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Study of the effect of mechanical impact parameters on an impact-mode piezoelectric ceramic power generator

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Abstract

This paper presents an analytical and experimental study on the effect of mechanical impact parameters on impact-mode piezoelectric ceramic power generators. The parameters are the velocity and mass. The method of analysis is based on a weight drop experiment. The results show that the peak of the instantaneous output voltage is proportional to the impact velocity, and for the output power, it is in a straight line relationship with the same parameter. For the same velocity of impact, the advantage of using heavy objects is clear because its momentum and the impact force are higher. However, an adjustment in the velocity of impact is found to be more effective for higher instantaneous output power than the mass. This finding is supported by the output power that is generated by a 4-g steel ball with a momentum of 4.34 g/s, which is almost 300% higher than that of an 8-g steel ball for the same momentum. The frequency responses of a vibration-based impact-mode piezoelectric ceramic power generator also support the same conclusion.

Keywords: Piezoelectric ceramic power generator; Impact mode

1. Introduction

Research achievements in mechanical vibration energy harvesting have been reported widely for decades. The objectives of the research are mostly to propose new designs and to evaluate factors that affect the optimum output power generation. In general, mechanical vibration is converted to electrical energy by using three types of devices: piezoelectric, electrostatic and electromagnetic. Both analytical [1] and experimental analyses [2–5] have shown that there are various factors that affect the performance of the devices. The evaluation of each factor is very subjective; the outcome depends on the devices, environment and type of vibration.

In cases of vibration energy harvesting with piezoelectric ceramics, for a linear motion of vibration, the basic operation of power generation can be divided into two modes. One mode is the bending mode, and the other mode is the impact mode. Usually, for bending-mode power generation with a piezoelectric cantilever beam, one end of the beams will be attached to the vibration sources, and the other end will freely vibrate according to the sources of the vibration. To improve the output power of the piezoelectric power generator in the bending mode, the shape of the device has been analyzed, and it is proven that a device with a triangular shape can more effectively generate electricity compared with the rectangular-shaped devices [6,7].

Another factor that was found to be important for the optimum output is the usage of matching impedance as the load [8,9]. However, the matching impedance is dependent on the resonant frequency of the structure, which means that for a low resonant frequency of a structure, large matching impedance is required.

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These are among the important factors that have been considered in the design of vibration-based bending-mode piezoelectric power generator.

In case of vibration-based impact-mode power generation, piezoelectric ceramics will not deform by the vibration. The deformation is due to the impact. As reported in [10], a structure with a freely moving steel ball in a case hits the piezoelectric wall repeatedly to generate electricity. At the beginning of the design process, a weight drop experiment is conducted. The output power from the free-fall experiment is found to be relatively high when compared to the output power of the designated device. One of the suggestions that has been proposed for the optimization of the output power is that the size of the steel ball must be large and heavy. Another design for an impact-mode piezoelectric power generator is reported by [11]. An impact-mode power generator that consists of a vibrating beam with a piezoelectric device on top of it and two other piezoelectric cantilever beams placed at each side of the beam is proposed. The vibrating beam has an extended rectangular tip, and a mass is fixed on it. When the beam vibrates, it hits both piezoelectric beams and, due to the impact, electricity is generated. The implementation target of the device is to harvest low frequency vibrations such as human motion-related environments. The optimization procedure is based on the matching impedance technique. Other analyses and discussion on the combination of bending and impact-mode power generation is reported in [12]. It is reported that in terms of the voltage, a bending-mode piezoelectric specimen generates a higher value than that of the impact-mode piezoelectric specimen. However, how the output can be optimized for the designated device was not discussed.

There are research studies on the effect of piezoelectric ceramic dimensions [13] and types of vibrations [14] on impact-mode piezoelectric power generation. However, the effect of mechanical impact parameters on impact-mode piezoelectric ceramic power generation has been discussed less by researchers. Therefore, this paper presents an analytical and experimental study on how to optimize the output power of an impact-mode piezoelectric power generator by analyzing two parameters that have been found to closely affect the output power. These parameters are the velocity of the impact and the mass. To identify the relationship of the output power with these two parameters, a weight drop experiment was conducted. Variations in the mass of the object and the heights that were related to the impact velocity were performed. The findings can be utilized in the design of an impact-mode piezoelectric power generator to harvest vibration energy in the vehicle systems and industry, which found to produce a large amount of vibrations.

2. Impact force of the weight drop in free fall

When an object is dropped from a certain height, it will give an impact force to the surface of the ground. A change in the energy also occurs where the potential energy of the object turns into kinetic energy upon impact. Let us assume that the mass of an object is m, the height is h_1 and the velocity upon impact is v. Therefore, the energy equation will become

$$mgh_1 = \frac{1}{2}mv^2 \tag{1}$$

where g is the acceleration of gravity. If the height h_1 is known, then the velocity of the impact would become $v = \sqrt{2gh_1}$. Based on the characteristics of the ground and the object, two situations can be expected to occur when an object is dropped. The first situation is that the object will penetrate the ground surface. This situation will occur if the ground surface is softer than the dropped object. Let us say that the penetration is h_2 before the object totally stops. In this case, the impact force from the object is denoted by following equation:

$$F = \frac{E_k}{h_2} = \frac{mv^2}{2h_2} \tag{2}$$

where E_k is the kinetic energy. As seen from the equation, the impact force is inversely proportional to the penetration distance h_2, which means that less penetration will result in a higher impact force.

The second situation that can be expected is that the object bounces back after striking the ground. This situation will occur if the ground surface is harder than the object. A greater change in the momentum from this situation leads to a greater impact force F. The object is expected to bounce back a few times until its momentum becomes zero. Another fact that can be seen from this equation is that a small change in the velocity affects the impact force more than a change in the mass. This arrangement occurs because the velocity is proportional to the F in the square function, while the mass is directly proportional to the impact force. Based on this relationship, it is expected that the output power of a piezoelectric power generator will be more dependent on the impact velocity than the mass of the object if their momentum or kinetic energy is equal.

3. Piezoelectric ceramic power generation by impact

Impact-mode piezoelectric ceramic power generation is an alternative to the vibration bending-mode power generation. In contrast to the bending mode, power generation by impact produces a discontinuous output. An instantaneous output will not last long. The frequency of the repetitive output is dependent on the frequency of the impact.

The maximum electrical energy per cycle output of a piezoelectric power generator in 33-mode is denoted by following equation:

$$E_{\max} = \frac{c}{ab} d_{33} g_{33} F^2 \tag{3}$$

where a, b and c are the width, length and thickness of the piezoelectric ceramic, respectively, and d_{33} and g_{33} are the piezoelectric charge (strain) and voltage (stress) constants; F is the force that acts on the devices. Impact-mode piezoelectric power generation is assumed to be in 33-mode operation,