ABSTRACT

Cable tension force is one of the most important structural parameters to monitor in cable-stayed bridges. For example, cable tension needs to be monitored during construction and maintenance to ensure the bridge is not overloaded. To economically monitor tension forces, this study proposes the use of an automated wireless tension force estimation system (WFTES) developed solely for cable force estimation. The design of the WFTES system can be divided into two parts: low-cost hardware and automated software. The low-cost hardware consists of an integrated platform containing a wireless sensing unit constructed from commercial off-the-shelf components, a low-cost commercial MEMS accelerometer, and a signal conditioning board for signal amplification and filtering. With respect to the automated software, a vibration-based algorithm using estimated modal parameters and information on the cable sag and bending stiffness is embedded into the wireless sensing unit. Since modal parameters are inputs to the algorithm, additional algorithms are necessary to extract modal features from measured cable accelerations. To validate the proposed WFTES, a scaled-down cable model was constructed in the laboratory using steel rope wire. The wire was exposed to broad-band excitations while the WFTES recorded the cable response and embedded algorithms interrogated the measured acceleration to estimate tension force. The results reveal the embedded algorithms properly identify the lower natural frequencies of the cable and make accurate estimates of cable tension. This paper concludes with a summary of the salient research findings and suggestions for future work.

INTRODUCTION

In recent years, there has been rapid growth in the number of long-span bridges constructed worldwide. Suspension and cable-stayed designs remain popular choices for long-span bridges. Within these bridges, cables are important load carrying elements; given their importance, cable force is an important parameter that should be routinely measured. In particular, there is a need to continuously or semi-continuously monitor cable forces during construction and maintenance.

Cable tension measurement methods can be classified into two categories: static (or, direct) and vibration (or, indirect) methods. Static methods directly measure tension force using a load cell or a hydraulic pressure-meter installed at the end of the cable. In contrast, vibration methods estimate cable tension using natural frequencies, material properties and geometric features. Given that static methods require complex and expensive instrumentation, vibration methods are more widely used because they require less invasive instrumentation and are easier to implement in a cost-effective manner. Vibration-based techniques employ accelerometers mounted to the surface of the cable to record the ambient vibration response; cable natural frequencies may be easily obtained from these responses.

Vibration methods find their origin in flat taut string theory [1]. Direct application of flat taut string theory can be difficult.
for bridge cables because factors contributing to cable dynamics including the cable bending stiffness and sag are not considered. To consider the bending stiffness of the cable, axially loaded beam elements must be included in the cable model to describe the relationship between tension force and the natural frequencies of a cable. For inclusion of cable sag in the model, an asymptotic solution proposed by Triantafyllou [2] could be considered. To calculate tension force in an inclined, but sagged cable, the nonlinear characteristic equation of the cable is solved by a trial-and-error approach [3]. Inclusion of bending stiffness and sag have been considered by many researchers [4, 5, 6] leading to accurate tension force estimation tools.

To generate the appropriate data for vibration-based tension force methods, accelerometers are typically mounted to the surface of the cable to record its vibration response to its natural ambient loading. Natural frequencies of the cable are obtained from the measured time-history response; it is these natural frequencies that are input to the tension force estimation methods. Unfortunately, the installation of accelerometers requires wired data acquisition systems to be used. Installation of extensive lengths of coaxial wires may be very difficult for an operational long-span bridge. Alternatively, the emergence of wireless sensors allows engineers to now install accelerometers upon large-scale bridges at low cost and with minimal labor requirements [7]. In addition, the computational capabilities of wireless sensors can be leveraged to automate the process of calculating tension forces of the monitored bridge cable. Such an approach is scalable to large numbers of sensors since high-bandwidth data streams (i.e., acceleration time histories sampled at high rates) are processed locally at the sensor, resulting in low-bandwidth data streams (i.e., tension measurements reported intermittently). Lower bandwidth data streams require less communication resources and preserve the life expectancy of wireless sensors powered by battery sources.

Straser and Kiremidjian [7] are one of the first to propose the design of a low-cost wireless monitoring system for civil structures. Lynch et al. [8] has built upon their work by integrating a more powerful computational core in the wireless sensor unit design. A wireless sensor platform featuring a computational core for sensor-based data processing has been under continual development by Lynch et al. for the past few years. Today, their platform includes algorithms for sensor-based and network-based execution such as the fast Fourier transform (FFT), and for autoregressive (AR) modeling and modal estimation [9, 10, 11]. Besides these academic wireless sensor platforms, a number of commercial wireless sensor platforms have also been modified for structural monitoring applications. A wireless sensor initially developed at the University of California-Berkeley and subsequently licensed by Crossbow [12] is the most widely used commercial platform. This Mote platform has been more recently advanced by Intel resulting in the iMote2 which is commercially available from Crossbow. Specifically, Spencer et al. [13, 14, 15] have explored the use of the iMote2 platform for various structural health monitoring applications. For additional information on the state of the art in the wireless structural monitoring field, readers are referred to [13, 16, 17].

In this study, an automated wireless tension force estimation system (WTFES) is proposed based upon the use of low-cost wireless sensor technology. The system is comprised of a low-cost hardware platform with automated software embedded. The hardware consists of a wireless sensing unit that includes a multi-channel analog-to-digital converter (ADC), microcontroller, memory, and wireless transceiver. In addition, an inexpensive MEMS accelerometer and signal conditioning board are integrated with the wireless sensing unit to record the time-history acceleration response of a cable. The system is able to wirelessly transmit either the entire time-history record (if needed) or the estimated value of tension. In this study, WTFES is validated during extensive laboratory testing of a partial-scale cable model. Accurate estimates of tension will be reported for the cable with various cable tension forces and sags introduced.

**WTFES HARDWARE DESIGN**

**Wireless sensing unit**

The wireless sensing unit (Figure 1) used in this study has been previously developed by Wang, Lynch and Law [18]. This powerful wireless sensing unit has been designed specifically for structural monitoring of large-scale civil structures. The design of the unit is based upon the integration of commercial of-the-shelf embedded system components. To collect data from a heterogeneous array of sensors, a 4-channel ADC (Texas Instruments ADS8341) with a 16-bit resolution is employed. The ADC is connected to and controlled by the 8-bit Atmel ATmega128 microcontroller. This specific microcontroller has been selected because it offers several convenient peripheral interfaces (e.g., serial peripheral interface (SPI), serial ports (UARTS)) making integration with

![Figure 1. Wireless sensing unit prototype [11]](image-url)
other hardware components easy. In addition, the microcontroller has 128 kB of on-chip flash memory where embedded algorithms are burnt into the chip via the In System Programmable (ISP) interface. With only 4 kB of random access memory (RAM) on the microcontroller, insufficient memory is available for data storage from sensors. In response to this limitation, an additional 128 kB of off-chip external static RAM is integrated in the wireless sensor design to store raw and processed data. After recording a certain amount of sensor readings (and processing them), data can be transmitted to a data server via the unit’s wireless transceiver. The Maxstream 9XCite wireless transceiver is used to communicate data over the 900 MHz radio band. With a simple whip antenna, the radio can communicate up to 300 m line-of-sight with an over-the-air data rate of 38.4 Kbps. The wireless sensing unit is powered by 5 AA lithium batteries (7.5V); the unit and its battery power supply are packaged in a hardened external container. The individual components of the wireless sensor are highlighted in Figure 1. It should be mentioned that this wireless sensing unit has been widely used to monitor the response of multiple bridges and buildings worldwide [11, 17, 18, 19].

Commercial MEMS accelerometer

A commercial MEMS accelerometer (Crossbow CXL02LF1) is implemented to measure the time-history acceleration response of an instrumented structure. This particular accelerometer is relatively inexpensive (< $250) yet offers impressive performance including high sensitivity (1000 mV/g) and low noise floors (<1 mg rms). The performance details of the accelerometer are summarized in Table 1. Since a bridge cable is generally characterized by relatively low natural frequencies, this accelerometer is suitable for cable vibration measurements.

Signal conditioning board

Though the accelerometer is capable of capturing low-amplitude accelerations, such low amplitudes might be close to the quantization noise inherent in the wireless sensor’s analog-to-digital conversion [19]. In that case, the performance of the wireless sensor can be improved if the analog output of the accelerometer is amplified before being sampled by the ADC. Towards this end, a signal conditioning board has been developed by Wang et al. [10]. The conditioning board has three primary functions: 1) amplification of the sensor output, 2) mean-shifting sensor outputs to 2.5V (not needed in this study since the accelerometer’s zero mean output is already at 2.5V), and 3) anti-alias (band-pass) filtering. The signal conditioning board is designed using discrete analog circuit elements and ordinary operational amplifiers (OP AMPS). By adopting a three-way switch, three amplification factors are provided to the user: 5, 10 and 20. Furthermore, a 0.02 to 50 Hz band-pass filter is included in the circuit design. The signal conditioning board shown in Figure 2 has been validated during several field applications [10, 11].

SENSOR-BASED SOFTWARE FOR WTFES

Tension force estimation

Of the various vibration methods that consider sag and bending stiffness of the cable in their tension force estimations, Zui’s [4] practical formula is selected in this study. The reason for its selection for embedment in the wireless sensing unit is because: 1) it is composed of seven equations that are easy to execute using the limited computing resources of the wireless sensing unit; 2) unlike other modern vibration methods, it does not require higher-order modes that are hard to extract from ambient accelerations; 3) it has been proven reliable for tension force estimation in both numerical [4] and experimental tests [6]; 4) it does not require iteration in its execution thereby reducing computational time and energy demands on battery power.

The algorithm is decomposed into three cases and seven states which are a function of the relative cable sag, $\Gamma$, and tension force, $\xi$. The first three states are affiliated with small cable sages ($\Gamma \geq 3$) while the next three are affiliated with relatively large sags ($\Gamma \leq 3$). Finally, the last state corresponds to a very long cable (irrespective of its sag). Table 2 summarizes the delineation of cases and states. The tension in the cable, $T$, can be determined using the following set of equations:

Table 1. Specification of MEMS type accelerometer (Crossbow CXL02LF1)

<table>
<thead>
<tr>
<th>Specification</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 rms)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>DC-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>

Figure 2. Developed signal condition board [10]
Table 2. Meaning of “Case” and “State”

<table>
<thead>
<tr>
<th>Case</th>
<th>Meaning</th>
<th>State</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not very long with relatively small sag</td>
<td>State 1</td>
<td>Large tension force</td>
</tr>
<tr>
<td>1</td>
<td>Not very long with relatively large sag</td>
<td>State 4</td>
<td>Large tension force</td>
</tr>
<tr>
<td>2</td>
<td>Very long cable</td>
<td>State 7</td>
<td>-</td>
</tr>
</tbody>
</table>

Case 1: Cable with sufficiently small sag (Γ ≥ 3): Using the first natural frequency, $f_1$:

State 1: $T = \frac{4w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 1 - 2.20 \frac{C}{f_1} - 0.550 \left( \frac{C}{f_1} \right)^2 \right] (17 ≤ ξ)$

State 2: $T = \frac{4w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 0.865 - 11.6 \left( \frac{C}{f_1} \right)^2 \right] (6 ≤ ξ ≤ 17)$

State 3: $T = \frac{4w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 0.828 - 10.5 \left( \frac{C}{f_1} \right)^2 \right] (0 ≤ ξ ≤ 6)$

Case 2: Cable with relatively large sag (Γ ≤ 3): Using the second natural frequency, $f_2$:

State 4: $T = \frac{w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 1 - 4.40 \frac{C}{f_1} - 1.10 \left( \frac{C}{f_1} \right)^2 \right] (60 ≤ ξ)$

State 5: $T = \frac{w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 1.03 - 6.31 \frac{C}{f_1} - 1.58 \left( \frac{C}{f_1} \right)^2 \right] (17 ≤ ξ ≤ 60)$

State 6: $T = \frac{w}{g} \left( \frac{fl}{f_1} \right)^2 \left[ 0.882 - 85.0 \left( \frac{C}{f_1} \right)^2 \right] (0 ≤ ξ ≤ 17)$

Case 3: Very long cable: Using the nth natural frequency, $f_n$ (2 ≤ n)

State 7: $T = \frac{4w}{N^2g} \left( \frac{f_nl}{f_1} \right)^2 \left[ 1 - 2.20 \frac{nC}{f_n} \right] (200 ≤ ξ)$

where $w$ denotes weight per unit length, $EA$ denotes extensional rigidity, $δ$ denotes sag-to-span ratio (s/lₙ), $θ$ denotes inclination angle, $C = \sqrt{12ζ^2/\omega n}$, $ξ = \sqrt{f_n/EL}$, and $Γ = \sqrt{wl/128EAs^2 \cos θ[(0.3ζ δ + 0.5) / (0.3ζ δ - 0.5)]}$. From the definitions for ξ and Γ, it can be inferred that they are relative amounts of tension force and sag, respectively. The geometric variables of the cable are denoted in Figure 3.

Automated force estimation strategy

To use the aforementioned formulas for tension force estimation, at least the first two natural frequencies of the cable must be extracted from the measured acceleration. Therefore, prior to embedding the tension estimation formulas, a peak-picking algorithm is embedded for automated identification of the lower natural frequencies of the cable. The peak picking algorithm is developed with consideration of the following spectral features typical of cables: 1) the response spectrum of a cable shows very sharp peaks at natural frequencies due to low damping; 2) in taut string theory, the nth natural frequency of a cable ($f_n$) is around n times that of the first natural frequency ($f_1$). Based on these two features, it is conceivable to arrive at a threshold value (e.g., average plus two times the standard deviation of the response spectrum power) to distinguish high power, modal peaks from small local peaks corresponding to noise in the spectrum. Once the first modal peak has been identified, the spectrum can be investigated in a select frequency band near $2f_1$ (e.g., look for $f_2$ in the band $f_1+0.8f_1$ to $f_1+1.2f_1$). The following algorithm is designed and implemented as follows:

Step 1. Calculate the discrete response spectrum, X(k), using fast Fourier transform (FFT) embedded into the wireless sensing unit.

Step 2. Start to scan from the first frequency response (X(1)), and if X(k) is a local peak, store k₁ and X(k₁) in the stack.

Step 3. Start to scan from X(k₁+1) to X(k₁+B) with B a buffer band equal to some set number of points predefined by the user. If X(k₂) where $k₂ ≤ k₂+\Gamma$ is a local peak and larger than X(k₁), replace k₁ and X(k₁) in the stack with k₂ and X(k₂). Repeat Step 3. If another local peak, X(k₃), larger than X(k₂) is not found, store k₃ to the memory as the first modal frequency.

Step 4. Repeat Step 3 until the desired number of modal peaks are found or until half of the discrete response spectrum is scanned.

Step 5. Calculate natural frequencies based on the obtained kₙ's, the number of points in the FFT, N, and the sampling frequency, fₛ.
The natural frequencies identified by the peak-picking algorithm then serve as input to the cable force estimation formulas. As is evident from the formulas, the sag and tension force conditions for each equation, $\Gamma$ and $\xi$, need to be calculated in advance to determine which equation will be used. However, $\xi$ is a function of $T$ while $\Gamma$ is a function of $\xi$. Therefore, it is difficult to simply determine the adequate equation without an idea of the current tension force. In this study, all the formulas are successively used to estimate the tension force with $\xi$ and $\Gamma$ inversely solved for using the estimated tension force. Calculated $\xi$ and $\Gamma$ are then used to verify which of the seven states is most appropriate for the cable.

The algorithm implemented in each wireless sensor starts with cable parameters as inputs. Then, the three lowest frequencies ($f_1$, $f_2$, and $f_3$) of the cable are extracted from the measured acceleration using the embedded peak-picking algorithm. Next, the case (as defined in Table 2) that will control the analysis is estimated using the length and design tension force of the cable. For that case, the first state is used to estimate the tension force. If $\xi$ and $\Gamma$ inversely calculated for that state do not agree with the conditions of the state, then the tension estimation formula of the next state is adopted. To reduce the calculation time and to prevent a continuous loop, the indices $\text{idx}_s$ (short) and $\text{idx}_l$ (long) are introduced to show which case has been conquered from the successive estimations for cable tension. A flow diagram of the embedded algorithm is presented in Figure 4.

![Figure 4. Embedded software flow chart that estimates tension force in cables](image-url)
VALIDATION TEST SET-UP

Test setup

To validate the developed automated wireless tension force estimation system (WTFES), laboratory testing was carried out on a scaled-down cable representing the cable of a cable-stayed bridge. Figure 5(a) presents the dimensions of the cable and its geometric orientation. A threaded rod whose end is connected to the bottom-end of the cable was bound with nuts to control the tension force and the corresponding sag; larger sag could be introduced by loosening the bolt. A portion of this threaded rod was ground down to offer four flat surfaces to which strain gages are attached. Four strain gauges were attached on each side of the machined square section of the rod to measure the applied average tension force as shown in Figure 5(b). The strain gauges were preliminarily calibrated using tensile load applied by a Material Testing System (MTS) load frame as shown in Figure 6(a). The linear relationship between the tension force and the average strain calculated from the 4 strain measurements is plotted in Figure 6(b).

Test procedure

A series of validation tests were carried out to assess the feasibility of the developed system. During testing, the location of the accelerometer, the tension force in the cable and the cable sag were all varied. In total, 6 sets of tests were carried out with the tension force gradually reduced, thereby introducing additional cable sag. In the tests, acceleration excited by small impacts on the cable were captured by the MEMS accelerometer; during acceleration measurements, the signal conditioning board was set to amplify the accelerometer output by a factor of 5. Three separate accelerometer-wireless sensor pairs were installed roughly 0.5 m (WTFES1), 1.0 m
Testing details corresponding to each of the 6 tests are summarized in Table 3. It is worth noting that CT1 and CT2 are intended to validate the developed WTFES system with minimal sag present while CT3 through CT6 are intended to quantify the performance of the developed system on a cable with ocular sag.

EXPERIMENTAL RESULTS

Validation tests of the WTFES system (CT1 and CT2)

First, the performance of the WTFES was investigated with the cable configured to have negligible sags (CT1 and CT2). Figure 7 is the response spectra obtained by the locally executed FFT at the wireless sensing units of all locations in CT1; the extracted peaks are also shown. Table 4 summarizes the tests results including tabulation of the 3 lowest natural frequencies extracted, the estimated tension forces, and the identified state described in Table 2. From Figure 7, it is clear that the response spectra corresponding to the 3 sensed outputs of the cable show perfect agreement in terms of identified peaks (at 6.8, 13.1, and 19.2 Hz). Furthermore, it was found that the natural frequencies identified by the proposed automated peak-picking algorithm matched exactly those determined off-line using the same time-history data. When comparing WTFES tension forces to those measured, the percent error is less than 2% which is negligible.

Additional tests with sag (CT3-CT6)

After the CT1 and CT2 validation tests, tension force of the cable was gradually decreased to introduce sag. The sag introduced for tests CT3 through CT6 are summarized in Table 3. It is worth noting that the sag-to-span ratios ($\delta = s/l_s$) of CT3 through CT6 are from $12.3\times10^{-4}$ to $36.6\times10^{-4}$ which is consistent with the range of sag-to-span ratios (from $8.4\times10^{-5}$ to $36.2\times10^{-4}$) of the Seohae Grand Bridge in Korea [20]. Therefore, the suitability of the WTFES for tension force estimation in cables of cable-stayed bridge may be established by these tests.

Table 3. Details of cable vibration tests

<table>
<thead>
<tr>
<th>Test name</th>
<th>Vibration measurement</th>
<th>Cable property</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sampling rate (Hz)</td>
<td>Amp. factor</td>
</tr>
<tr>
<td>CT1</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>CT2</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>CT3</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>CT4</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>CT5</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>CT6</td>
<td>40</td>
<td>5</td>
</tr>
</tbody>
</table>

* measured using strain gauges on a threaded rod at the cable end

(WTFES2), and 1.5 m (WTFES3) from the bottom end of the cable. Testing details corresponding to each of the 6 tests are summarized in Table 3. It is worth noting that CT1 and CT2 are intended to validate the developed WTFES system with minimal sag present while CT3 through CT6 are intended to quantify the performance of the developed system on a cable with ocular sag.

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Table 4. Results of validation tests CT1 and CT2

<table>
<thead>
<tr>
<th>Test name</th>
<th>Nat. freq. (Hz)</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
<td>2nd</td>
</tr>
<tr>
<td>CT1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>6.79</td>
<td>13.05</td>
</tr>
<tr>
<td>WTFES1</td>
<td>6.79</td>
<td>13.05</td>
</tr>
<tr>
<td>WTFES2</td>
<td>6.79</td>
<td>13.05</td>
</tr>
<tr>
<td>WTFES3</td>
<td>6.79</td>
<td>13.05</td>
</tr>
<tr>
<td>CT2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>6.30</td>
<td>12.15</td>
</tr>
<tr>
<td>WTFES1</td>
<td>6.30</td>
<td>12.15</td>
</tr>
<tr>
<td>WTFES2</td>
<td>6.30</td>
<td>12.15</td>
</tr>
<tr>
<td>WTFES3</td>
<td>6.30</td>
<td>12.15</td>
</tr>
</tbody>
</table>

* values in parentheses are percentage errors

Table 5 summarizes the results of tests CT3 through CT6 compared with the offline extraction of natural frequencies and measured tensions using strain gauges. Since the results from the three different sensor locations (WTFES1, WTFES2 and WTFES3) were identical, only the results from WTFES1 are offered in Table 5. It is clearly shown that the proposed automated peak-picking algorithm provided the same peaks as the offline extraction. In addition, the estimated tension forces of CT3 through CT6 also showed very good agreement.
Estimated states of CT3 and CT4 were state 1 (which corresponds to a short cable with relatively small sag and high tension force). Results obtained from CT5 and CT6 correspond to state 5 (a short cable with relatively large sag and medium tension force). These results seem reasonable considering the sags of CT5 and CT6 are larger than those of CT3 and CT4. Estimated tension forces by WTFES are compared with the tension forces measured indirectly using the strain gauges. As shown in Figure 8, the estimated tension forces compare well with those measured from the strain gauges.

SUMMARY AND CONCLUSIONS

The objective of this work is to develop a low-cost and automated wireless tension force estimation system (WTFES) for cable structures such as long-span suspension and cable-stayed bridges. A low-cost hardware platform based on wireless sensing and corresponding embedded software are developed. For the low-cost hardware, the system consists of a MEMS sensor, a wireless sensing unit made from off-the-shelf components, and a specially designed signal conditioning board with mean-shifting, amplification, and band-pass filtering functionality. For the automated software, a peak-picking algorithm is embedded into the computational core of the wireless sensing unit along with a tension estimation algorithm proposed by Zui et al\[4\]. An inherent attraction of the algorithm is its consideration of sag and cable bending stiffness.

To validate the developed WTFES, six sets of validation tests with various tension forces and cable sags were carried out on a scaled-down cable. From two tests with negligible cable sag, it was found that the proposed automated peak-picking algorithm is capable of extracting accurate estimates for the cable’s three lowest modes. In addition, the estimated tension force was very close to that determined based on strain measurements. In the other four tests, sags consistent with the sag-to-span ratio range reported for the Seohae Grand Bridge in Korea were introduced. Tension forces were estimated with an error bounded by 6%. These promising results prove the feasibility of the developed system for application to real cable-stayed bridges. A lasting contribution of this work is that it presents a sensor-based computational technique that is scalable to long-span bridges with tens of cables. For a complete verification of the proposed wireless system, testing on cables in actual cable-stayed bridges is required.

ACKNOWLEDGMENTS

This work was jointly supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2007-612-D00136), the National Science Foundation under Grant CMMI-0726812 (Program Manager: Dr. S. C. Liu), and the Smart Infra-Structure Technology Center (SISTeC) at KAIST sponsored by the Korea Science and Engineering Foundation.

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