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REVIEW ARTICLE

VIBRATION-BASED ENERGY HARVESTER FOR SUSTAINABLE STRUCTURAL HEALTH MONITORING SYSTEM: A CASE STUDY ON A PRESTRESSED CONCRETE GIRDER

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ABSTRACT

Energy harvesting technology generating electrical energy from structural responses has been in the spotlight recently because of the development of self-powered autonomous wireless sensor systems. This study proposed and tested a high-sensitivity, high-durability, low-cost vibration power-generating device using a magnetostrictive element (Fe-Ga alloy) on a real-scale prestressed concrete girder to investigate its practical performance. The device comprises a unimorph layer having a magnetostrictive element attached to a U-shaped frame with a permanent magnet for magnetic bias wound about by a coil. An evaluation of a prototype device using a Fe-Ga element of 4 × 0.5 × 16 mm was performed. With a weight of 1221 g attached, an open-circuit voltage of ~1 V at an oscillation of 9.058 Hz and 3.8 m/s2 was generated by free damped vibrations applied via a person jumping vertically from a chair to the girder. In addition, parametric studies were carried out by changing impact locations, weights, and device locations in order to examine their possible effects on the performance of the proposed energy harvester.

KEYWORDS

Magnetostrictive material, Prestressed concrete girder, Vibration-based power generation.

1. INTRODUCTION

The main problem with health monitoring systems for actual structures is battery power. The number of power supplies is not always sufficient for field experiments. Over the years, vibration-based power generation technology is utilized effectively in various fields. The self-powered autonomous wireless sensor system is also beneficial in structural health monitoring and factory to inform system abnormality of civil engineering works such as bridges. There, the battery replacement, troublesome work, is no more required.

So far, many studies relating to micro energy harvester using iron–gallium alloy have been performed. Ueno and Yamada (Ueno and Yamada, 2011) developed a bimorph vibration energy harvester in which two rods of the iron-gallium (Fe-Ga) alloy were employed and capable of producing 10 mW/cm^3. The advantages of this energy harvester over conventional ones, such as those using piezoelectric materials, are smaller size, higher efficiency and it also has high robustness and low electrical impedance. Four years later, the energy harvester was improved by using less volume of Fe-Ga and permanent magnet as compared to the previous version (Ueno, 2015). The device is based on a parallel beam structure consisting of cuboids of magnetostrictive material and iron yoke. This converts small force exerted by vibration to large mechanical stress to the material yielding change of magnetic flux due to the inverse magnetostrictive effect. Recently, a new vibration power-generating device using a Fe-Ga plate-like element adhered to a U-shaped magnetic frame is under investigation (Ueno, 2018). General environmental vibration occurs at frequencies of 20 to 100 Hz and accelerations of 0.05 G to 1 G. The device is required to generate power from mild to high-intensity vibrations.

In this study, the high-sensitivity, high-durability, low-cost power-generating device using an iron–gallium alloy plate (Fe-Ga plate) proposed by Ueno was tested on a real-scale prestressed concrete (PC) girder to demonstrate its practical performance. Specifically, the device's principle of operation is based on the inverse magnetostrictive effect of the plate. First, the vibration characteristics of the girder, such as the vibration frequencies, mode shapes, and damping ratios, were extracted from the measurement data of the vibration tests along with the generated open-circuit voltage of the device during each test. A parametric study was conducted on several preliminary options of the weight attached to the tip of the U-frame to examine the appropriate value for vibration resonance between the girder and the device. Finally, the effects of the impact location and the device location on device performance were also analyzed

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and evaluated by changing the locations of the human impact and energy harvester with a constant interval of 1.15 m on the top surface of the investigated girder.

2. Principle and Configuration of The Device

The structure of the device is shown in Figs. 1 and 2. The device has a unimorph base with a plate-like magnetostrictive element (Fe–Ga alloy) adhered to a U-shaped magnetic frame (Fig. 2 top). A coil is wound around the unimorph and permanent magnet is arranged in the space within the frame. The frame is designed so that the part where the magnetostrictive element is bonded becomes magnetically saturated by magnetic bias; the other parts remain unsaturated, and a uniform stress is applied in the longitudinal direction of the element when the unimorph is bent.

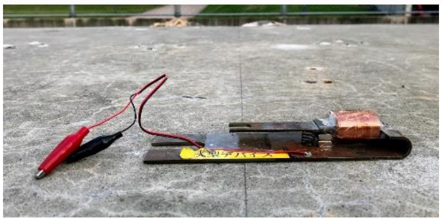


Figure 1: A prototype vibration power generator

Magnetostriction is a property of Fe-Ga alloy that causes them to change their shape during the process of magnetization. The operating principle of the device is based on the inverse magnetostrictive effect that the magnetization changes with stress. If there are uniform tensile and compressive stresses generated in the longitudinal direction of the Fe-Ga plate (Fig. 3), the magnetic flux is increased or decreased by the inverse effect. Therefore, voltages are induced in the wound coils around the Fe-Ga plate due to time-varying magnetic fields and the vibration energy is harvested.

The critical design feature of this structure is the easily molded frame, which can be cut out and bent from a Fe plate, thereby significantly reducing the cost. The generated power can be significantly increased by manipulating the layer thickness of the coil, while the generated voltage and resistance can be adjusted by manipulating the wire diameter. Furthermore, the unimorph is more easily vibrated by uniform curving compared to the conventional parallel-beam type, and also highly durable. Thus, the proposed structure satisfies both mass productivity and high performance.

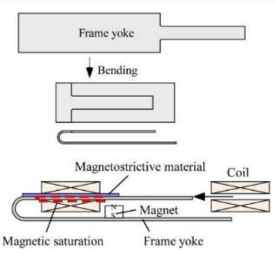


Figure 2: Frame (top) and device configuration (bottom)

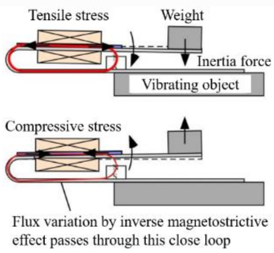
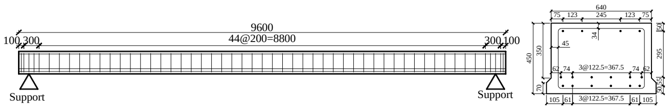


Figure 3: Principle of power generation: Inertial force downward (top) and upward (bottom)

3. Description of The Pc Girder

The side and cross-sectional views of the girder were shown in Fig. 4(a)–(b). The length and height were 9600 and 450 mm, respectively. The upper and lower edge widths of the cross section were 640 and 700 mm, respectively. The girder was supported by two points with a span length (L) of 9200 mm. With regard to prestressed tendons, sixteen strands (SWPR7BL1S 12.7 mm) were arranged longitudinally in three layers. Following the initial curing, they were placed in a sunny area outside the laboratory.



(a) Side view (b) Cros-sectional view

Figure 4(a)–(b): Diagram of PC girders (unit: mm)

4. Experiment Procedure And Parametric Study

In this study, 10 different cases were used for the parametric study which was then expected to provide the effects of objective parameters on the generated voltage (see Table 1). To obtain free damped vibrations of the PC girder, 14 accelerometers were placed on the girder with a constant interval of 1.15 m, as shown in Fig. 5. During each test, the impact excitations were applied alternately via a person jumping vertically from a chair at the locations depicted as "x" in Figs. 5 and 6. At every impact location, the measurement was conducted two times, with 10000 data points collected at a sampling period of 5e−3 s each time. The vibration parameters of the PC girders were extracted from the measured data using the eigensystem realization algorithm (ERA) (Juang and Pappa 1985). Cases 1–4 were employed for investigating the appropriate weight attached to the tip of the U-frame for vibration resonance between the girder and the proposed energy harvester. Specifically, weights of 1221 g, 1562 g, 1759 g and 2540 g were attached to the frame for Cases 1, 2, 3, and 4, respectively. The impact and device locations were at the span center of the girder. Regarding Cases 5–7, the impact point was changed in turn at positions 0.125L, 0.25L, and 0.375L, respectively, while the device was kept located at midspan (L = 9200 mm). In addition, Cases 5, 6, and 7 were supposed to give the effect of the impact location as compared with the voltage result inferred from the Case 1. Furthermore, Cases 8–10 were considered to investigate the variation trend of the generated voltage owing to the change in the location of the device. In particular, the data were measured when the device was placed in positions 0.125L, 0.25L, and 0.375L, while the jumping position was left unchanged at 0.5L.

Table 1: Cases for parametric study

Case	Impact location	Device location	Weight (g)
1	0.5L	0.5L	1221
2	0.5L	0.5L	1562
3	0.5L	0.5L	1759
4	0.5L	0.5L	2540
5	0.125L	0.5L	1221
6	0.250L	0.5L	1221
7	0.375L	0.5L	1221
8	0.5L	0.125L	1221
9	0.5L	0.25L	1221
10	0.5L	0.375L	1221

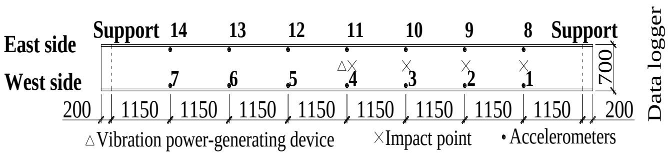


Figure 5: Sensor layout of cases 1, 5, 6, and 7

Figure 6: Impact test on the PC girder

5. Result and Discussions

5.1 Free vibration characteristics of the objective girder

At first, the vibration characteristic of PC girder was investigated. Fig. 7 shows the acceleration waveform and spectrum obtained at 7L/8 points when impact excitation was performed at the span center. Moreover, the modal properties were extracted from the measured data using ERA method. In particular, modes 1 (f = 9.016 Hz) was the first bending mode, while mode 2 (f = 29.924 Hz) was defined as the second bending mode.

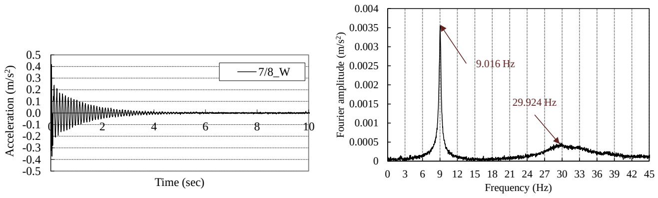


Figure 7: Vibration test result (Measuring point: 7L/8)

5.2 Parametric study

The energy harvester was fixed to the top surface of the girder with an adhesive tape with high adhesion. The vibration acceleration of the girder was obtained by 14 accelerometers placed on the girder with a constant interval of 1.15 m (Fig. 5), while the vibration of the frame was measured with an accelerometer mounted on the tip of the U-frame. For Cases 1–4, weights of 1221 g, 1562 g, 1759 g, and 2540 g were attached to the tip of the frame. Fig. 8 shows the frequency response results estimated by a fast Fourier transform (FFT) analyzer. When the weights are 1221 g, 1562 g, 1759 g, and 2540 g, the frequencies of the frame were 9.058, 8.276, 6.738 and 5.664 Hz, respectively. In addition, the voltage waveforms of the first four cases are shown in Fig. 9. The maximum voltage of ~1.03 V was generated in Case 1 using a weight of 1221 g attached to the tip of the U-frame. Under Cases 2–4, the maximum voltage at the beginning was obtained as 0.73, 0.23 and 0.18 V respectively. These outcomes demonstrate that the frequency of mode 1 of the frame decreased with the increase in the weight mounted. Moreover, with an attached weight of 1221 g, the frequency of mode 1 of the frame's oscillation matched the frequency of the 1st bending vibration of the girder, which was estimated to be ~9.016 Hz. This caused the system to oscillate with larger amplitude than when the other weights were applied, and thereby the resonance occurred and the open voltage could be observed at high value. When the weight increased, the Fourier amplitude of the peak decreased and the peak occurred at a lower frequency.

The acceleration waveforms and spectrums of Case 1 and Cases 5–7 obtained by an accelerometer mounted on the tip of the frame is shown in Fig. 10. Under the impact via a person jumping vertically from a chair to the girder and the weight of 1221 g on the frame, the maximum acceleration of the frame at the beginning was obtained as 3.802, 1.27, 2.735, and 2.951 m/s² for Cases 1, 5, 6, and 7, respectively. The frequency of the first mode of the frame vibration was estimated to be approximately equal to the frequency of the 1st bending mode of the girder (9.016 Hz). Moreover, from Fig. 11, the maximum voltage of 1.03 V is generated at the acceleration of 3.802 m/s². The generated voltage reduced when the impact position shifted away from the device location and towards the support, which led to a decrease in the amplitude of the acceleration of the frame at the beginning.

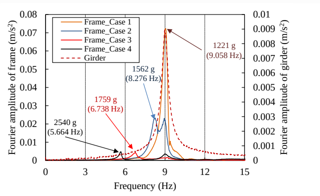


Figure 8: Frequency responses with varied weight

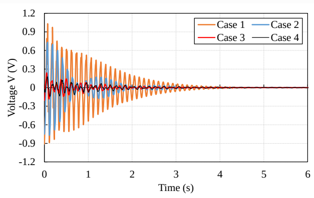


Figure 9: Generated voltage at free vibration with varied weight

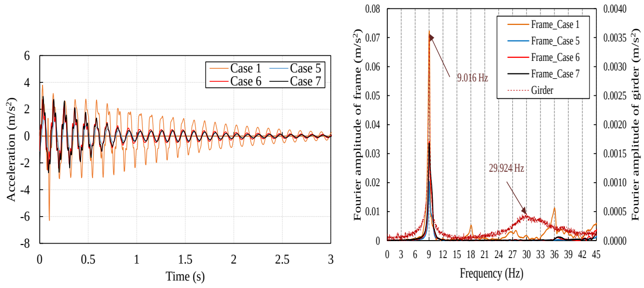


Figure 10: Waveform and spectrum obtained from Cases 1, 5, 6, and 7

Similar outcomes were also found with respect to Cases 8–10 when the device was placed in positions 0.125L, 0.25L, and 0.375L, while the impact position was left unchanged at 0.5L. A voltage of 1.03 V is generated at an acceleration of ~3.8 m/s² in Case 1 when both the impact location and the device location were at the midspan. Fig. 12 shows the relation between the max voltage at the beginning of impact excitation and the location of the device. From this figure, the generated voltage decreases when the distance between the impact point and the device is far apart. Moreover, a previous study of the authors (Ueno and Yamada 2011) showed that the generated voltage is proportional to the frequency due to Faraday's law of induction. Therefore, it is desirable to utilize resonant vibration of high frequency in order to generate high electrical energy efficiently. In this study, the harvester was verified to provide the maximum voltage of ~1 V at the first bending resonance of ~9 Hz as shown in Fig. 8. To obtain high electrical energy, the location of the device should be determined in consideration with the mode shapes and the corresponding frequencies of the girder. Moreover, the weight attached to the frame of the device should be modified to ensure that the measured frequency of the frame is equal or nearly equal to one of the frequencies of the high order modal shapes of the girder.

6. Conclusions

This study proposed and tested a high-sensitivity, high-durability, low-cost vibration power-generating device using a magnetostrictive element (Fe-Ga alloy) on a real-scale prestressed concrete girder to investigate its practical performance. A parametric study was conducted on several preliminary options of the weight attached to the tip of the U-frame to examine the appropriate value for vibration resonance between the girder and the device. The main conclusions drawn from this study are as follows.

- With a weight of 1221 g attached, an open-circuit voltage of ~1 V at an oscillation of 9.058 Hz and 3.8 m/s² was generated by free damped vibrations applied via a person jumping vertically from a chair to the girder.
- The generated voltage decreases when the distance between the impact point and the device is far apart.
- It is desirable to utilize resonant vibration of high frequency in order to generate high electrical energy efficiently.

In the present study, the harvester was verified to provide the maximum voltage of ~1 V at first bending resonance of ~9 Hz. This work is a start point for a simple novel vibrational power-generating device using magnetostrictive material for bridge monitoring system, and further research is needed on the subject. Regarding long-term prospects, to obtain high electrical energy, the location of the device and the weight attached to the frame of the device should be modified and improved. Moreover, the further numerical study should be carried out in order to predict accurately the behavior of the proposed device in actual situations, and future projects can target improvements in relation to the designs and simulation methods. In addition, studying the environmental effects on the performance of the proposed device is also important to effectively apply the monitoring methods and modifications on the design.

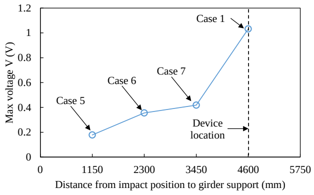


Figure 11: Effect of impact location on generated voltage

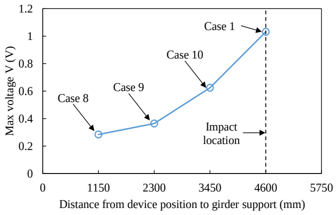


Figure 12: Effect of device location on generated voltage

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