Development of a tunable low-frequency vibration energy harvester and its application to a self-contained wireless fatigue crack detection sensor

Suyoung Yang1, Sung-Youb Jung2, Kiyoungh Kim1, Peipei Liu1, Sangmin Lee3, Jaeha Kim2 and Hoon Sohn1

Abstract
In this study, a tunable electromagnetic energy harvesting system, consisting of an energy harvester and energy harvesting circuits, is developed for harnessing energy from low-frequency vibration (below 10 Hz) of a bridge, and the harvesting system is integrated with a wireless fatigue crack detection sensor. The uniqueness of the proposed energy harvesting system includes that (1) the resonance frequencies of the proposed energy harvester can be readily tuned to the resonance frequencies of a host structure, (2) an improved energy harvesting efficiency compared to other electromagnetic energy harvesters is achieved in low-frequency and vibration, and (3) high-efficiency energy harvesting circuits for rectification are developed. Furthermore, the developed energy harvesting system is integrated with an on-site wireless sensor deployed on Yeongjong Grand Bridge in South Korea for online fatigue crack detection. To the best knowledge of the authors, this is the very first study where a series of low-frequency vibration energy harvesting, rectification, and battery charging processes are demonstrated under a real field condition. The field test conducted on Yeongjong Grand Bridge, where fatigue cracks have become of a great concern, shows that the proposed energy harvester can generate a peak voltage of 2.27 V and a root mean square voltage of 0.21 V from 0.18-m/s² root mean square acceleration at 3.05 Hz. It is estimated the proposed energy harvesting system can harness around 67.90 J for 3 weeks and an average power of 37.42 mW. The battery life of the wireless sensor is expected to extend from 1.5 to 2.2 years. The proposed energy harvesting circuits, composed of the AC–DC and boost-up converters, exhibit up to 50% battery charging efficiency when the voltage generated by the proposed energy harvester is 200 mV or higher. The proposed boost-up converter has a 100 times wider input power range than a conventional boost-up converter with a similar efficiency.

Keywords
Electromagnetic energy harvesting, low-frequency vibration, frequency tuning, energy harvesting circuits, wireless sensor, fatigue crack

Introduction
During the last few decades, wireless sensors have been widely used in various engineering fields,1–6 including structural health monitoring (SHM) of bridges.2,6 A number of wireless sensors have been deployed for SHM of real bridges, measuring a variety of physical quantities such as acceleration, wind speed, and strain.7–11

Despite the wide spread of wireless sensors and their adoption for SHM, powering wireless sensors is a very important issue and remains as a main concern. The majority of the off-the-shelf wireless sensors require batteries for power supply, limiting their application areas and lessening their advantage over wired sensors. As a rule of thumb, a 1-cm³ lithium battery used for a

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wireless sensor consuming 100-μW power can last less than 1 year. Furthermore, certain active sensors such as lead zirconate titanate (PZT)-based ultrasonic sensors have a much higher power demand (around 1 W) than conventional passive sensors such as strain gauges and accelerometers.

Solar, wind, and vibration energy harvesting techniques have been applied to bridge SHM. Solar cells are well studied and commercialized for bridge applications. For example, AM-5907 from Panasonic can generate a maximum power of 229 mW with 5 V. A few studies with wind energy harvesting have been reported, and their applicability to bridge SHM has been tested. Park et al. have developed a micro-wind turbine, and their energy harvester has produced a maximum power of 28.88 mW at 3.5 m/s wind speed. Note that damage such as fatigue crack often occurs at hidden and inaccessible locations inside a bridge structure, and solar and wind energy harvesters may not be suitable for such enclosed areas without light and wind.

Vibration energy harvesting can be an alternative option for such enclosed areas within a bridge structure, because traffic- and wind-induced vibrations always exist almost anywhere within bridge structures. One challenge is that bridge structures often vibrate at low frequencies, and their resonance frequencies are typically below 10 Hz. Although many vibration energy harvesting techniques have been proposed, it still remains as a daunting task to harness power at low-frequency ranges.

Table 1 summarizes electromagnetic energy harvesters developed for low-frequency vibration. Some of those harvesters have been tested under real bridge conditions, and around 5.02–2600 μW power was produced given 0.25–0.34 m/s² bridge vibrations at 2–3.7 Hz. However, those harvesters have only a single degree of freedom (DOF), and the resonance frequency of each energy harvester is tuned specifically to the resonance frequency of the bridge. Moreover, the previous studies mainly have focused on the harvester designs only, and little attention has been paid on the energy harvesting circuit. McCullagh et al. and Galchev et al. used a voltage multiplier circuit for AC–DC conversion and capacitor charging, but their maximum conversion efficiency was less than 30%.

This study develops an energy harvesting system consisting an energy harvester and energy harvesting circuits for harnessing energy from low-frequency vibration (below 10 Hz) of a bridge and demonstrates a series of low-frequency vibration energy harvesting, rectification, and battery charging processes on a real bridge structure. In particular, the developed energy harvesting system is integrated with a wireless fatigue crack detection sensor for real-time monitoring of a bridge structure.
The proposed energy harvesting system is unique in that (1) the resonance frequencies of the proposed energy harvester can be readily tuned to the resonance frequencies of a host structure, (2) an improved energy harvesting efficiency is achieved in low-frequency domains compared to other electromagnetic energy harvesters, (3) high-efficiency energy harvesting circuits for rectification are developed, and (4) the proposed energy harvesting system is integrated with a wireless sensor for online monitoring of a bridge structure.

This article is organized as follows. Section “Design of the proposed low-frequency vibration energy harvesting system” describes the design of the proposed energy harvester and the energy harvesting circuits. In section “Numerical validation of the proposed energy harvesting system,” the performances of the energy harvester and the harvesting circuits are numerically validated. Section “An overview of a wireless fatigue crack detection sensor” provides a brief overview of the stick-and-detect fatigue crack detection wireless sensor. Sections “Application to wireless fatigue crack detection sensors deployed on Yeongjong Grand Bridge” and “Application to Yeondae Bridge” present field validation tests conducted on Yeongjong Grand Bridge and Yeondae Bridge, respectively. Finally, the conclusion is provided in section “Conclusion.”

**Design of the proposed low-frequency vibration energy harvesting system**

**Design of the proposed energy harvester**

Figure 1(a) shows the overall configuration of the proposed electromagnetic energy harvester. The dimensions of the proposed energy harvester are $\Phi 50 \times 350 \, \text{mm}^3$, and it consists of a winding coil on a bobbin, a plastic circular casing, an aluminum guide, a metallic linear spring, a moving magnet, and two fixed magnets.

Top and bottom magnets constitute a nonlinear magnetic spring with respect to the moving magnet by placing the same poles of three magnets to face each other. The repulsion force between the moving magnet and the top and bottom magnets are inversely proportional to the square of the distance between them. When the moving magnet moves downward, the...
bottom magnet pushes the moving magnet upward. However, when the moving magnet travels upward, the top magnet drives it away. In this way, they act as a nonlinear spring, and the spring stiffness changes with the position of the moving magnet. The linear spring transfers bridge vibration into the energy harvester. Here, the velocity of the moving magnet is amplified when the stiffness of the linear spring and the total mass except the moving magnet and the linear spring satisfy a resonance condition. Based on Faraday’s law of induction, the amplified kinetic energy of the moving magnet is converted into electrical energy through the winding coil. Once the vibration frequency characteristic of a host structure is analyzed, two resonance frequencies of the proposed energy harvester can be tuned to the resonance frequencies of the structure by adding an additional mass to the casing and adjusting the distance of the bottom magnet with respect to the top magnet.

A stainless steel (STS304) spring having stiffness of 570 N/m is used as a linear spring, and its dimensions are \( \Phi 20 \times 25 \) mm\(^3\). Three ring-shaped neodymium magnets (NdFeB; N35 grade), constructing a nonlinear magnetic spring, have the same outer (40 mm) and inner diameters (7 mm). The height of the moving magnet is 25 mm, and the height of the top and bottom magnets are 10 mm. The mass of the moving magnet is 226.7 g. An aluminum guide is inserted into the center hole of the moving magnet so that the moving magnet can move along the guide. The winding coil is made by winding a copper wire (AWG40) on a bobbin with 1500 turns, and its size and internal impedance are \( \Phi 50 \times 15 \) mm\(^3\) and 580 ohm, respectively. Based on the numerical simulation of magnetic effects produced by the moving magnet, the optimal position of the winding coil is determined so that the center of the winding coil is aligned with the top edge of the moving magnet. All the magnets are protected by an acrylic plastic casing with low friction design. The cross section of the casing is designed as shown in Figure 1(a) to reduce the friction between the moving magnet and the casing. The thickness of the casing is 3 mm.

### Development of an equivalent 2-DOF spring-mass model

Figure 1(b) describes an equivalent 2-DOF spring-mass model of the proposed energy harvester. \( m_1 \) is the mass of the total system except the moving magnet and the linear spring, and \( m_2 \) is the mass of the moving magnet. The stiffness values of the linear and nonlinear magnetic springs are denoted as \( k_L \) and \( k_N \), respectively. \( c_1 \) is the parasitic damping coefficient of the linear spring, and \( c_2 \) is the summation of the parasitic damping coefficient of the nonlinear magnetic spring \( c_{2p} \) and the electric damping coefficient of the winding coil \( c_{2e} \). \( y_0 \), \( y_1 \), and \( y_2 \) are the displacements of a structure, the casing, and the moving magnet with respect to their initial equilibrium positions, respectively.

By the force equilibrium, the governing equation representing the displacements of the casing and the moving magnet can be expressed as

\[
M\ddot{y} + C\dot{y} + Ky = f
\]

where

\[
M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}, \quad K = \begin{bmatrix} k_L + k_N & -k_N \\ -k_N & k_N \end{bmatrix}, \quad f = \begin{bmatrix} c_1y_0 + k_Ly_0 \\ 0 \end{bmatrix}, \quad \text{and} \quad y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}.
\]

If \( y_0 \) is measured discretely with a time increment \( T \), then equation (1) can be represented in a discretized state-space form

\[
Y[k+1] = A_d Y[k] + B_d f[k]
\]

where \( k \) is the current time step, \( A = \begin{bmatrix} O & \mathbf{I} \\ -M^{-1}C & -M^{-1}K \end{bmatrix} \), \( B = \begin{bmatrix} O \\ -M^{-1} \end{bmatrix} \), \( Y = \begin{bmatrix} \dot{y} \\ y \end{bmatrix} \), \( A_d = e^{AT} \), and \( B_d = A^{-1}(A_d - \mathbf{I})B \begin{bmatrix} O \\ M^{-1} \end{bmatrix} \).

### Energy harvesting circuits design

**Overview of the proposed energy harvesting circuits.** Generally, an energy harvesting circuit for vibration energy harvesters has a two-stage rectification process. First, because the voltage generated by an electromagnetic energy harvester is AC voltage, an AC–DC converter is required to convert AC voltage to DC voltage. Second, a boost-up converter is necessary to increase the input DC voltage to the battery voltage so that the battery can be charged with the rectified energy.

Note that the voltage produced by the proposed energy harvester is typically less than \( \pm 1 \) V. The power generated by the proposed energy harvester continuously changes because the amplitude of bridge vibration changes all the time. Therefore, it is difficult to apply conventional energy harvesting circuits in this study due to the low voltage level produced by the proposed energy harvester and the continuous change of bridge vibration. To be more specific, a full bridge circuit or a voltage multiplier using passive diodes such as Schottky diodes is common solutions for AC–DC conversion. However, due to the forward bias of the passive diode (at least 0.2 V), more than 30% of the energy is lost during the AC–DC conversion. A boost-up converter is a switch mode DC–DC converter in which the output voltage is higher than the input voltage. Most of the
off-the-shelf boost-up converters have an internal oscillator with a fixed clock frequency. The oscillator turns the switch on/off whenever the oscillator gives a clock signal. The optimal input power range of a boost-up converter is determined by the clock frequency, and the conversion efficiency drops when the input power goes outside the range. Since the conventional boost-up converter has a single clock frequency, they cannot achieve high conversion efficiency with respect to changing inputs by the irregular bridge vibration.

In this study, high-performance two-stage energy harvesting circuits, composed of an active diode–based voltage doubler AC–DC converter and a boost-up converter having exponentially decreasing clock frequencies (800 kHz–100 Hz), are developed as shown in Figure 2(a). The proposed energy harvesting circuits exhibit up to 50% battery charging efficiency when the voltage generated by the proposed energy harvester is 200 mV or higher. To the best knowledge of the authors, this 50% efficiency is the best one compared to the existing energy harvesting circuits used for electromagnetic-based bridge vibration energy harvesters. The power consumption of the proposed energy harvesting circuits is less than 5 µW.

Voltage doubler AC–DC converter using active diode. Cheng et al. developed a simple voltage doubler circuit using two active diodes as shown in Figure 2(b). An active

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**Figure 2.** Schematics of the proposed energy harvesting circuits: (a) overview of the rectification process, (b) voltage doubler AC–DC converter, and (c) boost-up converter.
diode is composed of a voltage comparator and a metal-oxide-semiconductor field-effect transistor (MOSFET) switch (p-channel MOSFET (PMOS) or n-channel MOSFET (NMOS)). The voltage comparator (Texas Instruments, TLV3701) in an active diode $D_1$ compares its two input voltages (source and drain voltages of the PMOS) and turns on the PMOS switch only when the drain voltage is higher than the source voltage. On the contrary, the NMOS switch is turned on when the source voltage is higher than the drain voltage. When the input voltage from the proposed energy harvester is positive, only active diode $D_1$ with PMOS (Vishay, SI2329) is turned on, and capacitor $C_1$ (Kemet, T494B107M006AT; 100 $\mu$F and 6.3 V) is charged. Conversely, when the input voltage from the proposed harvester is negative, only active diode $D_2$ with NMOS (Vishay, SI2342) is turned on, and capacitor $C_2$ (Kemet, T494B107M006AT; 100 $\mu$F and 6.3 V) is charged. Therefore, the DC output voltage becomes twice of the input voltage.

Although the voltage comparator requires an external power supply from the battery, the active diode reduces the forward bias as low as 30 mV. Note that this forward bias of the active diode (30 mV) is significantly lower than that of the conventional passive diode (at least 0.2 V). Since the power supply voltage from a lithium iron phosphate battery (ENIX Energies, 18650) to the AC–DC converter is $\pm 3.2$ V, the input voltage to the AC–DC converter (or the output voltage from the harvester) cannot exceed $\pm 3.2$ V. When the battery is fully discharged, no power is supplied to the active diodes. Then, the diodes become passive diodes, increasing the forward bias to at least 0.2 V. Considering the operating current of voltage comparators (1.12 $\mu$A), the power consumption of the AC–DC converter is less than 4 $\mu$W.

**Boost-up converter.** Figure 2(c) shows the schematic diagram of the proposed boost-up converter, composed of a boost-up integrated circuit (IC), 10- and 2.22-M$\Omega$ resistors, and a 22-$\mu$H inductor. The IC compares the input voltage $V_{IN}$ (output voltage from the previous AC–DC converter) with the reference voltage $V_{REF}$ of 0.6 V whenever the oscillator inside of the IC gives a clock signal. Here, $V_{REF}$ is generated by dividing the battery voltage with two resistors in series connection.

The oscillator in the IC generates a clock signal with the clock frequency $f$. $f$ drops by half each time the clock signal is generated until $V_{IN}$ becomes higher than $V_{REF}$. Once $V_{IN}$ exceeds $V_{REF}$, the boost-up conversion is initiated. The MOSFET driver turns on the NMOS for a time period of $t_1$. Current flows to the ground through the inductor, and the inductor stores the energy in its magnetic field. When $V_{IN}$ becomes lower than $V_{REF}$, the MOSFET driver turns off the NMOS and turns on the PMOS for a time period of $t_2$.

Although the battery voltage is higher than $V_{IN}$, the energy stored in the inductor is transferred to the battery because an inductor has the characteristic of a current inertia. During the boost-up conversion ($t_1+t_2$), the clock signal is not generated. After the boost-up conversion is completed, $f$ is set back to 800 kHz and drops by half each time until the condition $V_{IN}>V_{REF}$ is met again. $t_1$ and $t_2$, the turn-on time of the NMOS and PMOS, depend on $V_{IN}$, $V_{BAT}$, and the internal resistance of the NMOS and PMOS. In this study, $t_1$ and $t_2$ are set to be around 5 and 1 $\mu$s, respectively.

The key idea for enhancing the efficiency for a wide input power range is to exponentially decrease the clock frequency. To achieve a high conversion efficiency, a low clock frequency (less than 10 kHz) is preferred for a low input power (less than 100 $\mu$W), while a high clock frequency (over 1 MHz) is needed for a high input power (over 1 mW). For the input power range (50 $\mu$W–3 mW) expected in this study, the IC first sets its clock frequency to the highest value (800 kHz) and drops its frequency by half each time the clock signal is generated to adaptively change the clock frequency.

There are many commercial boost-up converter chips for charging batteries. For example, BQ25504 from Texas Instruments operates for an input power range of 5 $\mu$W–25 mW with an input voltage of 0.5 V. Its efficiency to charge a 3.0 V battery varies from 40% to 85% depending on the input power. However, because the chip has the oscillator with a fixed clock frequency of 1 MHz, the chip can achieve an efficiency of 80% or higher only when the input power is confined from 1 mW to 10 mW. Note that this input power range (1 mW–10 mW) is only around 40% of the original input power range (5 $\mu$W to 25 mW). Therefore, to achieve a high conversion efficiency for a wider input power range, a boost-up IC developed in is used.

The prototype IC shows 80%–85% efficiency for the input power range of 0.5 $\mu$W–30 mW. Note that the input power range of the proposed IC is 100 times wider (twice wider in log-scale) compared to input power range of the conventional boost-up IC. Therefore, the proposed IC can charge the battery more effectively with a wider input power range. The total power consumption of the developed boost-up circuit is less than 1 $\mu$W, which can be further reduced by increasing the resistance values of the voltage dividing resistors.

**Numerical validation of the proposed energy harvesting system**

**Numerical validation of the proposed electromagnetic energy harvester**

To validate the power generation efficiency of the proposed energy harvester, a numerical simulation is...
Table 2. Parameter values used for numerical simulation of the proposed energy harvester.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$</td>
<td>2052.1 g (including 1.1 kg of additional mass)</td>
<td>$\zeta_1$</td>
<td>2.1%</td>
</tr>
<tr>
<td>$m_2$</td>
<td>226.7 g</td>
<td>$\zeta_{2p}$</td>
<td>10.3%</td>
</tr>
<tr>
<td>$k_L$</td>
<td>570 N/m</td>
<td>$\zeta_{2e}$</td>
<td>4.8%</td>
</tr>
</tbody>
</table>

performed according to the following steps. First, the initial condition $Y[0]$ is set to zero. $A_d[0]$ and $B_d[0]$ are computed using equation (2) to obtain $Y[1]$. Then, $k_N$ is updated based on the $Y[1]$, and $A_d[1]$ and $B_d[1]$ are constructed. This recursion is repeated until the end of the input bridge vibration.

Unlike a mechanical linear spring, the value of the nonlinear magnetic spring stiffness $k_N$ continuously changes depending on the position of the moving magnet. Hence, $k_N$ is expressed in terms of $dF_M/dy_2$, the slope of the force–displacement graph at a certain position $y_2$ from the equilibrium position. Here, $F_M$ is the force applied to the moving magnet, and this force is obtained by summing up the repulsion forces produced by the top and bottom magnets and the gravitational force.

When the relative displacement, $y_1 - y_2$, between the winding coil and the moving magnet is defined as $z$, the voltage generated from the winding coil, $v$, becomes

\[ v = Bl_\text{c} \dot{z} \]  

where $l_\text{c}$ is the total length of the winding coil affected by the magnetic field. $B$ is the magnetic flux density estimated by a Finite Element Method Magnetics software (FEMM 4.2).

The parameter values used for the numerical simulation of the proposed energy harvester are experimentally measured and summarized in Table 2. Damping ratio values are obtained by free vibration tests. Actual displacement from Yeondae Bridge was recorded with a sampling frequency of 100 Hz, and the recorded displacement was used as the input ($y_0$) for the numerical simulation. The displacement was obtained by a dynamic loading test, and the details of the bridge are presented in section “Application to Yeondae Bridge.”

The peak and average output voltages from the numerical simulation are 7.92 and 1.08 V, respectively. As shown in Figure 3, the output voltage from the numerical simulation is well matched with the power measured from the field test. Thus, the numerical simulation can be used for tuning the resonance frequencies of the proposed energy harvester to different bridge tests.

**Numerical validation of the proposed boost-up converter**

The boost-up converter including the IC, 10- and 2.22-MΩ resistors, and a 22-μH inductor is modeled using Synopsis HSPICE, which is one of the most popular IC analysis tools. The simulation result in Figure 4(a) shows the input voltage $V_{IN}$, the inductor current $I_L$, and the clock frequency $f$. The input power for the simulation is set to be 100 μW, which is the center value of the input power range (50 μW–3 mW) in a log-scale. The result shows that, whenever $V_{IN}$ becomes higher than the reference voltage of 0.6 V, the current from the previous AC–DC converter flows through the inductor to charge the battery. The oscillator oscillates with the highest clock frequency of 800 kHz whenever the MOSFET driver gives turn on/off signals to the MOSFET switches and then $f$ exponentially decreases after the boost-up conversion as depicted in the figure.

Figure 4(b) presents the measured input voltage $V_{IN}$, the inductor current $I_L$, and the clock frequency $f$ with an input power of 100 μW. Comparison of Figure 4(a) and (b) confirms the effectiveness of the numerical simulation to predict the performance of the developed boost-up converter.

**Figure 3. Comparison of the output voltages from the simulation (red solid line) and the field test (blue dashed line).**

**An overview of a wireless fatigue crack detection sensor**

Up to 90% of failures of in-service metallic structure are the result of fatigue cracks. Visual inspection and nondestructive testing (NDT) techniques such as ultrasonic, magnetic particle, X-ray, acoustic emission, and liquid penetrant testing are widely used for fatigue crack detection. However, these existing visual
inspection and NDT techniques are time-consuming, labor-intensive, harmful to inspectors, noise sensitive, and they can often detect a fatigue crack when a structure reaches about 80% of its fatigue life. Therefore, nonlinear ultrasonic techniques have been widely investigated to detect the onset of a micro crack (less than 100-μm crack width) in steel members. An active wireless sensor called stick-and-detect wireless sensor is developed by incorporating a nonlinear ultrasonic modulation based fatigue crack detection technique into a wireless sensor platform.

As shown in Figure 5(b), the stick-and-detect wireless sensor is composed of packaged PZT transducers, excitation/sensing module, data acquisition/processing core module, wireless communication module, and lithium iron phosphate battery. Each stick-and-detect wireless sensor contains the packaged PZT, composed of two excitation PZTs and one sensing PZT. Through the packaged PZT transducers, the excitation channels create two sinusoidal ultrasonic waves at two distinctive frequencies, and the ultrasonic waves cause crack opening and closing at fatigue cracks. Then, nonlinear ultrasonic modulation occurs at the sum and difference of input frequencies. The sensing channel captures the corresponding ultrasonic response. The data acquisition/processing core module manages the excitation/sensing module, and the captured ultrasonic response is stacked on a memory through a field programmable gate array (FPGA). A microcontroller, where a fatigue crack detection algorithm is implemented, carries out signal processing. The stick-and-detect wireless sensor can detect the presence of fatigue cracks in the circle with around 20-cm radius, and the details on the fatigue crack detection algorithm are explained in Liu et al. The wireless communication module constructs a wireless sensor network and transmits the fatigue crack detection diagnosis and the sensor identification. One lithium iron phosphate battery (ENIX Energies, 18650) having 3.2-V nominal voltage and 1500-mAh capacity supplies a stable power to the wireless sensor. The duty cycle of the stick-and-detect wireless sensor is set to 3 weeks so that the sensor module can wake up every 3 weeks for performing fatigue crack diagnosis and reduce the overall energy consumption. Table 3 summarizes specifications of the stick-and-detect wireless sensor. With this duty cycle, the sensor consumes 270.76 J for 3 weeks and 149.23 μW of power on average.

Application to wireless fatigue crack detection sensors deployed on Yeongjong Grand Bridge

Test setup

Yeongjong Grand Bridge links Yeongjong Island (Incheon International Airport) to South Korea mainland (Incheon), and it is the world first three-dimensional (3D) self-anchored suspension bridge maintained by New Airport Hiway Co. Its total length is 4420 m, and the length of the main span is 300 m. The bridge has a dual-deck structure, where the upper deck has six lanes for highway and the lower deck has

![Figure 4. Comparison of the simulation and laboratory test results for the developed boost-up circuit model: (a) simulation result and (b) laboratory test result.](image-url)
Figure 5. Stick-and-detect wireless sensor for fatigue crack detection: (a) prototype of stick-and-detect wireless sensor and (b) schematic of stick-and-detect wireless sensor.\textsuperscript{11}

Table 3. Specifications of stick-and-detect wireless sensor.

<table>
<thead>
<tr>
<th>Target structure</th>
<th>Steel members</th>
<th>Duty cycle</th>
<th>3 weeks</th>
</tr>
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<tbody>
<tr>
<td>Dimension</td>
<td>$85 \times 80 \times 36 \text{ mm}^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy/power consumption</td>
<td>$270.76 \text{ J} / 149.23 \mu\text{W}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>3.2 V lithium iron phosphate battery (1500 mAh)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Weight           | 160 g         |
| Maximum peak power | Around 1.2 W |
| Life expectancy  | Around 1.5 years |
The bridge was constructed in 2000. Incheon Airport Railroad Express (A’REX) started its operation in 2007, and the weight of the A’REX train is about 203 t. Korean Train Express also started passing Yeongjong Grand Bridge in 2014, and the weight of the KTX train is about 692 t, which is around 3.5 times heavier than the A’REX train. The passage of A’REX and KTX trains over Yeongjong Grand Bridge was not initially considered in the design stage, and these extra loadings have raised concerns for fatigue crack formation. Therefore, the aforementioned wireless sensor for fatigue crack detection was deployed on the bridge along with the proposed vibration energy harvesting system. The steel box girder located in the midpoint of the bridge was selected as the test point. The proposed energy harvester, a stick-and-detect wireless sensor, and an accelerometer were installed on the ceiling of the steel box girder as shown in Figure 6(c). Figure 7 describes the experimental test setup. An accelerometer (PCB Piezotronics, 3713B112G) measured the acceleration level of the test point. National Instruments (NI) USB 6366 device measures the acceleration level, voltage generated by the proposed energy harvester, and battery voltage. The current flow into or out of the battery is measured using Keithley 2000 digital multimeter.

**Test results**

The acceleration record measured by the accelerometer is displayed in the time and frequency domains in Figure 8(a) and (b), respectively. The root mean square (RMS) acceleration was 0.18 m/s², and the frequency content of the bridge vibration was mainly in the range of 2–6 Hz. The additional mass and the distance between the top and bottom magnets were set to 0.8 kg and 250 mm, respectively, in order to tune the resonance frequencies of the proposed energy harvester to the resonance frequencies of the bridge.

For a duration of 1000 s, the proposed energy harvester generated a peak voltage of 2.27 V and a RMS voltage of 0.21 V as shown in Figure 8(c). Without frequency tuning (additional mass: 1.0 kg, distance between the top and bottom magnets: 225 mm), the proposed energy harvester produced a peak voltage of 0.43 V, which is 80% less than the peak voltage achieved after frequency tuning.
The proposed energy harvesting circuits rectified the energy generated from the proposed energy harvester and charged the battery. A maximum current of 0.81 mA flowed into the battery increasing the battery voltage as shown in Figure 8(d). According to the past traffic records of Yeongjong Grand Bridge, it is estimated that the proposed energy harvesting system can harness around 67.90 J for 3 weeks and an average power of 37.42 mW. Although the harnessed energy is yet insufficient for a continuous operation of the stick-and-detect wireless sensor, the proposed energy harvesting system can supply power sufficient to operate other passive wireless sensors such as temperature and humidity sensors (less than 40 J energy consumption for 3 weeks). The battery life of the wireless fatigue crack detection sensor is expected to extend from 1.5 to 2.2 years when the proposed energy harvesting system is employed.

Application to Yeondae Bridge

To validate the performance of the proposed energy harvester, another field validation was performed on Yeondae Bridge as shown in Figure 9(a). Yeondae Bridge, located in Central Inland Highway, South Korea, is part of the two-lane test road constructed and maintained by Korea Expressway Co. The proposed energy harvester was attached at the midpoint of 45-m-long main span as shown in Figure 9(b). A 26 t truck ran over the bridge (Figure 9(b)) at 80 km/h speed to excite the proposed energy harvester, and a laser Doppler vibrometer (LDV) was used to measure the displacement of the bridge. The rest of the test configuration is identical to that of Yeongjong Grand Bridge test.

As describe in Figure 10(a) and (b), the peak displacement was 4.62 mm and the major bridge responses were within 2–4 Hz. The resonance frequencies of the proposed energy harvester were adjusted to cover the resonance frequencies of the bridge (additional mass: 1.1 kg, distance between the top and bottom magnets: 275 mm).

As shown in Figure 10(c), a peak voltage of 9.00 V and a RMS voltage of 1.41 V were induced by the proposed energy harvester after tuning, while only a peak voltage of 1.20 V and a RMS voltage of 0.17 V were induced without frequency tuning. To measure the power level generated by the proposed energy harvester, a 580-ohm resistor, which has the same impedance value as the winding coil, was connected to the proposed energy harvester. A peak power of 34.90 mW and an average power of 2.89 mW were produced as shown in Figure 10(d).

Conclusion

In this study, a new electromagnetic energy harvester with a high-efficient energy harvesting circuits is developed for harnessing energy from low-frequency (below
10 Hz) vibration of a bridge structure. A 2-DOF electromagnetic energy harvester with adjustable resonance frequencies is developed so that the resonance frequencies of the harvester can be tuned with the resonance frequencies of the host structure. Then, high-efficiency energy harvesting circuits for AC–DC conversion and boost-up conversion are developed specifically for the low input voltage (typically less than 1 V) and changing power generated by the proposed energy harvester. A series of low-frequency vibration energy harvesting, rectification and battery charging processes have been demonstrated through a field test at Yeongjong Grand Bridge. By adding an additional mass and adjusting the distance of the bottom magnet with respect to the top magnet, the resonance frequencies of the proposed energy harvester were tuned to the resonance frequencies of the bridge. The proposed energy harvester generated a peak voltage of 2.27 V and a RMS voltage of 0.21 V from 0.18-m/s² RMS acceleration at 3.05 Hz, and it is estimated that the proposed energy harvesting system can harness around 67.90 J. The battery life of the wireless fatigue crack detection sensor is expected to extend from 1.5 to 2.2 years. The proposed energy harvester generated a peak voltage of 9.00 V and a RMS voltage of 1.41 V from 0.21-m/s² RMS acceleration at 2.35 Hz. The proposed energy harvesting circuits exhibit up to 50% battery charging efficiency when the voltage generated by the proposed energy harvester is 200 mV or higher. The total power consumption is less than 5 mW. The proposed boost-up converter shows 80%–85% efficiency when the input power range from the AC–DC conversion is 0.5 μW–30 mW. Note that this input power range is a 100 times wider (twice wider in log-scale) than the input power range of the conventional boost-up converter with a similar efficiency.

Figure 9. Field test performed on Yeondae Bridge: (a) perspective view with the test point and (b) placement of the proposed energy harvester.

Figure 10. Field test results from Yeondae Bridge: (a) measured displacement in the time domain, (b) FFT of measured displacement in the frequency domain and the FRF of the proposed energy harvester with frequency tuning, (c) voltage generated from the proposed energy harvester, and (d) power generated from the proposed energy harvester.
Table 1 shows that the performance of the proposed energy harvesting system is comparable with or better than the performances of references found in the literature. The proposed energy harvesting system has a high power generation performance considering the acceleration level, frequency, and the size of the harvester. Two papers listed in Table 1 charged a capacitor using electromagnetic-based vibration energy harvesters, while this study charged a battery. It should be noted that charging a battery is more challenging than charging a capacitor because battery charging requires additional boost-up conversion. In addition, a capacitor is not best suited for continuous operation of wireless sensors because the capacitor has limited energy capacity and a fast discharge rate compared to the battery. To the best knowledge of the authors, this study is the very first study where a series of low-frequency vibration energy harvesting, rectification, and battery charging processes are demonstrated.

The main shortcoming of the proposed system is that the system malfunctions when the battery is fully discharged or the voltage generated from the harvester exceeds ±3.2 V. A future study is warranted to address this shortcoming and to improve a long-term reliability.

Declaration of conflicting interests

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