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Investigation and experimental verification of the effectiveness of the interfaced plate parameters on impact-based piezoelectric energy harvester

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ABSTRACT

This paper studies and validates the potential of the performance and output efficiency for the impact-mode piezoelectric energy harvesting system by introducing the additional interfaced plate. The interfaced plate is allocated between the ball dropped and piezoelectric disc. Therefore, the ball hits the piezoelectric disc indirectly. The impact force will be altered depending on different values of ball mass and height dropped. The two parameters such as diameter and height of the interfaced plate are investigated. The output efficiency of the piezoelectric disc increases when the diameter of the interfaced plate is decreased. While the amplitude of the output voltage and power increase as the height of the interfaced plate is increased. These statements are proven and determined by the results obtained in this paper. However, the output voltage and power of the piezoelectric disc without the interfaced plate is higher than the output power of the interfaced plate that is employed on the piezoelectric disc when the free fall experiment (instantaneous impact force) is conducted.

1. Introduction

Nowadays, energy harvesting in the development of portable devices of electronic application, especially for wireless sensor is gaining more attention from the researchers [1]. The ambient waste energy which is being captured, collected and stored for later use is determined as energy harvesting. Energy harvesting is also acknowledged as power harvesting or energy scavenging [1–3]. There are many different types of energy sources, such as thermal sources, ambient light, mechanical sources, ambient radio frequency and vibrational energy [1,2]. Energy harvesting is required by the portable electronic devices as they are self-powered and have a short life-span of the battery [3].

For the vibrational energy harvesting, there are some approaches to alter the mechanical energy into electricity: electromagnetic induction, electrostatic storage and piezoelectric transducer. The piezoelectric transducers are flexible and have higher energy efficiency compared to the electrostatic and electromagnetic techniques as the applied forced or mechanical vibrations can be transformed by the piezoelectric transducer into electricity with a simple configuration [1].

The pressure electricity can be represented by piezoelectricity. The piezoelectric crystal consists of elements like barium titanate, quartz, Rochelle salt and others which can yield electricity when pressure or force is applied. This deformation is known as direct effect and this behavior can be considered as a sensor. While the piezoelectric crystal that alters into mechanical strain energy when an electric field is applied, this deformation is termed as converse effect. The converse effect can be used as an actuator. Both behaviors can be demonstrated by Eqs. (1) and (2) below:

Direct piezoelectric effect:

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^{d} \sigma_m \tag{1}$$

Converse piezoelectric effect:

$$\varepsilon_k = d_{jk}^{c} E_j + S_{km}^{E} \sigma_m \tag{2}$$

where,

D_i = Dielectric displacement,
ε_k = Strain,
E_j = Applied electric field,
σ_m = stress,
d_{im}^{d} = piezoelectric coefficients,
d_{jk}^{c} = piezoelectric constants,
e_{ij}^{σ} = dielectric permittivity, and
S_{km}^{E} = elastic compliance matrix.

The converse effect and direct effect are symbolized as c and d, respectively. While the quantity which is measured at constant stress and constant electric field are referred to as σ and E, respectively [1].

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Impulsive loading is needed for some energy harvesting devices to yield electrical energy for certain applications. The impulsive loading is for example short duration acceleration or deceleration shock loadings such as explosion which impacts an object with the host system or vice versa. A single pulse or multiple pulses might be contained in the impact system. The characteristics and related motions of instantaneous impact energy harvesting device are sort duration and generate a high output amplitude. The impact-based energy harvesting device is required to have the ability of sustaining the physical damage efficiently to capture the produced electricity in a short duration and efficiently transfer the mechanical energy to energy harvesting device.

The impact-based energy harvesting devices are distributed into two groups. The short-duration loading for the directly impact force on the piezoelectric transducer is considered as the first group for the impact-based energy harvesters. The duration of the pulse is very small and lesser than a millisecond. Thus, it is challenging to capture and store the electrical energy efficiency for the first group of the impact-based energy harvesting devices. While the second group, an interfaced mechanism is used by the devices to transfer impact force or mechanical energy to a mechanical energy storage device. The stored mechanical energy is altered into electrical energy through a designed transducer like piezoelectric. A spring or plate can be utilized as an interfaced mechanism. The impact force is stored in the spring as a mechanical potential energy and/or as mechanical kinetic energy. When the dropped object is in its rest position, this behavior is known as mechanical potential energy. On the other hand, when the dropped object is in a vibration condition, this behavior is termed as mechanical kinetic energy. After that, the mechanical vibration energy is transferred to the piezoelectric with the aid of the piezoelectric elements, the mechanical vibration energy is transformed into electrical energy [4].

There are different types of approaches to enhance the output efficiency of the impact-based piezoelectric energy harvesting system. The approaches are: by using cantilever piezoelectric [5,6], impact-based frequency-up-converting method [7,8], free fall experiment [9–12], by using interfaced plate between hitting object and piezoelectric transducer [13,14], free moving object [15–20], human step [21–23], and impact of the rotating gear on the piezoelectric transducer [24,25]. All these techniques are utilized to amplify the amplitude of the output power of the piezoelectric transducer. Choi et al. in [5] demonstrated that the impact-based piezoelectric cantilever can harvest up to 20 times higher output voltage compared to vibration and bending approaches. As reported in [13,14], indirectly hitting the piezoelectric transducer using interfaced plate method was used by A.A.Basari and S. Hashimoto. They showed that with the aid of the interfaced plate, the performance and output efficiency of the impact-based piezoelectric energy harvesting system is increased about 4.3 times compared to directly hitting on the piezoelectric transducer. However, there is lack of information about the behavior of the parameters for the impact-based piezoelectric energy harvesting device.

Therefore, a novel concept of the effectiveness of the interfaced plate parameters to the performance of the piezoelectric disc is proposed here. The paper illustrates a combination approach of the free fall experiment by using the interfaced plate methods to analyze and study about the characteristic of the piezoelectric disc. There are five parameters that affect the performance of the piezoelectric disc with the interfaced plate which will be examined and evaluated in this paper. The parameters are: load resistance, diameter of the interfaced plate, height of the interfaced plate, ball mass and height of the ball dropped. During the free fall, gravity is the only force that operates upon the motion of an object and air resistance will be neglected. Therefore, the free fall experiment method is applied to demonstrate the relationship of the parameters to the performance and output efficiency of the piezoelectric disc. The analysis and examination of the parameters can be used to study the impact-mode piezoelectric energy harvesting system.

2. Impact force of object in free fall

Mechanical energy is acknowledged as an energy acquired by the work that is done upon the objects. Due to the object's motion or the object's position, there is an energy that is possessed by the object which is mechanical energy. There are two varieties of the mechanical energy which are kinetic energy and potential energy. The sum of the kinetic energy and potential energy of an object is described as the total amount of mechanical energy. When an object is dropped from a certain height, an impact force will be applied. The maximum potential energy is formed when an object stays at the highest position. After that, the potential energy will change to kinetic energy when the object is dropped and hit on the ground. Hence, the behavior can be demonstrated as Eq. (3) below.

$$mgh_1 = \frac{1}{2}mv^2 \tag{3}$$

where,

m = Object's mass,
g = Gravity's acceleration,
h_1 = Height, and
v = Velocity.

when the height, h_1 is being determined, the velocity, v can be found by using Eq. (4).

$$v = \sqrt{2gh_1} \tag{4}$$

when the ground is softer than the dropped object, the object will penetrate the ground. The softer the ground, the deeper the ground will be penetrated. The impact force for free fall object depends on the impact depth, h_2 of the ground when it is in a damp condition. It can be expressed as Eq. (5).

$$F = \frac{E_k}{h_2} = \frac{mv^2}{2h_2} \tag{5}$$

where,

E_k = Kinetic energy,
m = Mass,
h_2 = Impact depth, and
v = Velocity.

Eq. (5) indicates that the impact force is inversely proportional to the impact depth, h_2. The deeper the impact depth, the lesser the impact force. Moreover, it also demonstrates that the impact force is directly proportional to the mass of a dropped object and velocity factors. The impact force will increase as the velocity is increased, as well as mass of an object dropped factor.

If the ground is more solid than the dropped object, the object will bounce back from the ground for several times after hitting the ground. This situation will maintain until the momentum of the object becomes zero. This condition is determined as damping condition. The impact force can be modeled in Eq. (6).

$$F = \frac{dp}{dt} \tag{6}$$

where,

dp = Rate of change of momentum, and
dt = Unit time.

Thus, it illustrates that the output power of the piezoelectric energy harvester depends on the impact velocity of the dropped object likewise, the impact force of an object when the object's kinetic energy and momentum remain constant.

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