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Piezoelectric energy harvesting system with magnetic pendulum movement for self-powered safety sensor of trains

Jae Yong Cho[a], Sinwoo Jeong[b], Hamid Jabbar[a], Yewon Song[a], Jung Hwan Ahn[a], Jeong Hun Kim[a], Hyun Jun Jung[a], Hong Hee Yoo[b], Tae Hyun Sung[a,*]

[a] Department of Electrical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 136-791, Republic of Korea
[b] Department of Mechanical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 136-791, Republic of Korea

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ABSTRACT

We designed a piezoelectric energy harvesting system for self-powering a system like a black box that records the vibration and acceleration data of trains for their safety and health monitoring. To make the recording system self-powered, this harvesting system harvests inertial energy as well as vibration energy. To harvest these energies maximally, we proposed the piezoelectric energy harvesting system with magnetic pendulum movement (PEH-MPM).

In this system, there are two magnets: one located at the end of a pendulum rod and the other located at the free end of a piezoelectric cantilever with an acrylic case. The vibration data was acquired from an actual passenger train. When the train moves, the magnet on the pendulum rod makes the piezoelectric cantilever vibrate, amplifying movement of the magnet at its free end. We set structural conditions such as the magnet thickness, length of the pendulum rod, and distance between the magnets. We determined optimizing conditions for increasing output power by changing three conditions: pendulum direction, magnetic pole, and load resistance. The pendulum directions investigated were the X-direction in the direction of train motion and the Y-direction, perpendicular to train motion. The magnetic pole was either attraction or repulsion between the pendulum magnet and the tip magnet. Finally, the impedance varied from 10 kΩ to 1000 kΩ. The system's output power varied considerably with these three conditions.

In conclusion, the optimizing conditions were pendulum motion in the Y-direction, an attractive magnetic pole, and an impedance of 200 kΩ. Under these conditions, the system generated 40.24 $\mu W/cm^3$. This output power density is possible to be used as a power source for the safety sensor in trains.

1. Introduction

Piezoelectricity converts mechanical energy to electrical energy by compressing special materials called "piezoelectric materials". Piezoelectric energy harvesting systems have been studied in various applications, including vehicles, wind flow, and human movement [1–9]. Various studies on vibration energy harvesting related to trains have also been conducted [10,11]. However, currently, the vibration in vehicles has been decreasing for the comfort of passengers [12,13]. Thus, it is not efficient to harvest only the vibration energy in a train. In our previous researches, the experiment of piezoelectric energy harvesting in a train was conducted. The researches focus on harvesting only the vibration energy perpendicular to the bottom of the train [14,15]. It shows that the highest power is 55.36 $\mu W/cm^3$. However, it is hard to harvest the energy and to make use of the energy for some applications to train such as sensors because this is just peak power, not average power. So, in this paper, the piezoelectric energy harvesting system with magnetic pendulum movement (PEH-MPM) is suggested for harvesting the inertial energy as well as the vibration energy and supplying enough power to operate the sensors, especially a safety sensor for the trains. Safety sensor is a black-box type recorder device whose function is to record the acceleration data whenever the train passenger car experiences high accelerations. These recorded data can help in identifying problems in tracks or trains and can be crucial in case of accident investigation.

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* Corresponding author.
E-mail address: sungth@hanyang.ac.kr (T.H. Sung).

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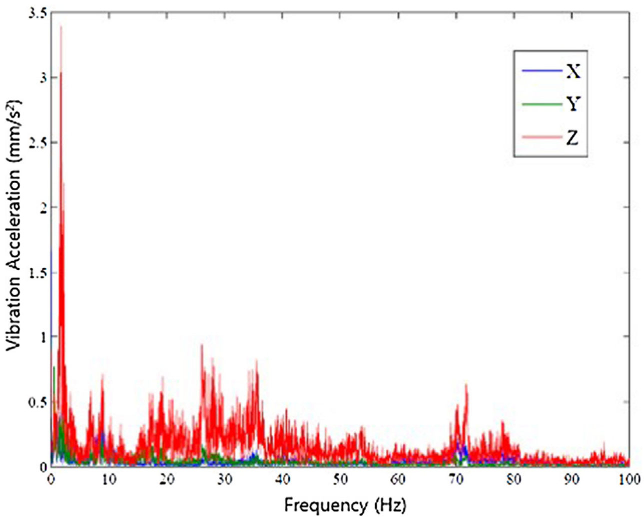

Fig. 1. Result of the vibration acceleration on the three axes of the train.

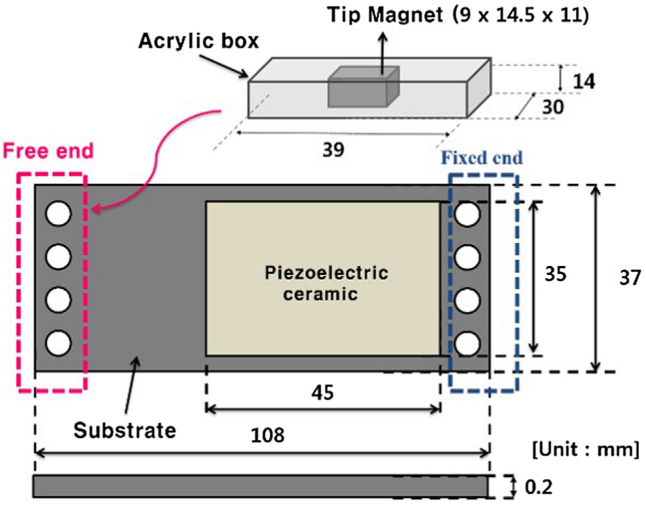

Fig. 2. Design and dimensions of the piezoelectric module.

2. Concept

2.1. Conceptual design

PEH-MPM can harvest two types of vibration energies: vibration energy in the direction of the train motion and vibration energy perpendicular to the train motion. Furthermore, PEH-MPM harvests two types of inertial energy: inertial energy from the tangential acceleration and inertial energy from the centripetal acceleration. As harvesting two types of energy, it can generate helpful power for operating the safety sensors. This generated electrical energy can be used as the power source for the safety sensors as well as wireless sensors in a train [16].

2.2. Real application analysis (input energy analysis)

For application to a train, we analyzed input energy of a train. First, we selected the Intercity Train eXpress (ITX) as the suitable train because the ITX is one of the most popular commercialized trains in Korea due to its small vibration noise. And then, we chose the shortest section of the train route for many experiments to verify reliability. It takes about 4 min to pass through.

We recorded and analyzed the vibration acceleration data of the ITX using a wave analyzer (3160-B-042, Bruel & Kjaer) and an accelerometer (4525-B-001, Bruel & Kjaer). Fig. 1 shows a Fast Fourier Transform (FFT) result of the vibration acceleration along the three axis of the train. It shows z-axis vibration is much more than the other vibrations (x, y-axis) and according to z-axis vibration, vibration acceleration is the highest value in low frequency band (3–6 Hz).

3. Design optimization

As shown in Section 2.2, we analyzed the input energy of the train. Considering the input energy of the train, we proceeded two types of analysis. One is resonance analysis of PZT because z-axis vibration is the most among the vibrations of the train. The other is magnet analysis making use of the fact that vibration acceleration is the highest in 3–6 Hz.

3.1. PZT resonance analysis (Z-axis optimization)

Because z-axis vibration acceleration is the highest value in 3–6 Hz, we designed the PZT which has the resonance frequency between 3 and 6 Hz as shown in Fig. 2. For this, the piezoelectric ceramic was placed on a steel substrate. There are four reasons why we chose steel as substrate. First, if there is no steel substrate, piezoelectric effect will disappear because the same amount of compressive and tensile strain occurs symmetrically in middle of the piezoelectric ceramic. Rather, if the piezoelectric layer is attached on the steel substrate, neutral surface of the beam will easily get far from the piezoelectric ceramic layer and bigger piezoelectric effect will occur as piezoelectric property. Second, it is hard to attach a tip mass (a tip magnet) on the end of the piezoelectric layer due to brittleness of the piezoelectric ceramic. So, we used the steel substrate for applying the tip mass to piezoelectric module easily. Third, the steel can protect the brittleness of the PZT because the steel has high mechanical strength. And lastly, we can find the steel substrate more easily than other substrates.

3.1.1. Verification &Simulation

A cantilever is a beam anchored at only one end. The beam carries the load to the support where it is forced against by a moment and shear force. Cantilever construction allows for overhanging structures without external bracing.

Before simulating the system, base excitation test was performed to find the damping ratio of the first mode of the cantilever beam. Here, acceleration of the base excitation was affixed to the value of 0.5 m/s^2 and the frequency ranged from 3.3 Hz to 4.3 Hz. Half power bandwidth method was used to find the damping ratio. The frequency of the maximum displacement is 3.8 Hz and half power points are 3.7, 3.9 Hz. As a result, damping ratio is found to be about 0.025. And then, using the damping ratio, computational simulation was conducted and the results from the simulation were compared with the experimental results.

Fig. 3 shows the results from the simulation and experiment. It seems that they are in good agreement. And simultaneously, we found the resonance frequency of the PZT is 3.8 Hz which is satisfied with the requested frequency condition (3–6 Hz).

3.2. Magnet analysis (X, Y-axis optimization)

3.2.1. Mathematical modeling of the magnetic force

For magnet analysis in simulation, mathematical modeling of the magnetic force should be needed. Measuring the magnetic force was conducted to find the magnetic moment for the two magnets.