ICWE 16
August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

Hybrid Energy Harvesting from Wind and Bridge Vibrations

Hai Dang Le [1], Soon Duck Kwon [1], Kincho H. Law [2]

[1]KOCED Wind Tunnel Center, Jeonbuk National University, Jeonju, Jeonbuk, South Korea,
sdkwon@jbnu.ac.kr
[2]Civil and Environmental Engineering, Stanford University, Stanford, CA, USA

SUMMARY:
This study aims to develop a hybrid energy harvesting device that can simultaneously scavenge electrical power from two different energy sources: natural wind flow and structural vibrations. The harvester has a cantilever structure in which the motion at the tip mass caused by wind flow and base excitation generates energy using an electromagnetic transduction mechanism. An analysis model is developed and simulation studies have been performed for feasibility evaluation. Validation tests have been conducted in a wind tunnel, with a vibration shaker, and on a bridge structure. A field test is being conducted at the Baekje Bridge in Korea to verify that the prototype hybrid energy harvester actually generates power from both low speed natural wind and traffic-induced ambient bridge vibration. The measured peak acceleration for a 20-minutes duration is about 0.38 m/s^2, and the average wind speed is 2.3 m/s. The generated peak and average power are respectively 15.9 mW and 0.4 mW. The simulation and validation test results confirmed that the hybrid energy harvester is able to transduce both low-speed natural wind flow and traffic-induced low frequency bridge vibration into usable energy.

Keywords: energy harvesting, galloping, bridge vibration.

1. INTRODUCTION

There have been many studies aimed to harvest energy from natural sources, such as wind and structural vibration, for powering electrical devices such as wireless sensors (Barrero-Gil. et al. 2010, Galchev et.al. 2011, Kwon et.al. 2013, Le and Kwon 2019). Most existing research deal with harvesting energy from a single energy using a single transduction mechanism. A hybrid harvester not only scavenges energy from multiple energy sources, but also converting energy into electrical power by means of multiple transduction mechanisms. Currently, most hybrid harvesters focus on applying multiple transduction mechanisms to general power from a single energy source. There has not been much active research on hybrid energy harvesting utilizing multiple energy sources. This study develops a hybrid electro-magnetic energy harvester that generates electrical power simultaneously from two readily available but distinct energy sources, namely low-speed natural wind flow and traffic-induced bridge vibration.

There are many constraints that hinder a harvester from continuously generating power from ambient natural energy sources. As a global average wind speed is typically around 3.28 m/s, a harvester needs to be able to generate power at a relatively low wind speed. Furthermore, since the fundamental frequencies of short or medium span bridges typically range from 2 to 8 Hz, a harvester needs to be able to generate power at low frequencies and low accelerations (less than 1 m/s^2). To satisfy these constraints, a cantilever structure is designed with an electromagnetic power generation mechanism. The cantilever structure is designed to vibrate significantly from aeroelastic instability even at a low wind speed. Furthermore, large oscillations occur for the cantilever structure from the dynamic excitation caused by traffic-induced bridge vibration (even when there is no wind). This paper discusses the design and analysis of the hybrid harvester and presents the simulation and experimental results obtained from wind tunnel tests, vibration shaker tests, and field tests on a bridge structure.

2. DEVICE CONFIGURATION AND ANALYSIS MODEL

Fig. 1(a) shows the schematic of the proposed hybrid energy harvester which consists of a bluff body with a tip (proof mass) prism, a metal plate, and an electromagnetic transducer. When encountering wind, the tip prism swings and gallops up and down because of wind-structure interaction. In addition, with the metal plate reacts to provide restoring force, the tip prism oscillates up and down due to base (support) excitation caused by bridge vibration. As the tip prism oscillates due to galloping or bridge vibration, the relative motion between the magnets (installed inside the tip prism) and the fixed coils generates the electrical power.

Fig. 1(b) shows the prototype device and the measurement system used in this study. The harvester and the transducers are assembled and housed as a single unit. The dimension of the tip prism is 110 mm long with a cross section of 25 mm × 25 mm. In the test set up, the wind speed is measured by a portable hotwire anemometer and the displacement of the tip prism is monitored by a laser displacement transducer. An accelerometer is used to measure the base acceleration brought on by a shaker or bridge vibration.

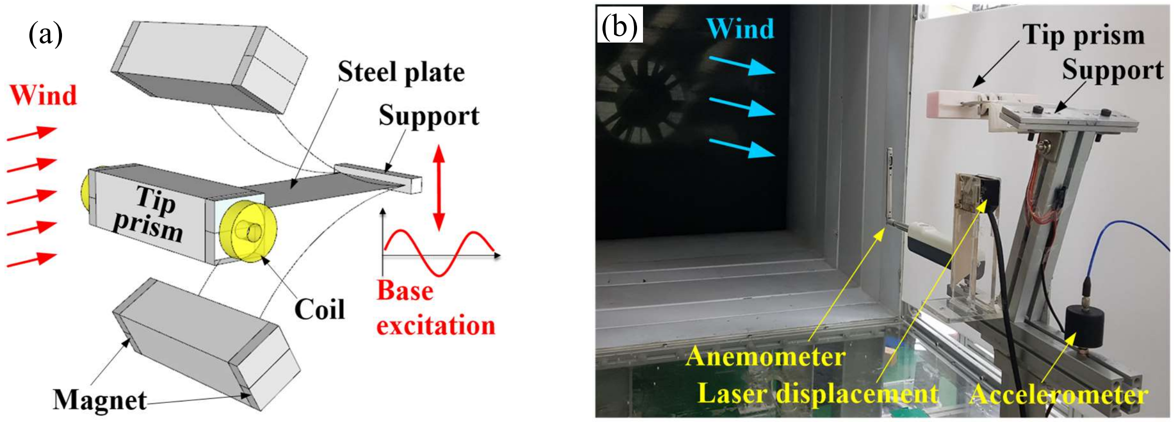

Figure 1. (a) Hybrid energy harvester, (b) prototype device and measurement system.

To model a single degree of freedom oscillator that is simultaneously subjected to forces from the crosswind, base excitation and electromagnetic field, the governing equations can be expressed as:

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F_{wind}(t) - \frac{\Phi}{R_L}V(t) - m\ddot{z}(t) \tag{1}$$

$$-\Phi(\mathrm{t})R_L\dot{y}(t) + L_C\dot{V}(t) + (R_L + R_C)V(t) = 0 \tag{2}$$

$$F_{wind}(t) = \frac{1}{2}\rho U^2 A\left[a_1\left(\frac{\dot{y}(t)}{U} - \frac{3y(t)}{2L}\right) + a_3\left(\frac{\dot{y}(t)}{U} - \frac{3y(t)}{2L}\right)^3\right] \tag{3}$$

In the coupled equations above, y denotes the tip displacement, $\ddot{z}$ is the base acceleration, m is the tip mass, k is the stiffness of the cantilever structure, V denotes the voltage, Φ is the electromechanical coupling coefficient, R_C is the coil resistance, R_L is the external load resistance, L_C is the inductance, U is wind speed, ρ is air density, A is frontal area of tip prism, L is the cantilever length, and a_1 and a_3 are empirical galloping coefficients associated with the shape of tip prism. The coupled governing equations are numerically solved in the simulation studies.

3. EXPERIMENTAL AND SIMULATION RESULTS

Fig. 2 shows the results of numerical simulations and experimental tests conducted to assess the performance of the hybrid harvester. It can be observed that, due to energy dissipation, the electrical load resistance affects the vibration amplitude and the galloping onset wind speed considerably. The cut-in wind speed gradually increases higher as load-resistance decreases. When galloping (and large displacement) is fully developed, more power can be harvested at a low external resistance. The additional electrical damping due to the low external resistance, however, increases the cut-in wind speed, and no electrical power can be harvested when the wind speed is too low. That is, there is a fundamental trade-off between electric power generation and cut-in wind speed that needs to be balanced.

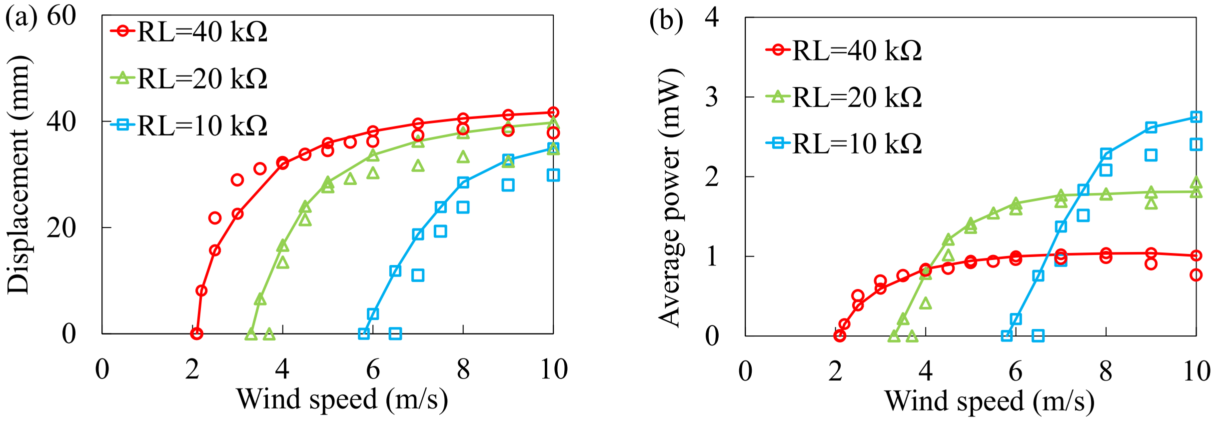

Figure 2. (a) Tip displacements and (b) average power according to wind velocity and external load resistance (measurements are shown with discrete symbols; simulated results are shown with lines connecting the symbols).

When load resistance gradually increases, the average voltage also increases but eventually converges to some constant value. On the other hand, as load resistance increases, the average power initially increases until reaching a maximum value and then decreases. The external load resistances at which the voltages converge equal to those that produce maximum powers. In other words, the optimal load resistance for achieving maximum power varies with wind speed.

4. FIELD TESTS ON BRIDGE STRUCTURE

To verify that the prototype hybrid energy harvester actually generates power from both low speed natural wind and traffic-induced ambient bridge vibration, a field test is being conducted at the Baekje Bridge in Jeonju, Jeonbuk, Korea, as shown in Fig. 3(a). The fundamental natural frequency of the four-span bridge is 2.73 Hz. The prototype device is installed on a guiderail at the midspan of the bridge. As shown in Fig. 3(b) and (c), the measured peak acceleration for a 20-minutes duration is about 0.38 m/s^2, and the average wind speed is 2.3 m/s. The generated peak and average power are respectively 15.9 mW and 0.4 mW. Although the results from the field test are generally lower than those from numerical simulations and laboratory tests, the ability of the hybrid harvester for generating electrical power from natural wind flow and traffic induced bridge vibration is sufficiently demonstrated.

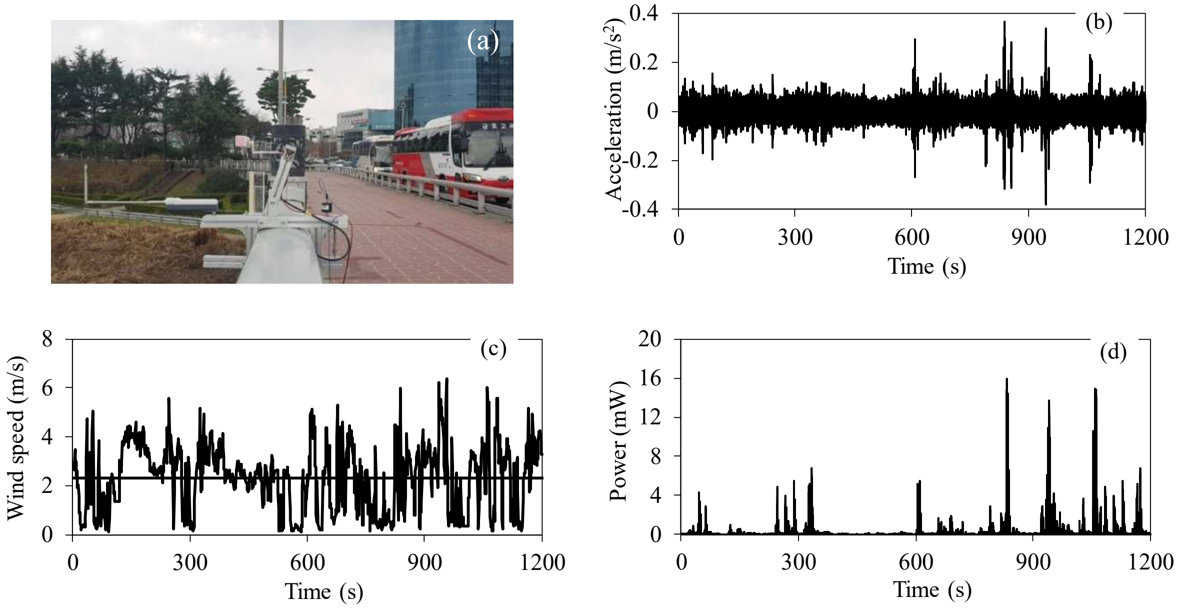

Figure 3. Field tests at Baekje Bridge, (a) prototype harvester installed at guardrail, (b) traffic induced bridge acceleration, (c) wind speed, (d) Power output.

5. SUMMARY AND CONCLUSION

This paper presents the design, fabrication and validation of a hybrid harvester for generating electrical power from both low speed natural wind flow and traffic-induced low frequency bridge vibrations. Numerical simulations have been conducted to show the feasibility of the prototype device. The prototype device has been validated in wind tunnel tests and shaker tests. Last but not least, the field test results have demonstrated the potential of the hybrid device in producing power from two different energy sources: wind and traffic-induced vibrations.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 2022B10200040). The research was also partially supported by the Stanford Center at the Incheon Global Campus (SCIGC), which is sponsored in part under the National Program to Subsidize Attracting Foreign Educational Institution and Research Institutes published by the Ministry of Trade, Industry, and Energy of the Republic of Korea and managed by the Incheon Free Economic Zone Authority.

REFERENCES

Galchev, T., McCullagh, J., Peterson, R. & Najafi, K., 2011. Harvesting traffic-induced vibrations for structural health monitoring of bridges. Journal of Micromechanics and Microengineering, 21, 104005.

Barrero-Gil, A., Alonso, G. & Sanz-Andres, A., 2010. Energy harvesting from transverse galloping. Journal of Sound and Vibration, 329(14).

Le, H.D. & Kwon, S.-D., 2019, An electromagnetic galloping energy harvester with double magnet design. Applied Physics Letters, 115, 133901.

Kwon, S.-D., Park, J. and Law, K.H., 2013. Electromagnetic energy harvester with repulsively stacked multilayer magnets for low frequency vibration. *Smart Materials and Structures,* 22(5).