A Commercial Speaker-Transformed Vibrational Energy Harvesting Device-Conceptual Study and Laboratory Trial on a Model Bridge

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***Abstract*—Advanced structural health monitoring is essential for infrastructure maintenance and management in developing a smart city and could contribute to a carbon-neutral smart city. For long-term bridge health monitoring (BHM), to power various types of wireless sensors, developing a stand-alone sustainable power supply system is of great engineering interest. Solar and wind energy harvesting techniques have been introduced into the long-term BHM field, but they could hardly work well on some monitoring targets that are closed, shadowed, or little sunlight or wind available. Vibrational energy harvesting could be an alternative energy harvesting technique, since almost all bridges vibrate when they are excited by external dynamic forces.**

This study focused on developing a vibrational energy harvesting device transformed from a commercial speaker, which is tailored for practical long-term BHM and characterized by simple structure, durability, commercial availability, and low cost. To develop this device, first the theoretical background on the vehicle-induced bridge vibrations and speaker principles were reviewed, then the fundamental concept of the commercial speaker-transformed vibrational energy harvesting device was presented. The basic idea was to transform a commercial speaker into a vibrational energy harvester that can convert the kinematic energy of low-frequency bridge vibrations into electric energy to charge batteries or to power sensor nodes.

This concept was verified in a laboratory experiment on a model bridge loaded by a moving model vehicle. In this experiment, the current energy harvester could output a maximum voltage of 2.49 mV and an Root Mean Squared (RMS) voltage of 0.14 mV from the bridge vibrations of a maximum acceleration 0.3 m/s^2 and an RMS acceleration 0.04 m/s^2. Also, it was observed that the energy harvester's output voltage was negatively correlated to bridge displacement but positively correlated to bridge acceleration. It suggests that, to harvest more energy from the bridge vibrations using the present device, any means that could excite the bridge with larger acceleration amplitudes might help, e.g., letting vehicles run faster.

***Keywords*—bridge structural health monitoring, bridge vibrations, commercial speaker, vibrational energy harvester**

I. Introduction

Advanced structural health monitoring is essential for infrastructure maintenance and management in developing a smart city [1]. It involves periodical or continuous monitoring of changes to the material or structural properties of engineering structures such as bridges [2]. It allows for the early detection of deterioration and aging in these structures, thereby enabling timely repairs and rehabilitations that can extend their service life and ensure safety. Also, it may aid the current periodical visual inspections which are more and more costly and laborious due to the declining birthrate and aging society. Furthermore, developing structural health monitoring systems could contribute to a carbon-neutral smart city. For one example in Japan, an average of 0.7 t-CO_2/m^3 would be emitted when a new bridge is constructed [3]. The CO_2 emission would be largely reduced if structural health monitoring could be implemented on many bridges nationally or even globally to prolong the bridges' service lives.

For long-term Bridge Health Monitoring (BHM), it is crucial to develop remote sensing and stand-alone powering system, because in Japan many bridges are constructed not only in urban areas but also in mountainous and coastal regions, where the periodical data collection and system maintenance are always costly and laborious. In the last several decades, wireless sensors have been widely used in BHM, to remotely collect various physical quantities, such as acceleration, strain, temperature, wind speed, etc. [2]. For long-term BHM, powering wireless sensors is a critical issue. Usually, batteries are used to power commercial wireless sensors, but they always have limited capacity and are far from sustainability. For one example, if a general Lithium rechargeable battery (e.g., JVCKENWOOD BN-RF1500, 1,536Wh) is used to power an in-house wireless sensor consuming a maximum of 11.1 W, it may run out of power in merely 1 year or less. Moreover, the power consumed by a wireless portable transceiver may demand 1 W or more. To power various types of wireless sensors, developing a stand-alone sustainable power supply system is of great engineering interest.

Solar, wind and vibration energy harvesting techniques have been introduced into the long-term BHM field. Solar energy harvesting techniques are well developed and commercialized. Many products can be found in real-world applications [4]. Wind energy harvesting techniques are fairly investigated and can be found in some BHM campaigns [5]. Generally, there are some limitations in solar and wind energy harvesting applications. One limitation is the dependence on weather conditions: solar energy harvesting is dependent on sunlight exposure strength and length, and wind energy harvesting is dependent on wind strength and direction. They could hardly work well on some monitoring targets that are closed, shadowed, or little sunlight or wind available, e.g., the bottom surfaces of decks, the inner of box girders, etc. [6].

Vibration energy harvesting could be an alternative energy harvesting technique. Almost all bridges vibrate when they are excited by external dynamic forces like running vehicles, walking pedestrians, winds, river flows, etc., and their vibrations could be energy sources to be converted into electric energy. For the reasons above, vibration energy harvesting techniques are drawing great attention, although currently they generate less energy than solar or wind energy harvesting techniques and are not yet fully put into practice and markets [7].

This study focused on developing a standalone vibrational energy harvesting device transformed from a commercial speaker, which is tailored for practical long-term BHM and characterized by simple structure, durability, commercial availability, and low cost. The basic idea is to harvest the low-frequency bridge vibration kinematic energy using the transformed commercial speaker and then to convert it into electric energy to charge batteries or to power sensor nodes. To develop this system, first the theoretical background on the vehicle-induced bridge vibrations and speaker principles were reviewed, then the fundamental concept of the commercial speaker-transformed vibrational energy harvesting system was presented, and a laboratory experiment was conducted to test its feasibility and to study several factors that govern its performance.

II. Theoretical Background

A. Bridge Vibrations

For a vibration energy harvester in a BHM system, bridge vibrations are the major energy sources. To understand the major characteristics of the bridge vibrations, the theoretical dynamic responses of a simply supported bridge loaded by a moving vehicle is briefly formulated as follows, while more details can be found in the references [8, 9].

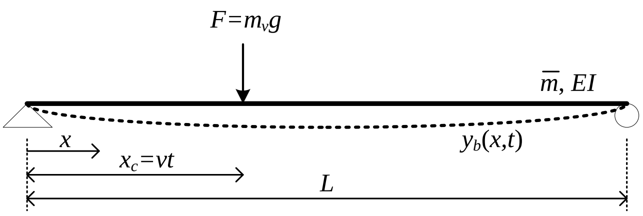


Fig. 1. Numerical model of a simply supported beam loaded by a moving force.

As shown in Fig. 1, the bridge was modelled as a 2-dimensional simply supported Euler-Bernoulli beam of span length L, linear density $\overline{m}$, and bending stiffness EI, and the moving vehicle of mass m_v is modelled as a load $F = m_v g$ moving at a constant speed v. The equation of motion for the bridge can be written as follows,

$$\overline{m}\ddot{y}_b(x,t) + EIy_b''''(x,t) = -m_v g \quad (1)$$

where $y_b(x,t)$ denotes the bridge displacement as a function of longitudinal coordinate x and time t, a prime (■)' indicates the derivative taken with respect to x, and an overdot ($\dot{■}$) indicates the derivative taken with respect to t. The dynamic bridge displacement response can be expressed by the closed-form solution to Eq. (1):

$$y_b(x,t) = \sum_n \frac{\Delta_{st,n}}{1-S_n^2}\left\{\sin\frac{n\pi x}{L}\left[\sin\frac{n\pi vt}{L} - S_n \sin\omega_{b,n}t\right]\right\} \quad (2)$$

where $\Delta_{st,n}$ denotes the static deflection, S_n the non-dimensional speed parameter, and $\omega_{b,n}$ the n-th bridge modal frequency, and they are expressed as follows:

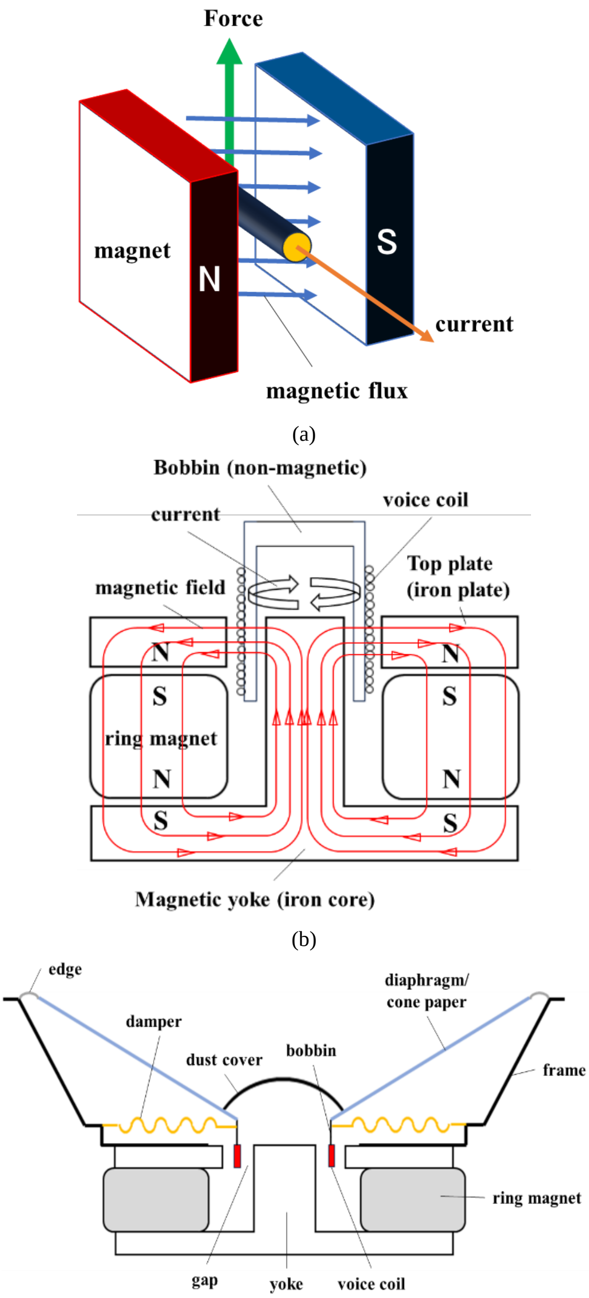
$$\Delta_{st,n} = \frac{2m_v gL^3}{n^4\pi^4 EI}\,;\ S_n = \frac{n\pi v}{L\omega_{b,n}}\,;\ \omega_{b,n} = \frac{n^2\pi^2}{L^2}\sqrt{\frac{EI}{\overline{m}}} \quad (3)$$

From Eq. (2), it is well-known that bridge dynamic responses are dominated by the following groups of frequencies. One group of frequencies are driving frequencies $n\pi v/L$. Usually driving frequencies are lower than 0.1 Hz and their corresponding response components are regarded as semi-static components. The amplitude of the displacement response components is $\Delta_{st,n}/(1-S_n^2)$. Known that S_n is usually smaller than 0.1, the amplitude is close to static displacement $\Delta_{st,n}$ and is usually smaller than 10 mm for real-world short- and median-span bridges. The other group are bridge modal frequencies $\omega_{b,n}$. It is natural that the bridge dynamic responses are governed by its modal frequencies. The first modal frequencies are usually 2 to 4 Hz for short- or median-span bridges. The amplitude of their corresponding displacement response components is $\Delta_{st,n}S_n/(1-S_n^2)$ and is usually smaller than 1/10 the amplitude of semi-static components, i.e., smaller than 1 mm. From the formulations above, it can be summarized that, as the energy sources of a vibrational energy harvester, the bridge vibrations are characterized by low frequencies and small amplitudes.

B. Speaker Principles

The structure and principle of a dynamic speaker are described herein. Basically, a dynamic speaker works following the Faraday's Law (see Fig. 2(a)). When an object carrying a varying electric current is placed perpendicular to a uniform magnetic field, a force is generated that acts perpendicular to both the magnetic field and the electric current. The direction of the force is determined by Fleming's left-hand rule. Since an audio signal is represented by an alternating current, when the direction of the current changes, the direction of the force also changes, resulting in vibrations of the object (conductor). Most dynamic speakers, headphones, and earphones, which currently dominate the audio equipment market, operate based on this principle.

Following the principle above, a commercial dynamic speaker generally works as follows (see Fig. 2(b), (c)). A doughnut-shaped ring magnet generates a magnetic field between the magnetic yoke and top plate. Positioned between the yoke and the top plate is a hollow cylindrical bobbin with a coil wound around it. When a sound is to be generated, an audio signal is first converted into an electric signal. Then the electric signal flows through the coil on the bobbin, and as indicated by Faraday's Law the electric current in a magnetic field generates a force that drives the top-structure (assembled by diaphragm, dust cap, bobbin, and voice coil) into vibrations. The vibrating diaphragm changes the air pressure and thus generates sound waves propagating in the air. The vibrating top-structure needs to return to its original position, and this is where the edge and damper components come into play, acting as springs and dampers to facilitate this movement.



(c)

Fig. 2. Conceptual illustrations: (a) Faraday's Law; (b) speaker principle; (c) speaker structure.

C. Concept of the Commercial Speaker-Transformed Vibration Energy Harvester

The main task of a vibration energy harvester is to convert vibration kinetical energy into electric energy. This conversion may work following the same Faraday's Law, but in the opposite way that a speaker works. A speaker converts electric energy into kinetic energy, and then the kinetic energy generates sound. The former electro-mechanical conversion process is of our interest. Using the same device, or a device of a similar structure, the electro-mechanical conversion process can be invertible. When the voice coil is excited and moves in a constant magnetic field, a current is generated in it along a direction following Fleming's right-hand rule. The excitation to the voice coil can be of any feasible form if it can generate a relative movement perpendicular to the magnetic field; it can be an external force loading on the top-structure (the diaphragm, dust cover, bobbin, and voice coil) or it can be a base motion on the base-structure (the yoke and ring magnet).

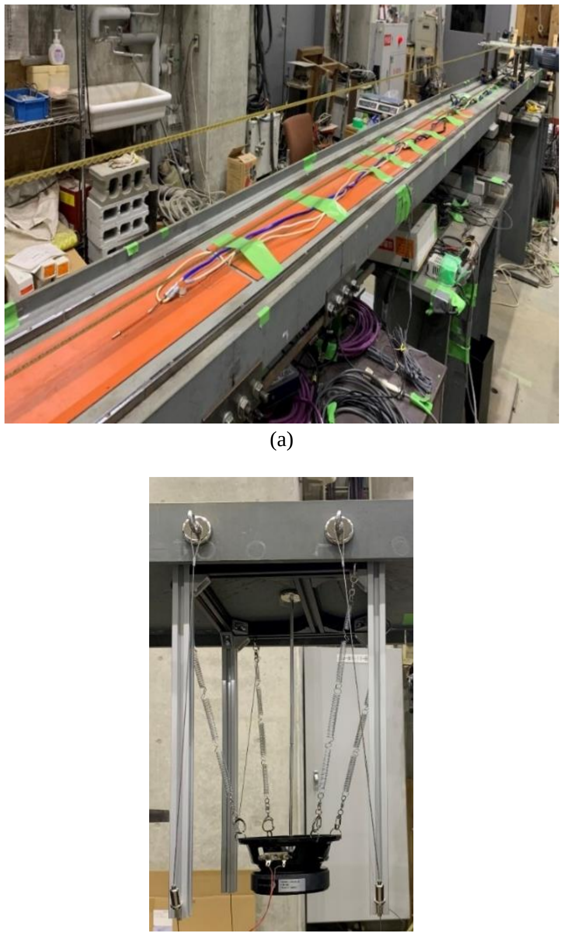
A device that converts kinematic or electric energy into each other is known as an electro-mechanical transducer. Speaker is a typical application of this type of transducer that is well studied, developed, and commercialized. It is chosen among various commercial or in-house electro-mechanical transducers for transforming into a vibration energy harvester because it is characterized by simple structure, durability, commercial availability, and low cost.

III. Laboratory Experiment

To verify the concept of transforming a commercial speaker into a vibrational energy harvester tailored for bridge health monitoring and to study several factors that govern the energy harvesting performance, a commercial speaker was modified and tested on a laboratory model bridge loaded by a moving model vehicle. The details of the experiment are given in the following sub-sections.

A. Model Vehicle and Bridge

The test bridge (see Fig. 3(a)) was a simply supported steel beam of a total length L_t = 5.6 m and span length L = 5.4 m. Its section was in H shape and provided a bending rigidity EI = 1.15×10^5 N-m^2. Its 1st bending modal frequency can be analytically calculated as 2.67 Hz (using Eq. (3)).



(b)

Fig. 3. photo of experiment devices: (a) the laboratory model bridge and vehicle; (b) the commercial speaker transformed vibration energy harvester attached on the model bridge.

The test vehicle was a model vehicle assembled by a steel plate and four-wheel sets installed at the four plate corners. The steel plate served as vehicle body, and each of the wheel sets were assembled by a spring and a plastic wheel attached below a vertical metal rod. The vehicle weight could be tuned by adding steel blocks. In this study, four vehicle weights (given in Table 1) were used to study their effect on the energy harvesting performance. A rubber belt was tied to both the front and back of the vehicle and connected to a pulley on each end of the steel beam. One pulley was connected to a motor that pulls the vehicle back and forth on the bridge. The vehicle's running speed was controlled by a digital controlling system, which could tune the motor's rotational speed to maintain constant within one run while vary it between runs. Three running speeds (given in Table 2) were used to study their effect on the energy harvesting performance.

Table 1. Vehicle weight in the experiment

Notation	Vehicle weight (kgf)
M15	15.16
M17	17.04
M19	18.92
M23	22.88
M27	26.84

Table 2. Nominal running speed in the experiment

Notation	Running speed (m/s)
S035	0.35
S070	0.7
S105	1.05

Three accelerometers (ARS-10A model produced by Tokyo Measuring Instruments Laboratory Co.) and three displacement transducers (CDP-25 model produced by Tokyo Measuring Instruments Laboratory Co.) were installed at the 1/4-, 2/4-, and 3/4-span of the bridge on the bottom surface. The sampling rate was set as 200 Hz throughout the experiment.

B. Vibrational Energy Harvester

A commercial speaker driver of PA130-8 model produced by Dayton Audio [10] was modified to serve as a vibrational energy harvester in the experiment (see Fig. 3(b)). Its edge and damper were partially cut off to reduce the structural stiffness and damping so as to amplify the coil movements and to prolong the vibration time and natural period. A metal cage was constructed to house the modified speaker. Inside the cage, the speaker was hung with four springs connecting the speaker's frame top edge and the cage's four top corners. A thin metal rod was attached on top of the dust cover and connected to the bridge bottom surface, to drive the speaker's top structure into vibration in phase with the bridge. The speaker's base-structure may vibrate out of phase with the top-structure. This relative movement of the coil and the ring magnetic may induce electric current in the coil. In the test, the speaker-transformed vibrational energy harvester was attached at the mid-span of the model bridge on the bottom surface, and its induced voltage was recorded by a data logger.

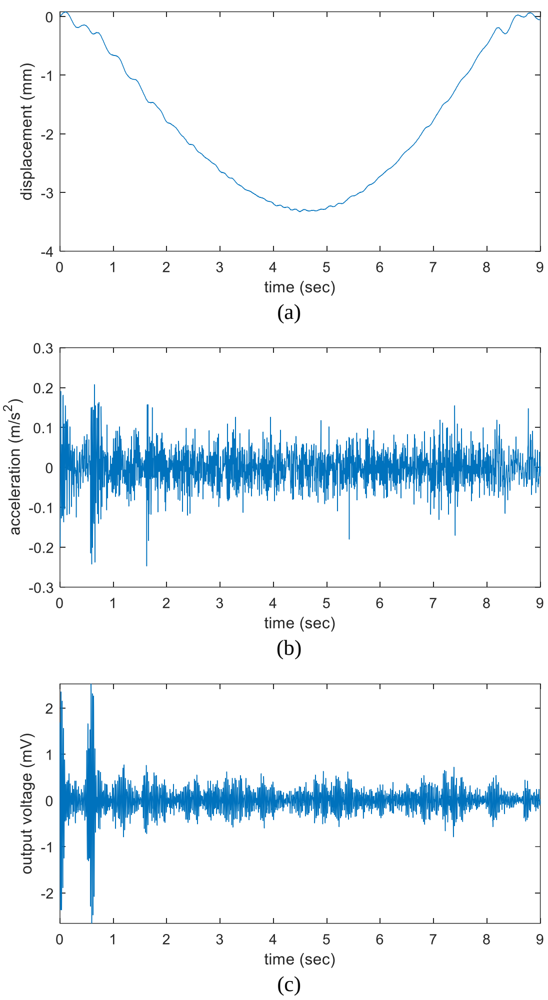


Fig. 4. Sample responses at the bridge mid-span: (a) displacement, (b) acceleration, and (c) output voltage.

IV. RESULTS AND DISCUSSIONS

In the experiment, when the model bridge was loaded by the model vehicle moving at a constant speed, the bridge displacement and acceleration responses were recorded at the three observation points (the 1/4-, 2/4-, and 3/4-span) and the energy harvester's voltage induced by the bridge vibrations were also recorded. As indicated in Sec. III.A, 4 different vehicle weights (M15, M17, M19, M23, M27) and 3 running speeds (S035, S07, S105) were tested, and each case was tested by 10 runs. The results are presented and discussed in the following sub-sections.

A. General Harvesting Energy

Taking the M15-S035 case (vehicle weight = 15 kgf, running speed = 0.35 m/s) for example, the bridge's mid-span displacement and acceleration responses and the energy harvester's output voltage response are shown in Fig. 4. It is observed that the displacement response was 3.3 mm and the acceleration was 0.25 m/s^2 in maximum amplitude, which were in a similar magnitude measured on a real short- and medium-span bridge. When the target bridge vibrated in this magnitude, the vibrational energy harvester was observed to output a voltage generally oscillating between +1 and −1 mV and a maximum instantaneous voltage of 2.49 mV.

This case was repeated 10 runs. In these runs, the maximum and Root Mean Squared (RMS) values are summarized in Table 3 for the bridge displacement and acceleration responses recorded at the 3 observation points and the energy harvester output voltage recorded at the mid-span. Not surprisingly, the displacement showed a larger value at the mid-span and a smaller value at the 1/4 and 3/4 span, and the acceleration showed almost the same magnitude at the three observation points for both maximum (about 0.3 m/s^2) and RMS (about 0.04 m/s^2). In this vibration magnitude, the energy harvester outputted a maximum voltage of 2.49 mV and an RMS voltage of 0.14 mV for 10 run records. The concept of transforming a commercial speaker into a bridge vibration energy harvester was preliminarily demonstrated.

Table 3. Maximum and RMS for bridge displacement, acceleration, and energy harvester output voltage measured at the 3 observation points for 10 runs

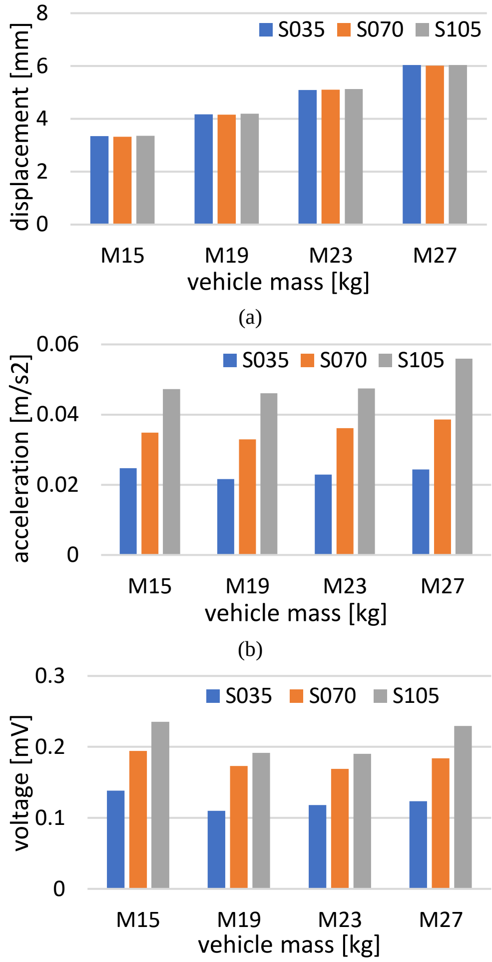
	3/4 span	2/4 span	1/4 span
Displacement max (mm)	2.51	3.33	2.23
Acceleration max (m/s^2)	0.294	0.317	0.283
Acceleration RMS (m/s^2)	0.040	0.035	0.041
Voltage max (mV)	--	2.49	--
Voltage RMS (mV)	--	0.14	--

B. Effect of Vehicle Weight and Speed

The effect of vehicle weight and speed is discussed here on the measured responses, including the bridge displacements, accelerations, and the energy harvester output voltages. Also, the link between the bridge responses and the energy harvester output voltage is also discussed.

Fig. 5 shows the bridge maximum displacement, RMS acceleration, and RMS energy harvester output voltage with respect to four vehicle weights and three vehicle speeds. In the figure, all values were taken by averaging the corresponding responses at the bridge mid-span from 10 runs. It is clear the bridge displacements were positively correlated to vehicle weight and little correlated to vehicle speed (Fig. 5(a)); the bridge accelerations were little correlated to vehicle mass and positively correlated to moving speed (Fig. 5(b)); the energy harvester output voltages were little correlated to vehicle mass and positively correlated to moving speed (Fig. 5(c)). In other words, when the when a heavier vehicle ran over the bridge, the bridge deflected more, but the bridge acceleration and the output voltage did not differ much from those when a lighter vehicle ran; when a vehicle ran faster over the bridge, the bridge acceleration and the output voltage were larger, but the bridge deflection did not differ much from those when a vehicle ran slowly.

Fig. 6 shows the correlation between the energy harvester's maximum output voltage and the maximum bridge displacement response, and Fig. 7 shows the correlation between the RMS output voltage and the RMS bridge acceleration, all measured at the bridge mid-span. It can be observed that the energy harvester's output voltage was negatively correlated to bridge displacement but positively correlated to bridge acceleration. It implies that the energy harvester could harvest more energy from a bridge vibrated with a larger acceleration amplitude, but not much more from a bridge vibrated with a larger displacement. It suggests that, to harvest more energy from the bridge vibrations, any means that could excite the bridge with larger acceleration amplitudes might help, i.e., letting vehicles run faster.



(c)

Fig. 5. Variation of responses measured at the bridge mi-span with respect to vehicle weight and speed: (a) maximum bridge displacement, (b) RMS bridge acceleration, and (c) RMS energy harvester output voltage.

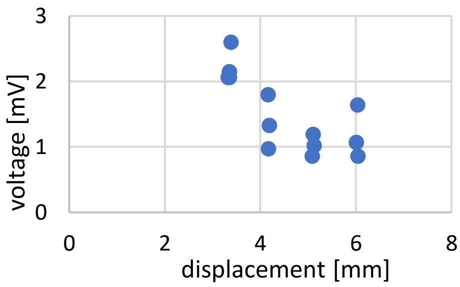


Fig. 6. Maximum output voltage vs. maximum displacement measured at the bridge mid-span.

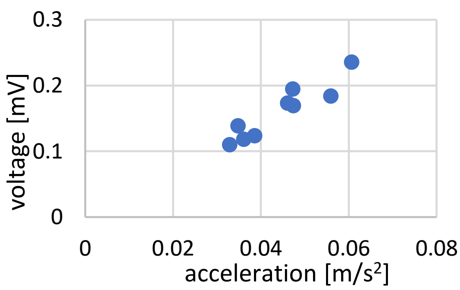


Fig. 7. RMS output voltage vs. RMS acceleration measured at the bridge mid-span.

V. CONCLUDING REMARKS

This study focused on developing a vibrational energy harvesting device transformed from a commercial speaker, which is tailored for practical long-term BHM and characterized by simple structure, durability, commercial availability, and low cost. To develop this device, first the theoretical background on the vehicle-induced bridge vibrations and speaker principles were reviewed, then the fundamental concept of the commercial speaker-transformed vibrational energy harvesting device was presented. The basic idea was to transform a commercial speaker into a vibrational energy harvest that can convert the kinematic energy of low-frequency bridge vibrations into electric energy to charge batteries or to power sensor nodes.

This concept was verified in a laboratory experiment on a model bridge loaded by a moving model vehicle. In this experiment, the current energy harvester could output a maximum voltage of 2.49 mV and an RMS voltage of 0.14 mV from the bridge vibrations of a maximum acceleration 0.3 m/s^2 and a RMS acceleration 0.04 m/s^2. Also, it was observed that the energy harvester's output voltage was negatively correlated to bridge displacement but positively correlated to bridge acceleration. It suggests that, to harvest more energy from the bridge vibrations, any means that could excite the bridge with larger acceleration amplitudes might help, e.g., letting vehicles run faster.

The findings in this study may apply to bridge vibrations of a similar magnitude and vibrational energy harvesting devices made in a similar type. To put the present device into practice and to enhance the energy harvesting efficiency, it is necessary to further study the effect of the following factors on the energy harvesting performance: the speaker's proof mass, stiffness, damping, frequencies, etc. Also, how the present vibrational energy harvesting device performs on a real-world bridge is of our current interest.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

K. C. Chang analyzed the data and drafted the paper; T. Nishino and K. Sugihara coordinated the research project; M. Onishi, W. Murata, T. Onodera, and S. Okada designed the test model; H. Tanigawa advised on the project. All authors had approved the final version.

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