Power Generation from Bridge Vibration under Ordinary Vehicle Load

Hoang Minh Ngo Le
School of Geosciences and Civil Engineering, Kanazawa University, Kanazawa, Japan
Email: ngolehoangminh97@gmail.com

Tuan Minh Ha
Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HUTECH), Ho Chi Minh City, Vietnam
Email: hm.tuan@hutech.edu.vn

Saiji Fukada
School of Geosciences and Civil Engineering, Kanazawa University, Kanazawa, Japan
Email: saiji@se.kanazawa-u.ac.jp

Toshiyuki Ueno
School of Electrical, Kanazawa University, Kanazawa, Japan
Email: ueno@ec.t.kanazawa-u.ac.jp

***Abstract*—This study conducted the structural eigenvalue analysis on a highway bridge model to investigate its vibration characteristics and to find out an appropriate location to set a new power-generating device using a magnetostrictive element (Fe-Ga alloy). The energy generator is consisting of a Fe-Ga element of 4 x 0.5 x 1.6 mm attached to a U-shaped frame with a permanent magnet for magnetic bias wound about by a coil and the weight attached to the tip of the U-shaped frame was adjusted to allow the frame vibrates with the frequency of the vibration source. First, a part of the elevated line of a highway bridge located in Kanazawa city was reproduced by using a commercial finite element software named DIANA. As the results, at the lateral brace between G1 – G2 main girders and P2 – P3 pier, which its frequency was estimated to be ~ 19Hz, is the optimal place for the device. Moreover, an open-circuit voltage of ~ 8V was recorded.**

***Index Terms*— vibration-based power generation, highway bridge, structural eigenvalue analysis**

I. INTRODUCTION

The self-powered autonomous system is an important part of the Internet of Things (IoT), which is one of the currently trending technologies. Especially in the building industry, structural health monitoring is an emerging problem. However, throughout the years, the power supply is still the major problem of the health monitoring system. Especially, the power supply is not always available or sufficient for field experiments due to the economic situation or the limitations of facilities. Lately, vibration-based power generation technology is utilized effectively in various fields and opened many opportunities to make a self-powered autonomous structural health monitoring system. This next-generation structural health monitoring system will be a safe and economical solution instead of battery-replacement or making an electric supplying system.

So far, there are many studies relating to the power harvester using magnetostrictive elements such as Iron – Gallium (Fe - Ga) alloy have been performed. A bimorph vibration energy harvester, which was employed two rods of the Iron – Gallium (Fe – Ga) and capable of producing 10 mW/cm^3, has been developed by Ueno and Yamada [1]. The advantages of this energy harvester over conventional ones, such as those using piezoelectric materials, are a smaller size, higher efficiency, higher robustness, and lower electrical impedance. In 2015, by using less volume of Fe – Ga alloy and the permanent magnet, the efficiency of the vibration energy harvester was improved [2]. This version was built on a parallel beam structure, which is consists of cuboids of magnetostrictive material and iron yoke. This structure allows to converting small force exerted by vibration to large mechanical stress to material yielding change of magnetic flux because of the inverse magnetostrictive effect. In 2018, a new design of the vibration power-generating device using a Fe- Ga element attached to a U-shaped magnetic frame was proposed [3]. The device was designed to generate power from mild to high-intensity vibrations. Recently, the performance of this new version was improved by calibrating the attached weight to make the frame vibrate with the frequency of the vibration source [4].

In this study, a part of the elevated line of a highway bridge located in Kanazawa city was simulated by using a finite element software named DIANA to investigate the optimal place to put the vibration power-generating device. The result of the simulation consisted of vibrational parameters, such as frequencies and mode

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Corresponding author: Hoang Minh Ngo Le

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shapes. In this study, the optimal place to set the device is assumed to be the location with the highest vibrational energy, which is determined based on the vibration amplitude and frequency. Then the device was tested on an actual highway bridge at the predetermined place and other locations to demonstrate its practical performance and to check the simulation's result.

II. CONFIGURATION AND OPERATION PRINCIPLE OF THE DEVICE

The design of the power generation device is shown in Fig. 1 and Fig. 2. This device has an unimorph base with a magnetostrictive element (Fe – Ga alloy) of 4 x 0.5 x 1.6 mm attached to a U-shaped magnetic frame (Fig. 1). A coil is wound on the unimorph and a permanent magnet is fixed within the U-shaped frame. The U-shaped frame is designed so that the part, where the magnetostrictive element is attached to, becomes magnetically saturated due to magnetic bias, while the rest of the frame still remains unsaturated. When the unimorph is bent, uniform stresses occur in the longitudinal direction of the element.

The principle of power generation is shown in Fig. 3. The device is fixed to a vibration source, and the weight attached to the tip of the U-shaped frame was adjusted to allow the frame to vibrate with the frequency of the vibration source. First, the device deforms due to the inertial force, which is caused by the movement of the attached weight, then the uniform tensile and the compressive stresses are generated in the longitudinal direction of the magnetostrictive element, and the magnetic flux is changed by the inverse magnetostrictive effect (Fig. 4). Figure 3 shows the cases for which the inertial force of the weight is downward (top) and upward (bottom). Due to the inverse magnetostrictive effect circulates in the closed magnetic circuit in series with the element, frame, magnet and gap; the change in magnetic flux is generated. The magnetic part is magnetically saturated; therefore, the magnetic resistance is high, and the change in the magnetic flux of the device does not go back through the magnetic part. Thus, an electromotive force proportional to the temporal change of the magnetic flux is generated in the coil. Voltages are generated in the coil wound around the Fe-Ga bar due to the time-varying magnetic field by Faraday's law of induction and the vibration energy is harvested.

The advantages of this design are the easily molded frame and the high customization. The U-shaped frame can be cut out and bent from an iron plate, the magnetostrictive element can be fixed to the frame and the air-core coil can be fitted later, thereby significantly reducing the production cost and suitable for mass production. The generated power can be significantly increased by changing the number of turns of wire in the coil, the generated voltage and resistance can be adjusted by changing the wire diameter, and the vibrational frequency of the device can be adjusted to allow the device vibrates with the vibration source frequency by calibrating the attached weight. In addition, compared to the conventional parallel-beam type [2], the unimorph is more easily vibrated by uniform curving, the durability is also improved. Consequently, this proposed design not only satisfies the high performance and high customization but also suitable for mass production.

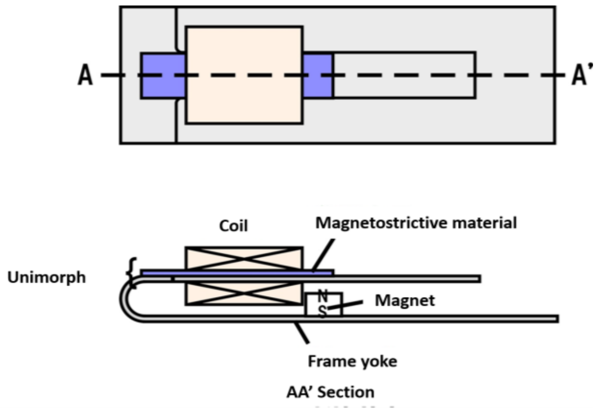


Figure 1. Frame and device configuration

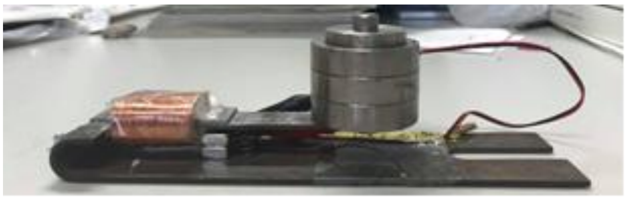


Figure 2. A prototype vibration power generation

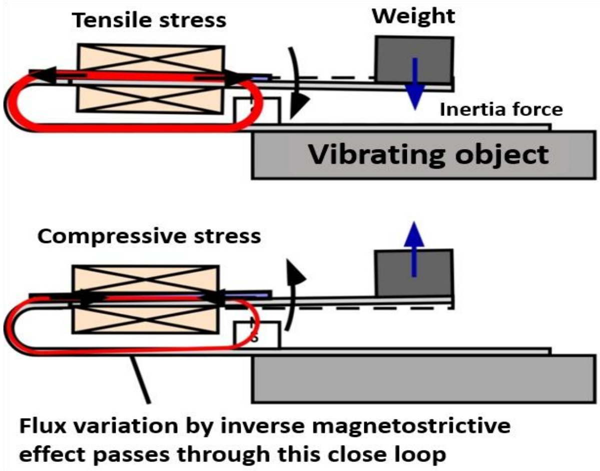


Figure 3. Principle of power generation: Inertial force downward (top) and upward (bottom)

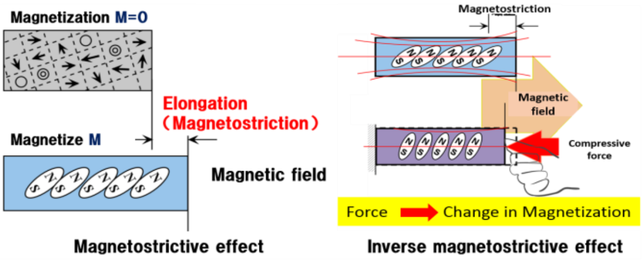


Figure 4. Inverse magnetostrictive effect

III. DESCRIPTION OF THE OBJECTIVE BRIDGE

The objective bridge of this study is a part of the elevated line of the expressway. As can be seen in Fig. 5 and Fig. 6, the 118m in length bridge is a composite bridge with a slab thickness of 220-mm, four main steel girders named G1, G2, G3, G4, and five bridge piers named P1, P2, P3, P4, and P5. The slab of the bridge has a constant width of 11.65-m with a slope percentage of 2% (Fig. 7) and a span length of about 29-m. Forty years on, the bridge is a part of the important route, which has a traffic volume of 27000 vehicles per day.

TABLE I. THE OBJECTIVE BRIDGE INFORMATION

		Note
Name	Kanazawa Highway Bridge	
Structure Type	Steel Girder Bridge with Concrete Slab	P1-P5 (Plan: P320-P324)
Length (Span's Length)	117.064m (29.094m+29.442m+29.440m+29.088m)	
Width	11.65m	
Slab Thickness	Concrete: 220mm; Asphalt: 75mm	
Traffic Volume	27000 vehicles per day	

Figure 5. The objective bridge

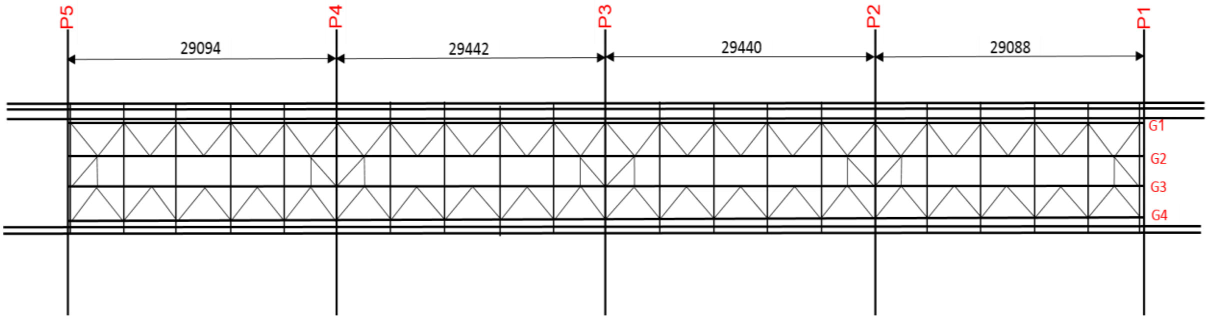


Figure 6. The objective bridge's plan

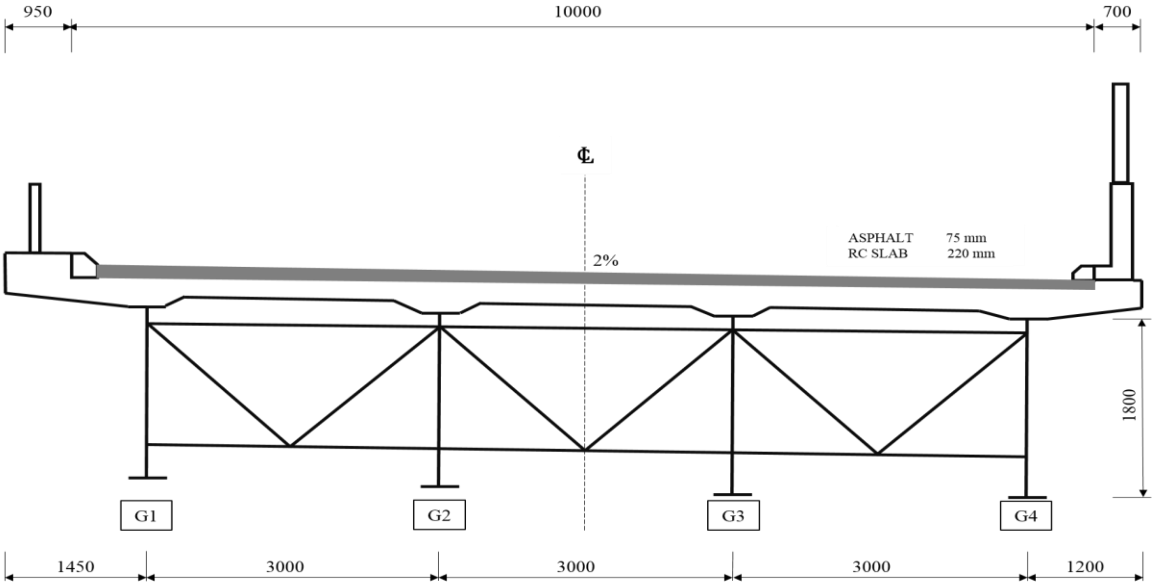


Figure 7. The objective bridge's plan

IV. NUMERICAL SIMULATION

The performance of the proposed device has been improved by calibrating the attached weight [4]. Besides, the device performance also depends on the vibration energy. Due to a large, complex structure of the objective bridge, which comprises many components, simulating this bridge to determine the highest vibration energy place is needful.

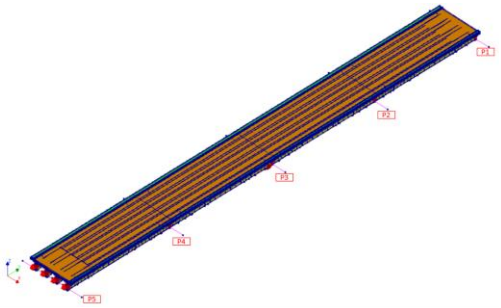


Figure 8. Three-dimensional (3D) analysis model

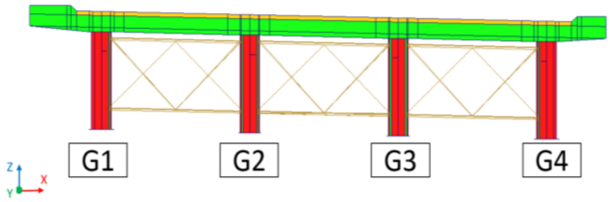


Figure 9. Three-dimension (3D) analysis model’s section

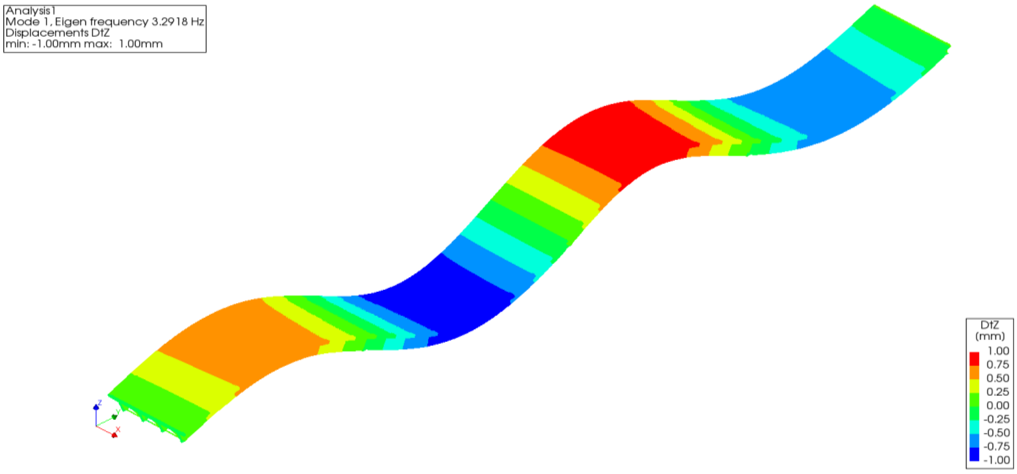


Figure 10. Bending mode 1 (3.29Hz)

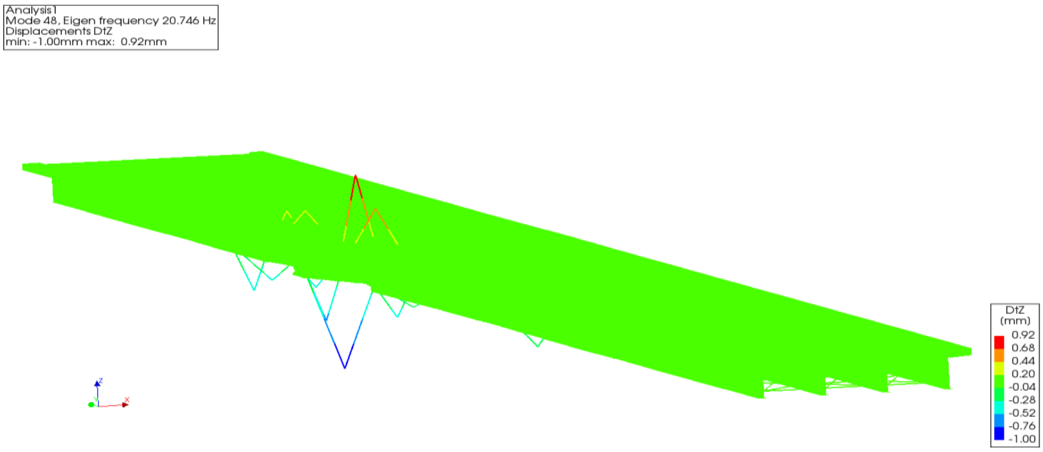
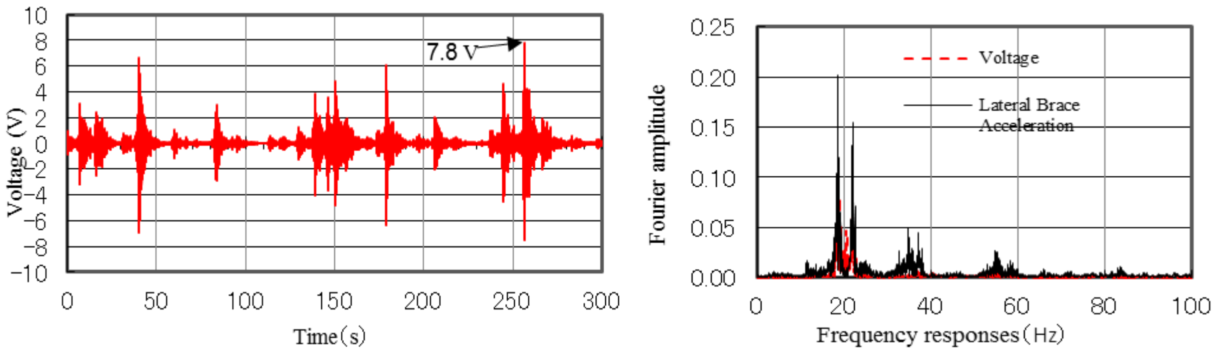


Figure 11. . The vibrations frequencies of the lateral braces between G1 and G2 at P2-P3 span – 20.746 Hz



(a) Generated voltage

(b) Frequency responses

Figure 12. Performance of the device at the optimal place

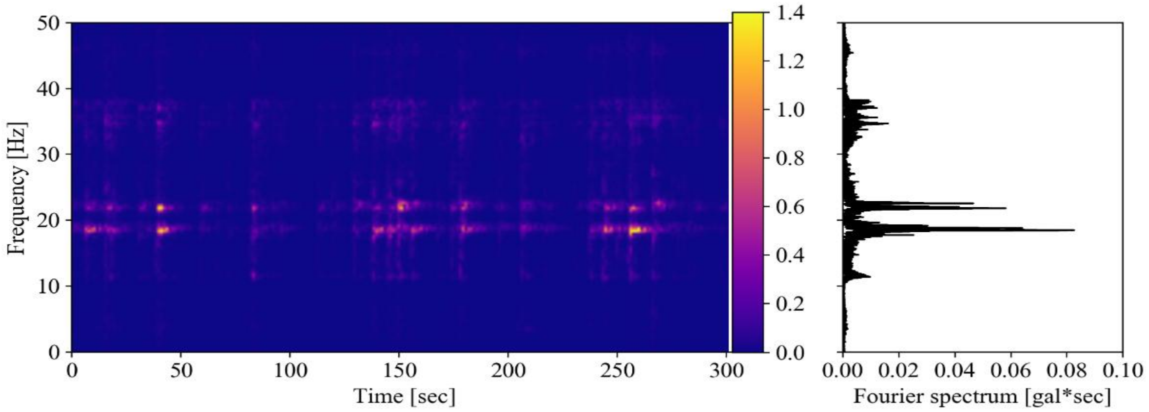


Figure 13. . Wavelet transform colormap of the frequency at the optimal place

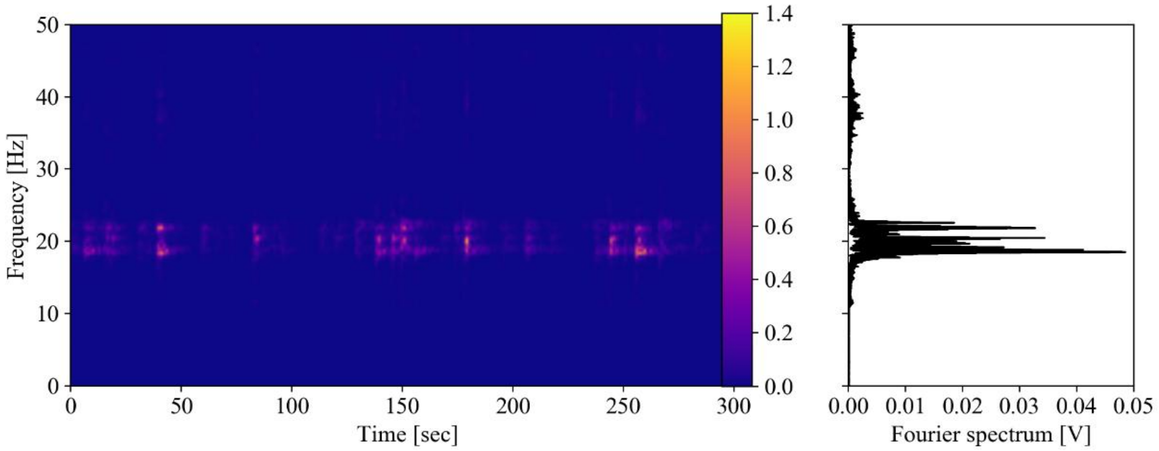
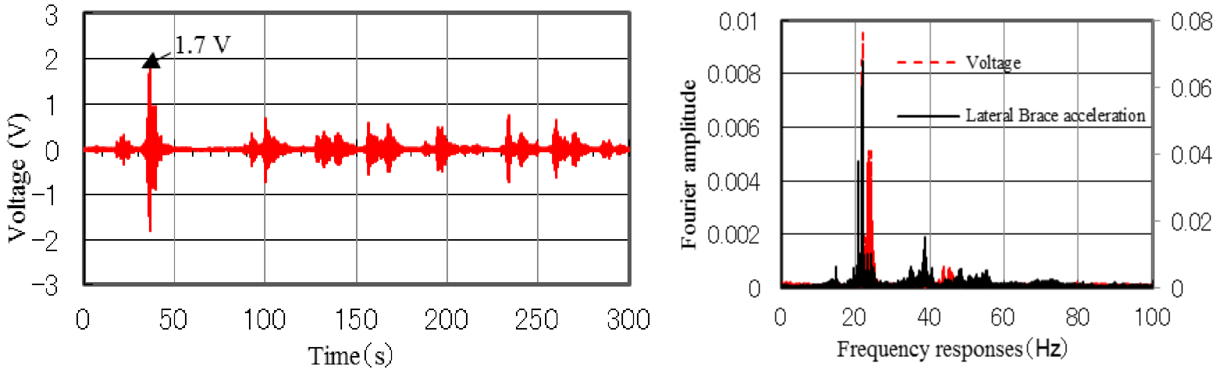


Figure 14. Wavelet transform colormap of the voltage at the optimal place



(a) Generated voltage

(b) Frequency responses

Figure 15. Performance of the device at the lateral brace near P1

To obtain a deep understanding of the variations in the vibration conditions of the objective bridge, numerical simulations were performed using the finite element method (FEM). As shown in Fig. 8, a three-dimensional (3D) numerical model was produced in accordance with the specifications of the construction drawing by using a finite element software named DIANA. As regards the element types used in the simulation, the girder was modeled as shell elements, the concrete and the asphalt were modeled as solid elements, while the sway and the lateral braces were modeled as beam elements. There is pin support at P3 pier and the others are roller supports. The bonding between the concrete and the reinforcement steel was assumed to be complete. Due to the main purpose is to obtain a deep understanding of the bridge's vibration conditions, the structural eigenvalue analysis is the suitable analysis method for this study. To facilitate simulation, several assumptions were simplified, such as the connection between the girders and the bracings, the mechanical properties of the materials and supports.

Regarding the material properties, steel materials were assumed to have the same Young's modulus E_s = 200000

N/mm2, the same Poisson's ratio υ = 0.3, and the yield stress depends on the thickness of the elements. The slab's concrete was defined by a property with Young's modulus of Ec = 30000 N/mm2 and the Poisson ratio υ = 0.167, while the similar specifications of the asphalt were E_a = 7000 N/mm2 and υ = 0.35.

V. COMPARISON BETWEEN SIMULATION RESULTS AND EXPERIMENTAL RESULT

The simulation result consists of the vibration frequency and mode shapes of the bridge. Besides, the vibration frequencies of some target elements are also investigated to calibrate the attached weight of the device at the laboratory. Then the accuracy of the simulation results was confirmed by the comparison with the experimental results.

Bending mode 1 of the bridge is shown in Fig. 10. The frequency of this mode is 3.29 Hz and the highest vibration amplitude was observed at the place between piers P2 and P3. The further from the fixed support at P3, the smaller the vibration amplitude. Similar outcomes were found with respect to the experimental results. In particular, the measured first bending mode ranged from 3.3 Hz to 3.8 Hz. In addition, the vibration frequency of the lateral brace between G1 and G2 at P2 – P3 span, where was predicted to be the optimal place for the vibration power-generating device, was defined by a value of 20.746 Hz (Fig. 11), while the field experiment's result was estimated to be ~19.7 Hz (Fig. 12). This result is used to calibrate the attached weight at the laboratory [4] [5].

Finally, the practical performance of the device was confirmed again by installing the energy harvester at the optimal place, i.e., the lateral braces between G1 and G2 near the P1 pier. As the result, at the optimal place, with an attached weight of 312.8g, the frequency of the frame's oscillation was estimated to be ~19 Hz and an open-circuit voltage of ~8 V was recorded by free damped vibrations under ordinary vehicle loads. The Colormaps of The wavelet transform of the frequency and the voltage at the optimal place are shown in Fig.13 and Fig.14. While at the lateral braces near the P1 pier, a voltage of ~1.7 V was recorded with the same conditions (Fig. 15).

There was a slight difference in the frequency between the numerical simulation results and the field experiment's result due to the relative contributions of the ordinary vehicle load and the environmental influence. However, these outcomes demonstrate that the lateral braces between G1 and G2 at P2 – P3 span is the appropriate place for the vibration power-generating device with the maximum voltage obtained as ~ 7.8 V, which was significantly higher than the voltage measured at the other places (~ 1.7V).

VI. CONCLUSIONS

This study proposed an optimal place in the actual highway bridge for a vibration power-generating device using a magnetostrictive element (Fe-Ga alloy) and test its practical performance. Furthermore, the numerical simulation by DIANA was performed to grasp a deeper understanding of the variations in the vibration conditions and the factors impacting the accuracy of the numerical simulation result. The remarkable conclusions in this study are as follows.

1) The installed position has a significant impact on the energy harvester device's performance.

2) At the proposed position, where is the lateral brace between G1 and G2 at P2 – P3 span, with a weight of 312.8g attached, an opened circuit voltage of ~7.8 V at an oscillation of ~19.7 Hz was generated by free damped vibrations under ordinary vehicle loads.

In the present study, the vibration energy harvester was verified to provide the maximum voltage of ~7.8 V at the frequency of ~ 19.7 Hz. This is a beginning for a simple novel vibrational power – generating device using magnetostrictive material for structural health monitoring systems, and further research is needed on the subject. About the long-term prospects, to obtain higher electrical energy, the design of the frame should be modified and improved, such as make a bigger device or change the material of the U-shaped frame. The electric current and the electric power also should be measured in order to design a power supply system used this device. Regarding the vibration simulation's model, the simulation's result was matched the experimental result, this is an important step forward for using this model in future research, such as a study on the structural behavior of the bridge. In addition, studying the environmental effects on the device's performance and the bridge's structures is also important to effectively apply the monitoring methods, modify the design, and to improve the simulation's result.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Hoang Minh Ngo Le and Saiji Fukada conducted the research; Hoang Minh Ngo Le and Tuan Minh Ha analyzed the data; Hoang Minh Ngo Le wrote the paper; Toshiyuki Ueno professor developed vibration generator device; all authors had approved the final version.

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Hoang Minh Ngo Le is a Master Student studied in School of Geosciences and Civil Engineering, Kanazawa University. His address is Kakuma-machi, Kanazawa City, Ishikawa Prefecture, Japan. And his Research Fields are Bridge Engineering, Bridge Vibration.

Tuan Minh Ha is Dr. Eng. in Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HUTECH). His address is Ho Chi Minh City, Vietnam. In 2014, he got bachelor degree of Civil engineering from Faculty of Civil Engineering, Ho Chi Minh City University of Technology. In October 2016, he obtained Master of Engineering from Graduate school of Natural Science and Technology, Kanazawa University, Japan. In March 2018, he got degree of Doctor of Engineering from Graduate school of Natural Science and Technology, Kanazawa University, Japan. In April 2018, he worked as Postdoctoral researcher in School of Geosciences and Civil Engineering, Kanazawa University, Japan
2019/07 Lecturer, Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HUTECH), Vietnam

Saiji Fukada is professor and Dr. Eng. in School of Geosciences and Civil Engineering, College of Science and Engineering Kanazawa University. His address is Kakuma-machi, Kanazawa City, Ishikawa, Japan. In 1999, he completed Doctor’s degree in Graduate School of Natural Science and Technology, Kanazawa University, Japan. And in 2017, he became the Professor of School of Environmental Design, Kanazawa University, Japan. His Academic Societies & Scientific Organizations include Japan Society of Civil Engineers (JSCE), Japan Concrete Institute (JCI)

Ueno Toshiyuki is associate professor and Dr. Eng. in School of Electrical, Information and Communication Engineering, College of Science and Engineering, Kanazawa University. His address is Kakuma-machi, Kanazawa city, Ishikawa, Japan. In 2001, he completed Doctor’s degree, Tohoku University, Japan. In 2017, he became the professor of Department of Civil Engineering, Kanazawa University, Japan. His Academic Societies & Scientific Organizations cover IEEE, The institute of electrical engineering of Japan, The magnetic society of Japan, The Japan Society of Applied Electromagnetics and Mechanics