Development and Application of a Low-cost Automated Wireless Tension Estimation System for Cable Structures

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ABSTRACT: A low-cost and automated wireless tension force estimation system (WTFES) for bridge cables is developed in this study. The developed system is composed of a low-cost wireless-based hardware platform including wireless sensing units, MEMS accelerometers, and specially designed signal conditioning circuits. Automated software is embedded into the wireless sensor to estimate cable tension force using a renovated modern vibration method in conjunction with a peak-picking algorithm for natural frequencies. A series of laboratory experiments on a scaled down version of a cable on a cable-stayed bridge were conducted to check out the feasibility of the developed WTFES for various sensing locations, cable tension forces and sags. The present system is going to be validated further through a US-Korea collaboration project on bridge health monitoring test bed for a cable-stayed bridge in Korea.

1 INTRODUCTION

Cable tension force is one of the most important structural parameters for structural health monitoring (SHM) of cable-supported bridges during construction and operation. The current measurement methods for cable tension force can be classified into two categories: static- (or direct) and vibration-based (or indirect) methods. Static methods directly measure the tension force of a cable using a load cell or hydraulic pressure-meter installed at the end of a cable, while vibration methods estimate tension based on the natural frequencies and the geometrical parameters of the cable. The vibration method is the most widely used due to its practicality and cost-effectiveness. It uses accelerometers mounted to the surface of the cable to capture the natural frequencies and the tension forces, thereafter. The vibration method is based on flat taut string theory (Irvine, 1981). However, taut string theory alone does not consider both bending stiffness and sag so that the application of the method may be limited to flat slender cables. To consider the bending stiffness of a cable, axially loaded beam theory was utilized to describe the relationship between the tension force and natural frequencies of a cable in practice (Kim & Park, 2007). Given the measured frequencies and the mode numbers, linear regression procedures were applied to identify the unknown tension force and the cable’s flexural rigidity simultaneously. This approach has been widely used by field engineers because of its simplicity and speediness. The solution for an inclined cable was derived by Triantafyllou (1984) with sag-extensibility considered in the solution. Finally, methods that include consideration of both sag and bending stiffness have been developed by several researchers with many of them proven to be accurate for most types of cables (Zui et al., 1996, Mehrabi & Tabatabai, 1998, Kim & Park, 2007).

Though the vibration method is practical and cost-effective, there is still an economic hurdle in realizing monitoring systems for cables on many bridges. The cost of the system components, such as sensors and data acquisition system is quite high (e.g., PCB 481A03 signal conditioner: $10000). In addition, the costs associated with the installation of extensive runs of coaxial cables between the sensors and the data acquisition system is prohibitive when considering installation on a long-span. Furthermore, the intense labor and time needed for installation of the monitoring system cables hinders the possibility of permanent and temporary SHM systems on large structures, especially for structures under construction.

To overcome this significant hurdle, there has been increasing interest in wireless sensor technologies within in the civil engineering field. Wireless sensors, which are one of the emerging “smart sensor” types, are now considered as a viable substitute for tethered sensors. When dealing with a large number of sensors for a civil structure’s SHM system, wireless communication between sensors and data repositories is very attractive in terms of the
system cost. Besides the economical benefit, wireless sensors can accommodate a computational capability which can infer some important information from measured data. This “smart” functionality is realized by employing a microcontroller which can execute embedded algorithms to interrogate data collected from attached sensors. Straser and Kiremidjian (1998) first proposed the design of a wireless monitoring system for civil structures by integrating wireless radios with sensors while Lynch et al. (2001) have proposed an improved wireless sensor prototype that emphasizes the design of a powerful computational core. The wireless sensor prototype has been continuously improved by Lynch’s group including the inclusion of the newest commercial off-the-shelf components and the embedding of various popular algorithms, such as the fast Fourier transform (FFT), the Yule-Walker method to determining autoregressive (AR) time series models, and the random decrement (RD) modal method (Lynch et al., 2003, Wang et al., 2005, Lynch, 2007, Zimmerman et al., 2008). Besides these academic wireless sensor prototypes, a number of commercial wireless sensor platforms have also been developed for SHM applications in recent years. The Mote wireless sensor platform which was initially developed at the University of California-Berkeley and subsequently commercialized by Crossbow (Crossbow, 2008), may be the most famous of the commercialized platforms. Today, the iMote2 developed by Intel and commercially produced from Crossbow, is the most advanced Mote sensor. Spencer’s group, which is one of the leading academic groups using the iMote2 platform, has illustrated its use for the decentralized SHM of civil structures (Spencer et al., 2004, Nagayama et al., 2006, Spencer et al., 2008). Interested readers are referred to the summary reviews by Spencer et al. (2004) and Lynch & Loh (2006) for a more complete review of the state-of-the-art in the wireless SHM field.

The work presented in this study builds upon prior research to create a low-cost automated wireless tension force estimation system (WTFES) for cable structures. Towards this end, a modern vibration method previously used for tension estimation is embedded into the computational core of a wireless sensor for autonomous execution. The low-cost hardware is composed of a wireless sensing unit, a MEMS accelerometer, and a signal conditioning circuit. The wireless sensing unit was developed by Wang et al. (2005) and employs a 16-bit multi-channel analog digital converter (ADC), an 8-bit microcontroller, 128kB random access memory (RAM), and a 900MHz wireless transceiver with a whip antenna. The MEMS accelerometer is interfaced with a signal conditioning circuit to measure, amplify, and anti-alias filter the sensor output (acceleration) prior to interfacing to the wireless sensor. For the automated software, a modern vibration method which considers the sag condition of a cable is embedded into the microcontroller to estimate tension force using the natural frequencies of the cable. To extract the natural frequencies without human intervention, a peak picking algorithm is proposed considering typical properties of the Fourier spectrum of a vibrating cable. To validate the proposed WTFES, a laboratory experiment which tests a scaled down version of a cable on a cable-stayed bridge was conducted. A series of forced vibration tests are executed to investigate the feasibility of the system for various sensing locations, cable tension forces, and sags.

2 WIRELESS TENSION FORCE ESTIMATION SYSTEM

2.1 Low-cost hardware platform of WTFES

2.1.1 Wireless sensing unit

The wireless sensing unit used in this study was developed by Wang et al. (2005). It is constructed using commercial off-the-shelf embedded system components. For the data acquisition of analog signals from sensors, a 4-channel analog-to-digital converter (ADC) (Texas Instruments ADS8341) is employed in the design of the unit. It has a resolution of 16-bits and is capable of sampling as high as 100 kHz, which is a convenient specification for capturing high-frequency-small amplitude vibrations. The wireless sensor’s ADC is connected to and controlled by the embedded 8-bit microcontroller (Atmel ATMega128). The microcontroller has its own 128kB flash memory to contain software which can be easily embedded using an In System Programmable (ISP) interface without requiring an expensive ROM writer. Since the ATmega128 contains only 4kB of RAM to store sensor data, an additional 128kB of RAM is employed to store measured and processed data. After measuring a set of data, it is transmitted to the data repository by the wireless transceiver (Maxstream 9XCite). The wireless transceiver consists of a 900 MHz radio with corresponding whip antenna. An attractive feature of this radio is that it can communicate up to 300 m line-of-sight with an over-the-air data rate of 38.4 Kbps. Reliability is provided through the use of frequency hopping spread spectrum encoding. The unit is fully assembled in a shock-proof hardened container along with a 5 AA lithium battery (7.5V) power supply. The wireless sensing unit prototype is shown in Figure 1 with individual components highlighted.
2.1.2 MEMS type accelerometer and signal conditioning circuit

In this study, a commercial microelectromechanical system (MEMS) accelerometer (Crossbow CXL02LF1) is used to measure the cable vibration at low cost (the accelerometer is roughly $250 per device). The accelerometer is selected for its high sensitivity of 1000mV/g and low noise level of 1mg \textit{rms}; its specification is described in Table 1. Since a tensioned cable is characterized by low natural frequencies due to its long and slender geometry, this accelerometer is well suited for this study.

The ADC of the wireless sensing unit is capable of reading the voltage signal within the range of 0 to 5V with its 16-bit resolution able to discriminate voltage signals greater than 7.63 x 10^{-5}V. Since the MEMS accelerometer also measures DC acceleration (e.g., orientation with respect to gravity), placement of the sensor on an inclined cable will shift its zero-mean output to something other than the 2.5 V output typical for zero-g conditions.

To shift the mean and to amplify the low-amplitude output of the inclined accelerometer, an external signal conditioning circuit developed by Lynch \textit{et al.} (2006) is adopted (Figure 2). The circuit has three primary tasks: 1) shifting the apparent zero-g output to 2.5 V, 2) amplifying sensor outputs, and 3) anti-alias filtering. The signal conditioning circuit is designed using discrete analog circuit elements and ordinary operational (OP) amplifiers. By adopting a three-way switch, three amplification factors are provided to the user: 5, 10 and 20. Furthermore, a 25 Hz anti-alias filter is included in the circuit design. The circuit has been validated during several field applications (Zimmerman \textit{et al.}, 2008, Lynch \textit{et al.}, 2006).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>± 2 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1000 mV/g</td>
</tr>
<tr>
<td>Noise level</td>
<td>1.0 mg \textit{rms}</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>DC to 50 Hz</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>5 V</td>
</tr>
<tr>
<td>Zero g output</td>
<td>2.5 V</td>
</tr>
</tbody>
</table>

Table 1. Specification of Crossbow CXL02LF1

2.2 Automated software of WTFES

2.2.1 Natural frequency estimation from ambient vibration

The embedded application software for the wireless sensing unit is written in a modular fashion. Many kinds of computational modules including the fast Fourier transform (FFT), auto-regressive (AR) and auto-regressive with exogenous input (ARX) time series models (Lynch \textit{et al.}, 2003), random decrement method, and centralized/decentralized frequency domain decomposition (FDD) method (Zimmerman \textit{et al.}, 2008) have all been previously developed and embedded in the wireless sensor. In this study, the embedded FFT module, which is capable of manipulating 4096 time-history data points to compute the Fourier spectrum of acceleration time histories is utilized for the identification of cable frequencies.

Generally, a select number of lower natural frequencies are required to estimate the tension force in a cable using modern vibration methods (Zui \textit{et al.}, 1996). In this study, an automated peak picking algorithm is proposed to obtain the natural frequencies from the Fourier spectrum without human intervention. It is motivated from the following unique features of cable vibrations: 1) the Fourier spectrum of a vibrating cable shows very sharp peaks at the cable’s natural frequencies due to low damping, and 2) the \textit{n}-th natural frequency (\textit{f}_\textit{n}) of a cable is about \textit{n} times that of the first natural frequency (\textit{f}_1) based on taut string theory. A threshold value to find the peaks for the natural frequencies is taken as 2 times the square root of the average power of the Fourier spectrum. The automated procedure for the natural frequency estimation is summarized as:

1. For \textit{f}_1: The initial estimate (\textit{f}_1') is taken from the first peak greater than the threshold value. Then it
is updated as the frequency of the largest peak in the frequency range of \( f_{1} \rightarrow 1.8 f_{1} \). The same procedure is consecutively taken on the updated \( f_{1} \), till no larger peak is found in the updated frequency range.

(2) For \( f_{n} (n>1) \): A similar peak searching procedure is taken for \( f_{n} \) in a frequency range of \((f_{n-1}+0.8f_{n}) - (f_{n-1}+1.6f_{n})\). In this study the frequency searching is carried out up to the third natural frequency \( f_{3} \).

### 2.2.2 Tension estimation from natural frequencies

Among the several algorithms available for cable tension force, \( T \), estimation considering sag and bending stiffness of the cable, a method proposed by Zui et al. (1996) is utilized in this study. It consists of 7 formulas for different cases of cable properties:

**CASE 1** - small sag \(( \Gamma \geq 3 \)\): Using \( f_{1} \)

\[
T = \frac{4w}{g} \left( f_{1} \right)^{2} \left[ 1 - 2.20 \frac{C}{f_{1}} - 0.550 \left( \frac{C}{f_{1}} \right)^{2} \right], \quad 17 \leq \xi \quad (1-a)
\]

\[
T = \frac{4w}{g} \left( f_{1} \right)^{2} \left[ 0.865 - 11.6 \left( \frac{C}{f_{1}} \right)^{2} \right], \quad 6 \leq \xi \leq 17 \quad (1-b)
\]

\[
T = \frac{4w}{g} \left( f_{1} \right)^{2} \left[ 0.828 - 10.5 \left( \frac{C}{f_{1}} \right)^{2} \right], \quad 0 \leq \xi \leq 6 \quad (1-c)
\]

**CASE 2** - large sag \(( \Gamma \leq 3 \)\): Using \( f_{2} \)

\[
T = \frac{w}{g} \left( f_{2} \right)^{2} \left[ 1 - 4.40 \frac{C}{f_{2}} - 1.10 \left( \frac{C}{f_{2}} \right)^{2} \right], \quad 60 \leq \xi \quad (2-a)
\]

\[
T = \frac{w}{g} \left( f_{2} \right)^{2} \left[ 1.03 - 6.33 \frac{C}{f_{2}} - 1.58 \left( \frac{C}{f_{2}} \right)^{2} \right], \quad 17 \leq \xi \leq 60 \quad (2-b)
\]

\[
T = \frac{w}{g} \left( f_{2} \right)^{2} \left[ 0.882 - 85.0 \left( \frac{C}{f_{2}} \right)^{2} \right], \quad 0 \leq \xi \leq 17 \quad (2-c)
\]

**CASE 3** - very long cables: Using \( f_{n} \) \((2 \leq n)\)

\[
T = \frac{4w}{n^{2}g} \left( f_{n} \right)^{2} \left[ 1 - 2.20 \frac{nC}{f_{n}} \right], \quad 200 \leq \xi \quad (3)
\]

where \( f_{1}, f_{2}, \) and \( f_{n} \) are the 1st, 2nd, and \( n \)th natural frequencies measured, respectively; \( \xi = \sqrt{\Gamma/El} \); \( \Gamma = \sqrt{wl/128EA\delta^{2} \cos \theta(0.31\xi + 0.5)/(0.31\xi - 0.5)} \); \( w \) = weight per unit length; \( C = \sqrt{El/wl^{3}} \); \( EA \) = extensional rigidity; \( EI \) = flexural rigidity; \( \delta \) = sag-to-span ratio \( (= s/l_{0}) \); and \( \theta \) = inclination angle as shown in Figure 3.

It is important to note that two parameters \( \Gamma \) and \( \xi \) are needed at the outset to select the appropriate formula for tension estimation. In general, \( \Gamma \) and \( \xi \) may be initially taken based on the design tension value. Then they are revised based on concurrently identifying tension force until convergence in \( T \), \( \Gamma \) and \( \xi \) is achieved. As discussed in the following section, it has been found that only few iterations are needed (with many instances requiring no additional iteration) to properly select the formula to identify the cable tension value. The formulas require only a few lower natural frequencies, which can be easily obtained from the ambient acceleration measurements of the cable. Several numerical and experimental studies were reported to show the validity of the method (Zui et al., 1996, Kim & Park, 2007). The embedded software was developed to select a proper formula for cable tension estimation without human intervention.

### 3 EXPERIMENTS FOR VALIDATION

#### 3.1 Experimental setup

To validate the proposed WTFES, laboratory tests were carried out on a scaled-down model of a cable from an actual cable-stayed bridge as shown in Figure 4. To measure the tension force of the cable, a threaded rod connected to the lower end of the cable was ground to have a square cross section so that 4 metal foil strain gauges could be attached on 4 sides. The threaded rod with strain gauges was preliminarily calibrated by controlled tensile testing using an MTS load frame; excellent linearity was found between the tension force and the average strain from the 4 strain gauges (Figure 5).
3.2 Experimental procedure

A series of validation tests were carried out to check the feasibility of the proposed WTFES for various sensing locations, tension forces, and sags. Tests were carried out for 10 cases with different cable tension forces (with varying levels of sag). Impacts were applied at arbitrary locations on the cable. To check the effect of various sensing locations, 3 wireless sensors are installed on the cable at 0.5 (S1), 1.0 (S2), and 1.5 m (S3) when measuring from the lower end of the cable as shown in Figure 4. The details of the test cases are shown in Table 2. It can be seen that the sag increases as the tension force decreases. It is worthy to note that Cases T1-T4 correspond to the cable with small levels of sags while Cases T5-T10 are for cables with large sags.

Table 2. Details of the various experiment tests

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Sampling rate (Hz)</th>
<th>Gain</th>
<th>Sag (mm)</th>
<th>Sag-to-span ratio</th>
<th>Tension (N)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>50</td>
<td>5</td>
<td>&lt; 3.0</td>
<td>&lt; 1×10⁻³</td>
<td>1162</td>
</tr>
<tr>
<td>T2</td>
<td>50</td>
<td>5</td>
<td>&lt; 3.0</td>
<td>&lt; 1×10⁻³</td>
<td>1023</td>
</tr>
<tr>
<td>T3</td>
<td>40</td>
<td>5</td>
<td>6.4</td>
<td>1.23×10⁻³</td>
<td>858</td>
</tr>
<tr>
<td>T4</td>
<td>40</td>
<td>5</td>
<td>7.9</td>
<td>1.51×10⁻³</td>
<td>617</td>
</tr>
<tr>
<td>T5</td>
<td>40</td>
<td>5</td>
<td>12.7</td>
<td>2.43×10⁻³</td>
<td>522</td>
</tr>
<tr>
<td>T6</td>
<td>40</td>
<td>5</td>
<td>19.1</td>
<td>3.66×10⁻³</td>
<td>308</td>
</tr>
<tr>
<td>T7</td>
<td>40</td>
<td>5</td>
<td>50.8</td>
<td>9.73×10⁻³</td>
<td>99.5</td>
</tr>
<tr>
<td>T8</td>
<td>40</td>
<td>5</td>
<td>63.5</td>
<td>12.16×10⁻³</td>
<td>48.7</td>
</tr>
<tr>
<td>T9</td>
<td>40</td>
<td>5</td>
<td>95.3</td>
<td>18.26×10⁻³</td>
<td>28.8</td>
</tr>
<tr>
<td>T10</td>
<td>40</td>
<td>5</td>
<td>130.2</td>
<td>24.94×10⁻³</td>
<td>13.4</td>
</tr>
</tbody>
</table>

* measured directly using strain gauges on threaded rod.

4 EXPERIMENTAL RESULTS

4.1 Tests with small sag: T1-T4

Test cases T1-T4 were carried out on the cable with small levels of sag, where sag-to-span ratios are less than 1.51×10⁻³ as shown in Table 2. For case T1, Figure 6 shows the Fourier spectra of the measured accelerations from the 3 wireless sensors (S1-S3). The natural frequencies estimated using the embedded peak picking algorithm are marked in the figures. The frequencies autonomously estimated at 3 sensor locations are found to be identical. Similarly identified results were obtained from 3 sensors for the other test cases (T2-T4). Fourier spectra of the accelerations measured at S3 for cases T2, T3 and T4 are shown in Figure 7. In Table 3, the estimated frequencies for cases T1 through T4 are compared with the values (marked as “Ref.”) obtained by off-line operations requiring human intervention. The estimated natural frequencies are found to be identical to the reference values for all test cases.

For the cable tension estimation, two condition parameters (Γ and ξ) were initially evaluated using an arbitrary large tension value of 10 kN, which is much larger than the true values correspond to all of the test cases as listed in Table 2. Thus Equation (1-a) was selected at the first iteration for the tension estimation for test cases T1 through T4. Table 3 shows the estimated cable tension forces along with the results from the strain gauges (marked as “Ref.”). All of the estimated tension values are found to be in excellent agreement with the corresponding reference values; the discrepancies were less than 2%. It has been found that no additional iterations were necessary for tension estimation in these four test cases. The present results indicate that the embedded software of the proposed WTFES is working correctly in a completely automated fashion.
To investigate the feasibility of the present method of cables with large sags, test cases T5 through T10 were carried out for sag-to-span ratios in the range of 2.43×10⁻³ to 24.94×10⁻³ as shown in Table 2. Example Fourier spectra of the measured accelerations and the peak picked natural frequencies are shown for Cases T5, T7 and T9 in Figure 8. Again, consistent natural frequencies were obtained regardless of the sensor locations for all of the test cases. Furthermore, these frequencies are identical to those obtained off-line as shown in Table 4.

For cable tension estimation, two condition parameters were initially evaluated using an arbitrary large tension force of 10 kN as in the previous tests. Accordingly, Equation (2-a) was selected for the first iteration in cases T5 through T10. In Table 4, the estimated cable tension forces are compared with the values obtained using the strain gauges. The estimated tension forces show larger discrepancies than those obtained using the strain gauges: less than 7% in cases T5 through T8 and about 12% for case T9. The larger discrepancy in case T9 may have come from the relatively large sensitivity of the measured tension force using strain gauges for the case with a small tension force (in the order of tens of Newtons). It has been also found that only one or two iterations were needed for tension estimations: one iteration from Equation (2-a) to Equation (2-b) for T5 and T6, and two iterations from Equation (2-a) to Equations (2-b) and (2-c) for T7-T10.

Table 3. Results of validation tests with small sags (T1-T4)

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Natural frequencies (Hz)</th>
<th>Tension forces (N)</th>
<th>Error (%)</th>
<th>Selected formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>6.79 13.05 19.18 1162</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>6.30 12.15 17.80 1023</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>5.85 11.24 16.59 858</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>5.04 9.70 14.38 617</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Ref. : natural frequencies obtained by offline operation and tension force measured using strain gauges

Table 4. Results of tests with large sag (T5-T10)

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Natural frequencies (Hz)</th>
<th>Tension forces (N)</th>
<th>Error (%)</th>
<th>Selected formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5</td>
<td>4.73 9.08 13.49 522</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>3.80 7.34 10.84 308</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T7</td>
<td>2.33 4.50 6.33 99.5</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T8</td>
<td>1.88 3.61 5.44 48.7</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T9</td>
<td>1.59 3.02 4.57 28.8</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td>1.39 2.68 4.00 13.4</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Ref. : natural frequencies obtained by offline operation and tension force measured using strain gauges
4.3 Summary of the estimated tension forces

In Figure 9, all of the estimated tension forces using the WFTES are plotted against the tension forces measured from the strain gauges. It is interesting to note that the sag-to-span ratios of T3 to T6 are in the range of $12.3 \times 10^{-4}$ to $36.6 \times 10^{-4}$, which are very similar to the values for the stay-cables of the Seohae Grand Bridge (Korea) which are from $8.4 \times 10^{-4}$ to $36.2 \times 10^{-4}$ (Ahn et al., 2001). It is clearly shown that the present WFTES using the wireless sensors shows excellent performance for cable tension estimation for a wide range of cable tension force and sag, particularly for the cases applicable to the cables in a realistic cable-stayed bridge.

Figure 9. Comparison of estimated and measured tension forces using strain gauges (from 10 sets of tests)

5 ON-GOING US-KOREA TESTBED PROJECT

A US-Korea Collaboration Research Project, supported jointly by the National Science Foundation (NSF) in the US and the Korean Science and Engineering Foundation (KOSEF), is in progress. The objective is to integrate and validate cutting-edge sensors and structural health monitoring methods under development for monitoring the long-term performance and structural integrity of highway bridges (Yun et al., 2008) Emerging sensors and monitoring technologies are currently under investigation on several operational bridges in Korea. As a part of this project, the field validation of the present WFTES is going to be carried out on the Seohae Bridge in Korea. For validation of the proposed method in the field, elasto-magnetic (EM) sensors which utilize the dependency of the magnetic properties of the steel cable on the state of stress will be used for baseline comparison.

6 SUMMARY AND CONCLUSIONS

A low-cost and automated wireless tension force estimation system (WTFES) is developed for steel cables in long-span bridges. The low-cost hardware system consists of a wireless sensor made of commercial off-the-shelf components, a cheap commercialized MEMS accelerometer, and a specially designed signal conditioning circuit with amplification, mean-shifting, and anti-aliasing filtering functionality. The software embedded in the wireless sensor is composed of a peak picking algorithm for identification of the natural frequencies of a cable and a vibration approach for tension force estimation using the identified natural frequencies. A key feature of the approach is the inclusion of the cable sag and bending stiffness. The system is also designed to be fully autonomous requiring no human intervention.

A series of validation tests were carried out on a scaled down version of a cable from an operational cable-stayed bridge (Seohae Bridge, Korea). In total, 10 cases were considered with various sag-to-span ratios, which represent small and large sags. The results of the experimental study are summarized as follows. (1) Consistent results can be obtained for the first three natural frequencies (regardless of the sensor location along the cable) using the proposed peak-picking algorithm. (2) The cable tension forces estimated by the present method are very close to the values measured using strain gauges for the cases with sag-to-span ratios similar to those of the cables in the Seohae Grand Bridge, which indicates the applicability of the present system to realistic cable-supported bridges.

7 ACKNOWLEDGMENTS

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Website: Crossbow Technology Inc. http://www.xbow.com
