Self-sufficient and self-contained sensing for local monitoring of in-situ bridge structures

Hoon SOHN¹, Hyung Jin LIM¹, Ji-Min KIM¹, Suyoung YANG¹, Jun LEE¹, Yongtak KIM¹, Peipei LIU¹, Yujin JANG², Gun-Woo Moon³, Yung YI³, Daewoo KIM³, Jaeha KIM³, Sung-Youb JUNG⁴

¹ Department of Civil and Environmental Engineering, KAIST, Republic of Korea, hoonsohn@kaist.ac.kr, limhj87@gmail.com, jimin.kim@kaist.ac.kr, suyoung091@kaist.ac.kr, shins2aya@gmail.com, kkyt2002@kaist.ac.kr, peipeiliu@kaist.ac.kr

² Department of Future Vehicle, KAIST, Republic of Korea, yujinjang@kaist.ac.kr, gwmoon@kaist.ac.kr

³ Department of Electrical Engineering, KAIST, Republic of Korea, yiyung@kaist.ac.kr, dwkim@lanada.kaist.ac.kr

⁴ Department of Electrical and Computer Engineering, Seoul National University, Republic of Korea, jaeha@snu.ac.kr, syjung@mics.snu.ac.kr

Abstract

While conventional vibration-based monitoring provides an overall assessment of a bridge structure’s condition, it often fails in providing early warning for local damage. In this study, two separate sensor modules are developed for online tracking of post-tension (PT) tendon force loss and fatigue crack detection. An embeddable PT tendon force monitoring sensor, which periodically inspects the force level of the PT tendons inside a pre-stressed concrete (PSC) bridge, is developed based on eddy current measurement, and magnetic inductive coupling is used to transmit power and data between an external measurement system and the eddy current sensor embedded inside a PSC bridge. Next, a wireless fatigue crack detection sensor is developed to detect nonlinear ultrasonic modulation produced by a fatigue crack, and the sensor module is powered by a multi-mode energy harvester, which harnesses energy from sun light, low-frequency vibration and RF signals. Laboratory and field tests have demonstrated that the proposed techniques can detect a fatigue crack smaller than 100 μm in width and about 40% loss of the initial PT tendon force.

Keywords: Local monitoring, Fatigue crack detection, Post-tension cable monitoring.

1 INTRODUCTION

Bridge structures are susceptible to deterioration and damage during their service lifetime. PT tendon has been a widely-using structural member to assemble modularized and pre-fabricated modules for rapid and high quality bridge construction. As time passes, the initial tendon force is gradually lost, compromising structural safety. Also, crack is one of the primary culprits for the failure of metallic structures. It is estimated that up to 90 percent of failures of in-service metallic structure are the result of fatigue cracks [1]. While conventional vibration-based monitoring provides an overall assessment of a bridge structure’s condition, it often fails in providing early warning for local damage, which may lead to catastrophic failures.

The primary goal of this study is to develop self-sufficient and self-contained sensor nodes for PT tendon force and fatigue crack monitoring in bridge structures. The uniqueness of this study lies in that: (1) Online local monitoring of PT tendon force and fatigue crack, (2) Wireless power and data transmission through concrete using magnet inductive coupling, (3) Multi-mode energy harvester, which harnesses energy from sun light, low-frequency vibration and RF signals, (4) Validation through laboratory and field applications.
2 DEVELOPMENT OF POST-TENSION TENDON MONITORING SENSOR

This study proposes a PT tendon monitoring sensor which measures eddy current to estimate a material’s stress level [2]. The main assumption is that tendon force inside a PSC girder and compressive stress of the outer surface of a wedge are related [3]. According to the magneto-elastic effects [4], a magnetic permeability of a ferro-magnetic material is altered by its stress condition. Therefore, the stress variation resulted from PT tendon force alteration changes the intensity of the eddy current on the wedge surface, and this change is picked up by an eddy current sensor (ECS). The working principle of the proposed sensor is as follows (Fig. 1). First, ECS consisting of driving and sensing coils is mounted on the outer surface of the wedge. AC voltage is applied to the driving coil, and the primary magnetic field is generated inducing eddy current on the wedge surface. Then, the eddy current subsequently produces the secondary magnetic field, and the sensing coil picks up the variation of eddy current induced by PT tendon force alteration.

![Figure 1: Generation and measurement of eddy current using an Eddy Current Sensor (ECS) mounted on the wedge surface.](image)

The hardware design of the proposed PT tendon monitoring sensor is described in Fig. 2, comprised of (1) a DC-DC voltage converter, (2) a signal generator, (3) a data acquisition unit, (4) a data processing and storing unit, and (5) a data packet generator. The operating power and acquired monitoring data of the developed PT tendon monitoring sensor are transferred by a separated wireless power and data transfer (WPDT) module [5] consisting of (1) primary and secondary circuits and (2) transmitting (TX) and receiving (RX) coils.

![Figure 2: Configuration of PT tendon monitoring sensor and wireless power and data transmission modules.](image)

First, the primary circuit of the WPDT module generates AC power, and applies it to TX coil. TX and RX coils are inductively coupled, thus power is wirelessly transferred to RX coil through reinforced concrete. The transferred AC power is rectified in the secondary circuit, and changed to the operating voltage of PT tendon monitoring sensor through the DC-DC voltage converter. Then, the powered monitoring sensor starts monitoring. First, AC voltage signal is generated to excite the driving coil and induces eddy current on the wedge surface, and the eddy current is acquired through the sensing coil and the data acquisition unit. The acquired signal is stored in an embedded memory and processed using the embedded force
evaluation algorithm. The evaluated tendon force information is converted into 8 bits binary data packet, and transferred back to the primary circuit [5].

The embedded force evaluation algorithm owns two steps: (1) acquisition of reference responses under an initial tendon force level, and (2) an online tendon force monitoring through damage index (DI) calculation. In Eq. (1), DI is defined as RMSD (root-mean-square-deviation) between the obtained responses at unknown and reference (initial) conditions:

$$DI = \sqrt{\frac{\sum_{i=1}^{N}(R_i^{\text{unknown}} - R_i^{\text{reference}})^2}{N}}$$

where N is the total number of data points in the obtained responses. $R_i^{\text{unknown}}$ and $R_i^{\text{reference}}$ are the i th value of the responses in the sensing coil at unknown and reference tendon force conditions, respectively. As the tendon force is seriously altered from the reference condition, the DI value becomes larger and the sensor warns loss of the PT tendon force.

3 EXPERIMENTAL RESULTS OF PT TENDON MONITORING

3.1 Lab-scale testing of PT tendon force monitoring

Fig. 3(a) shows the experimental setup of the ECS system. A 3.3 m long and Φ 15.2 mm prestressing strand is inserted on a universal tensile machine (UTM), and a load cell and a hydraulic actuator are located at the right and left sides of the UTM, respectively. Baseline data is acquired at the initial tensile force level of 180 kN. Then, the tendon force is gradually decreased to 30 kN with an incremental value of 30 kN.

![Figure 3: Experimental setup of ECS system (a) universal tensile machine (UTM), (b) ECS attached to the wedge surface, and (c) DI variation at different tendon force levels.](image)

A coin-shape ECS is designed and manufactured using a copper wire of Φ 0.1 mm and Φ 0.08 mm for the driving and sensing coils. The inner and outer diameters of ECS are 17.2 mm and 26.5 mm, respectively. ECS is continuously stacked up until the electric resistances of the driving and sensing coils reach 20 Ω and 2.5 Ω, respectively. The manufactured ECS is attached to the surface of the wedge at the same side of the load cell, which is the sensing part of load in UTM, as shown in Fig. 3(b).

An arbitrary wave generator (AWG) generates a chirp signal with a bandwidth of 10 kHz to 1,000 kHz and a peak-to-peak voltage of 12 V. For measurement, data is collected for 0.1 second with a sampling rate of 4 MHz. Fig. 3 (c) shows the DI value calculated at each tendon force level through Eq. (1). As the tendon force is gradually relaxed, DI increases. The relationship between DI and tendon force turns out to be monotonic. Hence, ECS can be used to estimate the force relaxation from its initial condition.
3.2 Full-scale testing of PT tendon force monitoring

A full-scale test is performed to validate the proposed PT tendon force monitoring system. As shown in Fig. 4(a), 30 m long Pre-stressed Concrete girder (PSC), with 30 m long and Φ 15.2 mm pre-stressing tendons, is casted in POSCO Global Center (Incheon, Korea). In this test, tensile load is gradually increased with a step of 40 kN until it reaches 260 kN and then baseline data is acquired under maximum load at the end.

![Fig. 4](image)

Figure 4: PT tendon force loss monitoring experiment for 30 m long PSC (a) 30m PSC Girder, (b) Positions of installed ECS and (c) DI variation at different tendon force levels.

In this test, ECS is manufactured using copper wire by stacking up the coils until its electric resistance becomes 20 Ω and 2.5 Ω for drive and pick-up coils, respectively. Three ECSs are attached to the surface of the wedge at the side of the dead end which is the opposite side of jacking. Fig. 4(b) shows specific positions of attached ECSs.

Same as the lab-scale test, a chirp signal is generated with a bandwidth of 10 kHz to 1,000 kHz and a peak-to-peak voltage of 12 V. For measurement, data is collected for 0.1 second with a sampling rate of 4 MHz. The monitoring result in Fig. 4(c) is similar to the lab-scale test. Except the DI value under the fixed load, the relationship between the load and DI seems to be monotonic at all the ECSs.

3.3 Inductive coupling based wireless power and data transmission test

A wireless power and data transmission system is tested with a reinforced concrete with steel rebars. The spacing between the steel rebars is 150mm. The overall experimental setup is shown in Fig. 5(a). The resonators are designed with 10 turns and a diameter of 300mm. The values of the self-inductance and resistance are 42μH and 0.2Ω, respectively. The transmitter circuit for WPT has a half-bridge topology with series-series capacitor compensation. The receiver circuit consists of a resonator and a full-bridge rectifier and connects a load to the output, together with a load ON/OFF control switch (SL) for data transmission. When the WPT circuit is operated at a switching frequency corresponding to the resonant frequency, it achieves the maximum power transfer [5].
The measured power transmission results with different types of transmission medium are listed in Table 1. WPT efficiency of 43.6% at 300mm distance is obtained for type 3. The efficiency of type 3 is similar to that of type 2, which means the transmission medium has little influence on the WPT efficiency.

<table>
<thead>
<tr>
<th>Transfer distance</th>
<th>Air (type 1)</th>
<th>Concrete (type 2)</th>
<th>Concrete with data transfer circuit (type 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm</td>
<td>66.7</td>
<td>63.6</td>
<td>63.2</td>
</tr>
<tr>
<td>200 mm</td>
<td>60.1</td>
<td>57.7</td>
<td>57.2</td>
</tr>
<tr>
<td>300 mm</td>
<td>46.3</td>
<td>44.1</td>
<td>43.6</td>
</tr>
</tbody>
</table>

Table 1: Measured wireless power transmission efficiency for varying distance and different medium.

The data transmission experiment is performed on a concrete structure. The function generator in the receiver makes a sinusoidal signal at 1.5 kHz, which varies the load output voltage. Fig. 5(b) shows that data is transmitted from the receiver to the transmitter with a data rate of 1500bps. It is confirmed that data is transmitted from the receiver to the transmitter without distortion. The obtained results indicate that the proposed data transmission method using load variation is effective in delivering tendon force information through concrete structures. Also, the data transmission has almost no influence on the WPT efficiency.

4 DEVELOPMENT OF A WIRELESS FATIGUE CRACK DETECTION SENSOR

Recently, a large volume of research has been performed on nonlinear ultrasonic techniques, which look for nonlinear characteristics such as harmonics and modulations (spectral sidebands) created by fatigue cracks. The sensitivity of the nonlinear techniques to cracks has been shown to be far better than that of the linear ones [6].

Consider two sinusoidal waves a and b, where their frequencies are \( \omega_a \) and \( \omega_b \) \( (\omega_a < \omega_b) \). When these waves propagate through a nonlinear region of a plate-like structure (e.g. fatigue crack), the solution for the total particle displacement, \( \mathbf{u}_T \), can be written as the summation of the linear response, \( \mathbf{u}_L \), harmonics, \( \mathbf{u}_H \), and modulations \( \mathbf{u}_S \) by solving the Navier equation with nonlinear boundary conditions [7]:

\[
\mathbf{u}_T = \mathbf{u}_L + \mathbf{u}_H + \mathbf{u}_S \\
\mathbf{u}_L = \mathbf{u}_a e^{-i\omega_a t} + \mathbf{u}_b e^{-i\omega_b t} + \text{c. c.} , \\
\mathbf{u}_H = \mathbf{u}_{2a} e^{-i2\omega_a t} + \mathbf{u}_{2b} e^{-i2\omega_b t} + \text{c. c.} , \\
\mathbf{u}_S = \mathbf{u}_{b_{\pm a} e^{-i2(\omega_b \pm \omega_a) t}} + \text{c. c.}
\]

where c. c. is complex conjugate, \( \mathbf{u}_a \) and \( \mathbf{u}_b \) are the amplitudes of the linear waves at \( \omega_a \) and \( \omega_b \), \( \mathbf{u}_{2a} \) and \( \mathbf{u}_{2b} \) are the amplitudes of the nonlinear harmonics at \( 2\omega_a \) and \( 2\omega_b \), and \( \mathbf{u}_{b_{\pm a} (=}
is the amplitude of the first spectral sideband at due to the mutual interaction of the LF and HF signals.

This study develops a wireless fatigue crack detection sensor based on the aforementioned nonlinear ultrasonic technique. The wireless fatigue crack detection sensor is composed of four major components: excitation/sensing module, data acquisition/processing core module, wireless communication module and power supply module, as shown in Fig. 6. The excitation/sensing module consists of two excitation channels and a sensing channel and they are connected with a packaged piezoelectric transducers (PZTs). Excitation channels generate sinusoidal ultrasonic inputs at two different frequencies, and the sensing channel acquires the ultrasonic response. The data acquisition/processing core module owns a data logger, a memory and a microprocessor. The data logger receives the acquired response in real time and the response is saved on the memory. The microprocessor, where a fatigue crack detection algorithm is implemented on, controls the excitation/sensing module and conducts signal processing. The wireless communication module (Custom CC2538 module) takes charge of wireless network formation and wireless data transmission of the detection result. The power supply module consists of a rechargeable Lithium battery, multi-mode energy harvester and a wireless power transmission system. The Lithium battery provides stable power with the wireless sensor [8]. A multi-mode energy harvester, which harnesses energy from ambient sunlight [9], low-frequency vibration [10] and the RF signals, is used to charge the battery, as shown in Fig. 7.

The embedded crack detection algorithm is programmed according to the following steps:

**Step 1:** Both LF and HF inputs are applied simultaneously to the structure, and the corresponding ultrasonic response is measured. Then, only HF input are applied N times to get the ultrasonic noise responses at .

**Step 2:** Modulation and noise levels at each modulation frequencies are extracted using a modified Discrete Fourier Transform (DFT) and exponential distribution is fitted to the noise levels. Threshold values corresponding to a 99.9% confidence interval are calculated.
Step 3: The nonlinear index (NI) is calculated as:

\[ NI_{b \pm a} = u_{b \pm a} - T_{b \pm a} \]  

Step 4: Repeat Steps 1 to 3 over various frequency combinations.

Step 5: Calculate ‘Skewness’ and ‘Median’ of NI values. Here, ‘Skewness’ is the third standardized moment and defined as skew[NI] = \[E\left(\frac{NI - \mu}{\sigma}\right)^3\], where \(\mu\) and \(\sigma\) are the mean and standard variation, respectively. The presence of damage can be determined depending on the signs of ‘Skewness’ and ‘Median’ values. The ‘Skewness’ is effective in detecting a fatigue crack when the nonlinear modulation occurs at a limited number of frequency combinations among all the investigated frequency combinations. On the other hand, the ‘Median’ is useful when the nonlinear modulation occurs at the majority of the investigated frequency combinations. When both ‘Skewness’ and ‘Median’ are <0, the structure is determined to be intact, otherwise, damaged.

![Figure 7: Various energy harvesting strategies (a) Solar energy harvesting [9], (b) Vibration energy harvesting [10] and (c) RF-based wireless power transmission [11].](image)

5 EXPERIMENTAL RESULTS OF FATIGUE CRACK DETECTION

5.1 Lab-scale testing of fatigue crack detection

A test using two Aluminum dog-bone specimens validates the performance of the proposed wireless sensor. Through a cyclic loading test, a 15 mm long fatigue crack is introduced to one specimen on its center. An identical test is performed using a conventional wired system as presented in Fig. 8. For both the wireless sensor and the conventional wired system, HF and LF signals with a peak-to-peak 20 V amplitude are applied and their frequencies are swept from 185 kHz to 186 kHz and 40 kHz to 50 kHz (with 1 kHz increment), respectively. The ultrasonic response are measured with 1 MHz sampling rate for 0.25 sec and averaged 4 times in the time domain.

![Figure 8: Lab-scale test for fatigue crack detection (a) Wireless sensor and (b) Conventional wired system.](image)

In Fig. 9, the NI values from the intact and damaged specimens measured by the wireless sensor and the conventional wired system are derived from Eq. (3). It is demonstrated that the
wireless sensor detects the fatigue crack successfully. The discrepancy of the NI values from the sensor and the wired system is attributed mainly to the different hardware specifications.

![Image 1](image1.png)

![Image 2](image2.png)

Figure 9: Experimental results from (a) the sensor and intact specimen, (b) the sensor and damaged specimen, (c) the wired system and intact specimen, and (d) the wired system and damaged specimen.

### 5.2 Field application on Yeongjong Grand Bridge

Field applicability of the wireless sensor is tested by installing the developed sensors to Yeongjong Grand Bridge in South Korea. As presented in Fig. 10, two wireless sensor nodes are installed in the box girder at the west end of the suspension section where high stress concentration is expected due to high speed train passages. Additionally, three relay nodes are installed because the sensors are placed inside enclosed spaces. All the measurement parameters are identical to the lab test except that the frequencies of HF signal are set to 197 kHz and 198 kHz. And the robustness of the wireless sensor is validated by four independent tests. Each test is performed with a two-hour time interval. Though the skewness and medial values vary each time, all the values remain negative (Indication of ‘Intact’) as summarized in Table 2.

![Image 3](image3.png)

![Image 4](image4.png)

Figure 10: Deployment of the wireless sensors on Yeongjong Grand Bridge: (a) Cross section view, (b) Side view, (c) Wireless sensor locations in the box girder and (d) Wireless sensor installed on location B.
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Location A</th>
<th>Location B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Skewness</td>
<td>Median</td>
</tr>
<tr>
<td>1</td>
<td>-0.31</td>
<td>-0.13</td>
</tr>
<tr>
<td>2</td>
<td>-0.41</td>
<td>-0.49</td>
</tr>
<tr>
<td>3</td>
<td>-0.08</td>
<td>-0.09</td>
</tr>
<tr>
<td>4</td>
<td>-0.09</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

Table 2: Summary of the repeated field test results.

### 5.3 Field test for multi-mode energy harvesting

A solar panel (Sanyo AM-1816) is installed on the lower flange (outside box girder) at the west end of the suspension section as shown in Fig. 10(a) and Fig. 11(a). The light level at the test point is below 200 lux, and the temperature is around 2 °C. After rectification by the energy harvesting circuit, the solar panel charges the Lithium battery at an average power of 897.27 μW. Based on daylight hour record near Yeongjong Grand Bridge [12], the solar energy harvesting is expected to gather over 470 J energy for 3 weeks and this value is higher than the energy requirement of the wireless sensor (398.22 J for 3 weeks).

An electromagnetic vibration energy harvester is tested in Yeondae Bridge, South Korea. As presented in Fig. 11(b), the energy harvester is suspended from the bottom part of the box girder and excited by a 26 ton truck with 90 km/h speed. The energy harvester generates 1.33 mW power for 20 sec, and the accumulated energy for 3 weeks is around 80 J based on the traffic statistics [13] assuming 70% rectification efficiency.

An RF-based wireless power transmission device is also tested in the same bridge. Fig. 11(c) shows the experimental setup in the steel box girder. The target signal band is 915 MHz, and the power at Tx is amplified to 10 W. After the conversion to DC by the energy harvesting module, average power of 60 mW is attained at 50 cm distance. The test reveals that the RF-based wireless power transmission device is able to charge 398.22 J in 106 minutes [11].

### 6 CONCLUSIONS

This study develops two separate sensor modules for online tracking of PT tendon force loss and fatigue crack detection. Laboratory and field tests have demonstrated that the proposed sensor modules can detect a fatigue crack smaller than 100 um in width and about 40% loss of the initial PT tendon force. A follow-up study will focus on sensor node optimization and permanent installation of these two developed sensor modules to field structures.
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