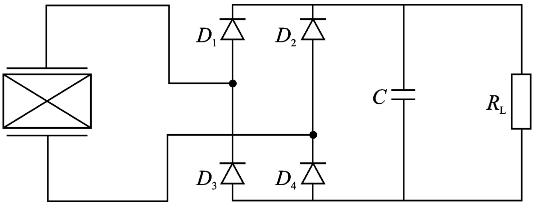


Fig. 3 Standard energy harvesting circuit

In Fig. 3, the capacitor has a capacitance of 47 μF. The voltage is measured and the data is shown in Fig. 4, at a frequency of 10 Hz with amplitude of 10 MPa.

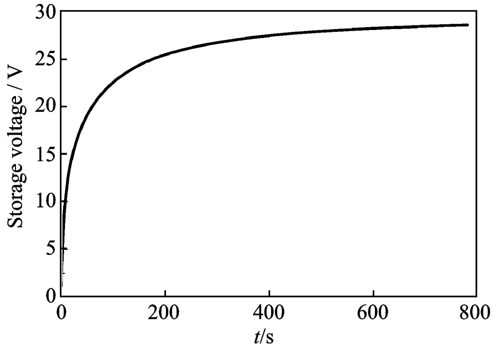


Fig. 4 The open circuit voltage for a standard energy harvesting circuit

Here, the capacitor, $C_r$, is used as the energy storage element that then acts as a steady power source for the following section of the circuit.

The capacitance of the capacitor should be chosen according to the power consumption, voltage stability, and operating voltage. To illustrate the effect of the capacitance on the output voltage variation, simulations are shown in Fig. 5.

Fig. 5 shows the pattern of a charging capacitor in an energy harvesting circuit. In a WSN node, the capacitor value should be carefully selected while considering the leakage resistance and duty ratio.

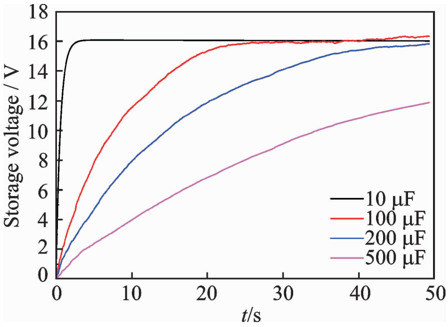


Fig. 5 Simulations for different filtering capacitors

### 1.3.2 Load-carrying capacity

Load-carrying capacity is an index used to evaluate a power source. Load-carrying capacity influences the energy extraction circuit. The standard energy extraction circuit is evaluated with the capacitor $C = 22\ \mu F$, the preload stress $T = 25$ MPa, and the amplitude of 10 MPa at a frequency of 10 Hz, acting on the sample of p-43 piezoceramic. After calculating the voltage and current, the output power is shown in Fig. 6.

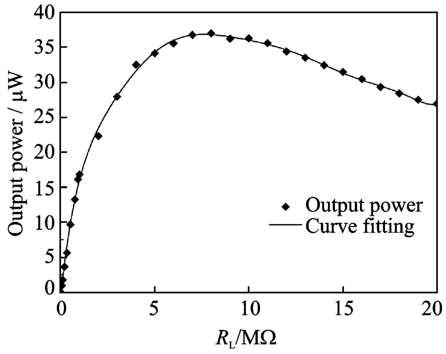
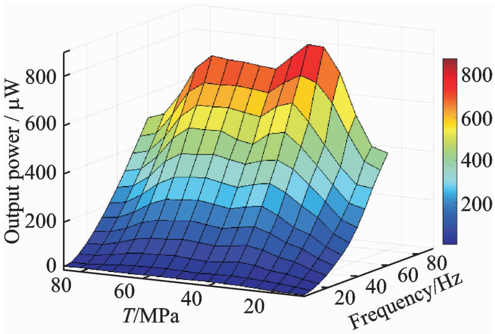


Fig. 6 Influence of the load on output of energy

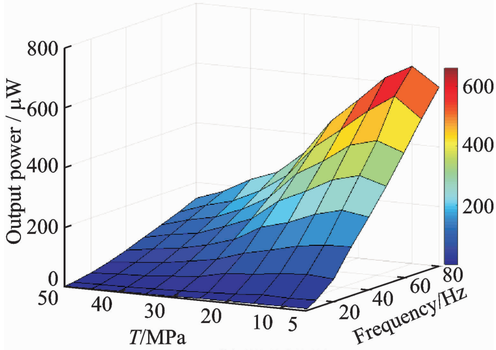
In Fig. 6, the load has a large effect on the output power in a nonlinear manner. For our specimen and conditions, the best load selection is approximately 8 MΩ, which leads to a maximum output power density of 261.7 $\mu W/cm^3$.

### 1.3.3 Output power evaluation

The output power of a piezoceramic depends upon the stress amplitude and the frequency. To satisfy the power consumption of a WSN node, a comprehensive evaluation of the piezoceramic output should be made. With this evaluation, the appropriate electronic components can be selected as the piezoceramic acting as a power source. In this paper, two types of piezoceramics have been tested under various stimulations. With the standard circuit where $C = 22\ \mu F$, $R_L = 8$ MΩ, p-43 ($\Delta T = 20$ MPa) and PMgN-51 ($\Delta T = 10$ MPa), the output power of the piezoceramic has been measured. The results are shown in Fig. 7.



(a) p-43



(b) PMgN-51

Fig. 7 Output of piezoceramic samples under different frequencies and stress amplitudes

Compared with PMgN-51, p-43 is a hard piezoceramic. As the amplitude increases, p-43 has a double wave crest in which the first peak is much larger than the second. In contrast, we can see that PMgN-51 has only one peak after which the output power rapidly decreases because of the piezoceramic depolarization under high stress. Because the output power is proportional to $(d_{33}T)^2$, we can conclude that $d_{33}$ of the p-43 decreases rapidly when the external stress reaches a certain threshold and then its decline slows down until the next threshold. The soft piezoceramic reached its turning point at a lower stress and its $d_{33}$ is greatly affected by the stress. The nonlinearity of the material coefficients should be taken into consideration when necessary given the expected external excitation on the piezoceramic. The hard piezoceramic has the ability to be deployed in a large range of stress stimulations.

## 2 Self-Powered WSN System

### 2.1 Transmission media

Given the requirements of the energy consumption and the operating conditions, the transmission media should be carefully selected. RF is currently the most popular transmission media[20]. In addition to being license-free, infrared/optics has the advantages of easy set-up and low cost[21].

### 2.2 WSN system design

Here, both the hard and soft piezoceramics were used in the energy harvesting experiment and the power supply characteristics that were preliminarily studied indicate that more than 800 μW could be generated by a piezoceramic (∅6×5 mm). Many electronic components reach their rated operating conditions at hundreds of microwatts. Even milliwatt-level consumption components may work with energy management strategies. After considering the piezoceramic output power characteristics, LTC3588-1 (Linearity) can be used as the energy extraction module, low energy consumption PIC18LF14K50 (Microchip) can be used as the MCU, and A110LR09A (Anaren) can be used as the integrated RF module, which has a temperature sensor embedded. In addition, BMA222E (BOSCH) can be chosen as a motion state monitoring sensor[22]. To simulate the operating state of an embedded-integrated wireless node′s energy consumption, a 470 kΩ resistor is used to represent the sleeping mode. The working mode is simulated by two resistors connected in parallel, 470 kΩ with 200 Ω controlled by a switch, as shown in Fig. 8.

The energy storage of the extraction circuit and the power consumption of the simulated WSN are shown in Fig. 9. In Fig. 9, ″energy storage″ indicates all the energy stored in the capacitor $C_s=47$ μF, while the ″energy consumption″ is due to the wireless sensor node. With low energy consumption electronic components and an energy management strategy, piezoceramics are promising power sources for wireless sensor networks. Piezoceramics realize the self-powered goal.

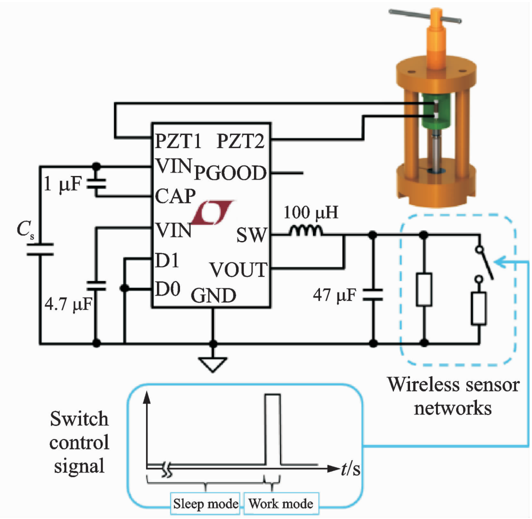


Fig 8 Simulations for self-powered WSN

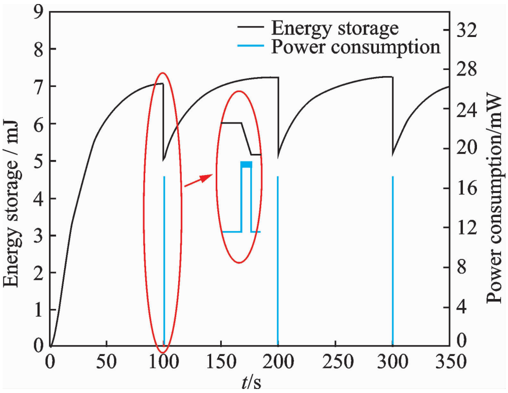


Fig. 9 Simulations of energy storage and power consumption in a self-powered node

## 3 Conclusions

Energy harvesting from a piezoceramic is investigated under various stimulations, especially at high stress and low frequency. The results provide a guideline for using a piezoceramic in different stimulation states and the output power at those chosen states. For the embedded wireless sensor/actuator in the infrastructure, a bulk piezoceramic is a good choice as a power source in an infrastructure with a characteristic vibration. According to the energy harvesting experiment and simulations, 1 $\text{cm}^3$ could accommodate all of the mentioned electronic components in a self-powered wireless sensor. The double peak phenomenon of p-43 should be taken into consideration, especially in stimulation environments with a large range. Future studies will concentrate on the self-powered node and WSN design.

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