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Experimental investigation on piezoelectric energy harvesting from vehicle-bridge coupling vibration

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ABSTRACT

Piezoelectric energy harvesting from vehicle-bridge coupling vibration is tested in this work. Firstly, a vehicle-bridge coupling platform is introduced, and the dynamic response of the bridge is measured and analyzed. Based on the vibration characteristics of the coupling platform, two piezoelectric energy harvesters (PEHs) with different fundamental frequencies are designed and manufactured, denoted as PEH-1 (designed with the natural frequency of the bridge) and PEH-2 (designed with the frequency of vehicle-bridge coupling vibration). The electromechanical characteristics of the PEHs are tested experimentally. Then, the voltage outputs of the PEHs are measured under nine different cases and the energy harvesting performance of the PEHs are discussed. Finally, the influences of the resistance load on energy harvesting are analyzed theoretically. Experimental results show that the voltage output of PEH-1 has its peaks when the vehicle enters into or leaves the bridge, and is almost zero when the vehicle moves on the bridge. The voltage output of PEH-2, by contrast, is still obvious when the vehicle moves on the bridge. The experimental results also show that more energy can be harvested when the PEHs are installed at the middle of bridge. An interesting result is found. The harvested energy is different even if the PEHs are installed at two symmetric positions of the bridge.

1. Introduction

To ensure vehicles running safely, an effective method is to install a huge amount of wireless sensors to monitor the structural health of the bridge [1–4]. Batteries are usually used in wireless sensor system. However, repeated replacements are needed through the lifetime of the bridge, which is excessively expensive and infeasible in some special situations. At the same time, energy harvesting from vibration environment has been researched [5,6]. Due to the high-power density and easy fabrication, vibration-based piezoelectric energy harvesting technology has received increasing attention. Significant researches have been carried out on analysis or design guidance for piezoelectric energy harvesters [7–12]. The power requirement for most of the commercially available wireless sensor nodes is in the level of mW [13,14]. The potential use of piezoelectric energy-harvesting systems for civil infrastructure has recently begun to receive attention. As one type of endless energy sources, energy harvesting from vibration of bridges is considered as a great potential energy supply for wireless sensors used in traffic infrastructures [15,16]. However, the true potential for applications in the field of civil engineering has yet to be realized.

The simplest way to harvest energy from vibration in a bridge is to patch a piezoelectric element on the surface of the bridge. The energy can be harvested by the piezoelectric element when the bridge is deformed. Assadi et al. [17] presented a theoretical formulation for energy harvesting from a simply supported beam subjected to a single moving mass. The results indicate that the piezoelectric voltage and power were increased by increasing the mass or its moving speed. Amini et al. presented a theoretical study on energy harvesting from vibrations of a beam subjected to multi-moving loads [18] or multi-moving masses [19]. Their results show that the maximum power is achieved at critical velocities. For subcritical velocities the produced power increases with the increase of moving velocity, but the inverse relation was observed for supercritical velocities. These phenomena are identical to the results given by Xiang et al. [20]. Kim et al. [21] fabricated a simply supported composite beam specimen attached with piezoelectric patches. A three-point bending test was performed under cyclic loads. The load amplitudes, the load frequencies and the loading velocity were changed to simulate various traffic conditions. Their test results indicate that the voltage outputs of patches are sensitively affected by the strain rate and peak strain that are related to the moving speed and weight of vehicles. Cahill et al. [22] analyzed the feasibility of using a piezoelectric patch to harvest energy caused by train-bridge interaction. The piezoelectric power outputs were only 588 μW for

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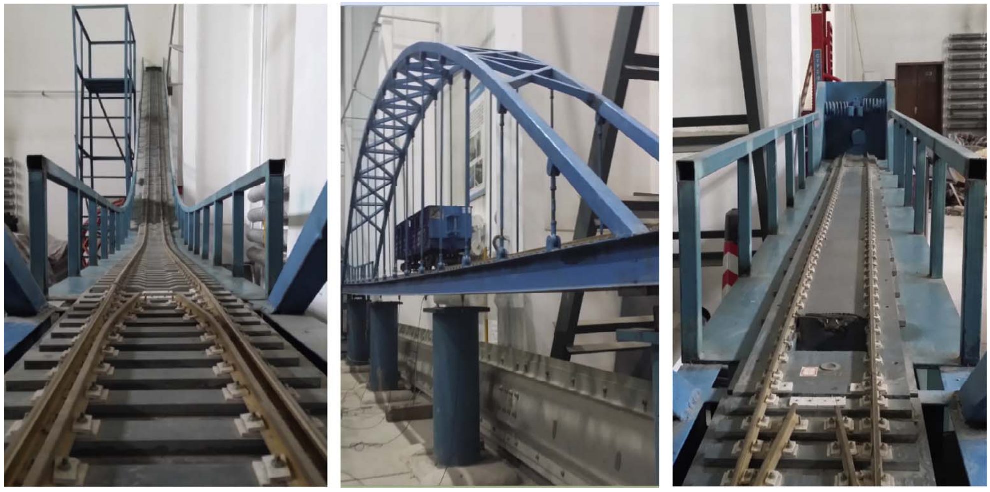

(*a*) Acceleration section   (*b*) Test section   (*c*) Braking section

Fig. 1. The vehicle-bridge coupling platform.

passenger trains and 24.1 μW for freight trains. The harvested power is very low because the strain in a real bridge is very small. Therefore, it is not the best choice to harvest vibration energy of bridges using a piezoelectric patch.

Notice that the overall frequency and acceleration content in the bridge vibration is in the range of 1–40 Hz and 0.01–3.79 g, respectively. These bridge vibration levels can be utilized to generate power with vibration-based piezoelectric energy harvesters (PEH) [23]. The vibration-based PEHs may produce maximum power when they are operated at the resonant frequency. Zhang et al. [24] simulated the energy harvesting from four typical concrete bridges under realistic conditions using the finite element method. The average power output for the bridges with continuous passing vehicles may reach to 3.5 mW. It is feasible for piezoelectric energy harvesting to power the wireless sensor network in civil infrastructures. Some theoretical works have been done on the design of vibration-based PEHs for bridges. Ali et al. [25] simplified the vehicle-bridge system as a simply supported Euler-Bernoulli beam subjected to a moving point load. The harvester fixed on the beam was approximated as a single degree of freedom model. Based on their explicit expression for the voltage and power output, they suggested that the harvester resonance frequency should be tuned to one of the natural frequencies of the bridge to scavenge more energy. Using a similar method but the vehicle is modeled as a moving mass, Karimi et. al. [26] found two peaks in power spectral density diagrams at two frequencies. One frequency corresponds to forced vibration frequency of the bridge due to the motion of mass. For heavy and high speed masses traversing over a beam, the travelling mass inertial effects should be taken into account. Another frequency is fundamental frequency of the bridge. The power at the resonant frequency of the bridge has larger amplitude. As a consequence, in order to extract maximum power from bridge vibrations, one should tune the harvester resonance frequency to the natural frequency of the bridge. Peigney and Siegert [27] designed a cantilever piezoelectric harvester that was tuned to the natural frequency of a transverse bending mode of the bridge. Even though the considered bridge vibrations are characterized by small amplitude (i.e., below 0.6 m/s^2), it is shown that mean power of the order of 0.03 mW can be produced. Based on a distributed model for the harvester, Erturk [28] presented a transient solution in the time domain for power output. He pointed out that the speed of the moving vehicle should be considered for the design of harvester. In the case of lower speed, the fundamental resonance frequency of the harvester should be chosen as the vehicle-induced frequency, which is equal to $\pi v/L_b$ where v is the speed of vehicle and L_b is the span length of bridge. Recently, Zhang et al. [29] conducted a mechanism exploration on piezoelectric energy harvesting from vibration in bridges subjected to moving harmonic loads. Much energy can be harvested if the characteristic frequency of the harvester system (including the harvester and the external circuits) is tuned to $\varpi_n \pm \omega_n^0$, where ϖ_n is the nth natural frequency of the bridge and ω_n^0 is equal to $\pi nv/L_b$. They also pointed out that the vehicle vibration frequencies in the vertical direction have considerable influence on the harvested energy. The vehicle vibration is mainly determined by the vehicle-bridge interaction. Cahill et al. [30] pointed out that there exists a bandwidth for the vehicle speed at which harvester scavenges the maximum amount of energy, while vehicle speeds outside of this bandwidth generate notably lower levels of energy. The optimal vehicle speed range for energy harvesting depends on the bridge-vehicle interaction.

In previous studies, the bridge is simplified as a simplify supported beam and the vehicle is approximated as a moving load, a moving mass or a moving oscillator. In practical aspects, it is still an open problem to design a PEH for existing bridges with considering effects of both bridge and vehicle, especially the effect of vehicle-bridge interaction. This study provides a well-designed “experimental setup” to mimic realistic vibration in bridges and measure the time-varying output performances of the PEH device. This work is organized as follows. In Section 2, a vehicle-bridge coupling platform is introduced, and the dynamic characteristic of the platform is measured and analyzed. In Section 3, two PEHs with different natural frequencies are designed to match the vibration frequencies of the bridge and the vehicle-bridge coupling system, respectively. The electromechanical characteristics of these two PEHs are modeled theoretically and measured experimentally. In Section 4, the voltage outputs of the two PEHs are measured experimentally from the vehicle-bridge coupling vibration, and the effect of the resistive load on energy harvesting is investigated theoretically. Finally, some concluding remarks and design strategies for PEHs are presented in Section 5.

2. Vehicle-bridge coupling dynamic test platform

The energy harvesting potential from bridge vibration will be tested from a vehicle-bridge coupled dynamic platform as shown in Fig. 1. Before performing the energy harvesting test, the dynamic characteristic of the dynamic platform under a moving vehicle is tested and analyzed. The natural frequencies of the bridge and the whole vehicle-bridge coupling system will be distinguished, which is important for designing PEHs.