The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Dynamic stress monitoring system for stay cables using piezoelectric strain sensors

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ABSTRACT

This study presents a dynamic stress monitoring system for stay cables using piezoelectric strain sensors. First, a dynamic strain-based monitoring system to estimate cable stress in real-time manner is schematized. In this approach, the static stress of cable is estimated by using natural frequencies extracted from the dynamic piezoelectric voltage signal. Meanwhile, the dynamic stress component is estimated from magnitude of the signal. The signal of the piezoelectric sensor, which is strain-induced voltage, is calibrated with the strain signal measured from a commercial electrical strain gauge. Next, the proposed monitoring system is evaluated by an experiment on a lab-scale steel cable.

1. INTRODUCTION

Cables are the critical structural components of cable supported structures such as cable-stayed bridges, suspension bridges. Cable systems have to carry most of the dead load from decks and various kinds of live loads such as vehicle traffic, wind and/or temperature variation. Since the cables are very flexible, their vibration due to those loads would potentially cause fatigue cracks in the cables. Additionally, stress relaxation in the cables due to loosening of cable anchorages can strongly occurs. Those kinds of damages could not only lead to the local failure of the cables but also affect to the loading capacity of the structures and global structural integrity.

For monitoring of cables, vibration-based techniques utilizing acceleration features of cables are widely used for estimating indirectly the static cable stress (Zui et al. 1996; Kim and Park 2007). However, those techniques can not measure the variation of stress. A few researchers have attempted to monitor both the static component and variation of cable stress using fiber Bragg grating strain sensors as a direct method (Li et al. 2009; Ma and Wang 2009). However, the data acquisition system associated with this technique is expensive, complicated, heavy and hard to set up for real stay cables.

This study presents a dynamic stress monitoring system for stay cables using piezoelectric strain sensors. The static stress of a cable is estimated indirectly by using natural frequencies extracted from the dynamic piezoelectric voltage signal. Meanwhile, the stress variation component is estimated directly from the time history voltage signal. The piezoelectric voltage is transformed to strain signal by calibrating it with strain signal of an electric strain gauge. Then the stress variation is calculated from the strain variation response by knowing the elastic modulus of the cable. For validation, an experiment on a lab-scale steel cable has been carried out with various static cable force cases and impact conditions.

2. CABLE DYNAMIC STRESS MEASUREMENT VIA PZT SENSORS

The fundamental of piezoelectric materials (e.g., PZT sensors) for strain measurement has been studied by Sirohi and Chopra (2000). It is based on the direct effect of piezoelectric materials that an electrical field is produced due to dynamic mechanical strain of a PZT patch. For monitoring cable stress, it is necessary to measure both the static stress and stress variation in the cable. In this study, stress statement of stay cables is estimated by using time history response and frequency response of PZT signals. The schematic of dynamic stress monitoring for stay cables is designed in Fig. 1. First, the dynamic voltage of PZT which represent cable's strain variation is measured. Next, this signal is calibrated with a calibration factor to obtain strain and stress variation. In a parallel manner, frequency response is calculated from PZT dynamic voltage signal and natural frequencies are extracted by an automated peck-picking algorithm. Cable force is estimated using the extracted natural frequencies and the static stress is obtained hereafter. Finally, dynamic stress of the cable is obtained by adding the static stress with the stress variation.

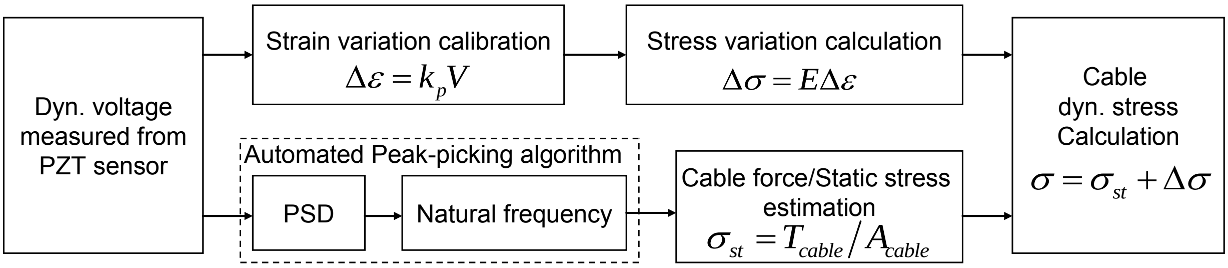


Fig. 1 Schematic of dynamic stress monitoring system for stay cables

2.1 Calculation of stress variation of cable

Once a PZT patch is surface-bonded to a stay cable, strain variation of the cable can be expressed in term of dynamic voltage measured from the PZT's terminals as:

$$\Delta\varepsilon = \left(\frac{\overline{e_{33}^{\sigma}}}{d_{31} t_p \overline{Y^E}} \right) V = k_p V \tag{1}$$

where $\Delta\varepsilon$ is the strain variation of the cable; V is output voltage across the terminals of the PZT patch; t_p is thickness of the PZT patch; $\overline{e_{33}^{\sigma}}$ is the dielectric constant of the PZT patch; d_{31} is the piezoelectric coupling constant; and k_p is the calibration factor. If elastic modulus (E) of the cable is known, the stress variation ($\Delta\sigma$) can be calculated from the strain variation as:

$$\Delta\sigma = E\Delta\varepsilon \tag{2}$$

2.2 Calculation of static stress of cable

In order to obtain the static stress of the cable, natural frequencies are first extracted, and then utilized for estimating cable force. The process is performed in the three major steps as follows:

Power spectral density calculation

The power spectral density (PSD) is calculated from the dynamic voltage signal as follows (Bendat and Piersol 1993)

$$S_{xx}(f) = \frac{1}{n_d T} \sum_{i=1}^{n_d} \left| X_i(f,T) \right|^2 \tag{3}$$

where X_i is the dynamic response transformed into the frequency domain (FFT transform); n_d is the number of divided segments in the time history response; and T is the data length of a divided segment.

Natural frequency calculation

Next, natural frequencies are obtained from the automated peak-picking algorithm. The basic concept of the algorithm is to search the local maxima of the PSD curve, which represent natural frequencies. Assuming that natural frequencies of the cable are periodic and the allowable loss of tension force is as maximal as 80% of the design force, the automated peak-picking is performed as follows: Firstly, the size of frequency band (*df*) is selected as:

$$df \leq (f_1)_{20} = \sqrt{T_{20}/(4mL^2)} \tag{4}$$

where $(f_1)_{20}$ is the fundamental frequency corresponding to 20% of the design force (T_{20}). Secondly, the entire frequency range (i.e., from 0 to the cut-off frequency, f_c) is divided into N number of sub-frequency ranges, in which $N = f_c / df$. For example, sub-frequency range 1 is 0~*df,* sub-frequency range 2 is *df*~2*df*, …, and sub-frequency range N is (f_c-*df*) ~ f_c. Finally, by examining each sub-frequency range, the natural frequency is picked if its magnitude is the largest in the range and at least 5 times greater than the magnitude mean. Sometimes, the false natural frequency can be picked together with the true one if the peak is very close to the boundary of a sub-frequency range. To avoid this situation, if the gap between two subsequent picked frequencies is less than $0.5df$, only the greater peak is selected as the natural frequency.

Static stress estimation

The method proposed by Zui *et al.* (1996) which considers effects of both flexural rigidity and cable-sag on cable force estimation is used to estimate tension force of the cable as follows:

Case 1. Cable with small sag ($\Gamma \geq 3$)

$$T = 4m(f_1L)^2\left[1 - 2.2\frac{C}{f_1} - 0.55\left(\frac{C}{f_1}\right)^2\right]; \xi \geq 17 \tag{5a}$$

$$T = 4m(f_1L)^2\left[0.865 - 11.6\left(\frac{C}{f_1}\right)^2\right]; 6 \leq \xi \leq 17 \tag{5b}$$

$$T = 4m(f_1 L)^2\left[0.828 - 10.5\left(\frac{C}{f_1}\right)^2\right]; \xi \le 6 \tag{5c}$$

Case 2. Cable with large sag ($\Gamma \le 3$)

$$T = m(f_2 L)^2\left[1 - 4.4\frac{C}{f_2} - 1.1\left(\frac{C}{f_2}\right)^2\right]; \xi \ge 60 \tag{6a}$$

$$T = m(f_2 L)^2\left[1.03 - 6.33\frac{C}{f_2} - 1.58\left(\frac{C}{f_2}\right)^2\right]; 17 \le \xi \le 60 \tag{6b}$$

$$T = m(f_2 L)^2\left[0.882 - 85\left(\frac{C}{f_2}\right)^2\right]; \xi \le 17 \tag{6c}$$

Case 3. Very long cable

$$T_n = \frac{4m}{n^2}(f_n L)^2\left[1 - 2.2n\frac{C}{f_n}\right]; \xi > 200 \tag{7}$$

where f_1, f_2, f_n are respectively measured natural frequencies corresponding to first, second and n^{th} modes ($n \ge 2$); $C = \sqrt{EI/(mL^4)}$; $\xi = \sqrt{F/(EI)}L$; $\Gamma = \sqrt{(mgL)/(128EA\delta^3\cos^5\theta}[(0.31\xi + 0.5)/(0.31\xi - 0.5)]$; EI is the flexural rigidity of cable; L is the span length of cable; m is the mass of cable per unit length; δ is sag-to-span ratio which can be calculated as: $\delta = mgL/(8F)$; and θ is inclination angle of cable. Static stress of the cable is calculated by the following equation:

$$\sigma_{st} = T/A \tag{8}$$

3. EXPERIMENTAL VERIFICATION

3.1 Feasibility verification of PZT dynamic strain

An experiment was carried out to verify the feasibility of PZT sensor on dynamic strain measurement. As shown in Fig. 2, the test beam is a lab-scaled 600×60×10 mm aluminum cantilever beam. A PZT sensor FT-20T-3.6A1 produced by APC International, Ltd, was installed at the fixed end location. Dynamic voltage from the PZT was measured by a data acquisition system which consists of a DAQ card, a terminal block and a PC with MATLAB software. For calibration, an electric strain gauge (ESG) TML FLA-5-11-1L was also placed at the fixed end location. The data acquisition system for the ESG consists of a bridge box TML SB120B, a universal recorder Kyowa EDX-100A and a PC with DCS-100A software. The impact force was applied at the location 180 mm distanced from the free end.

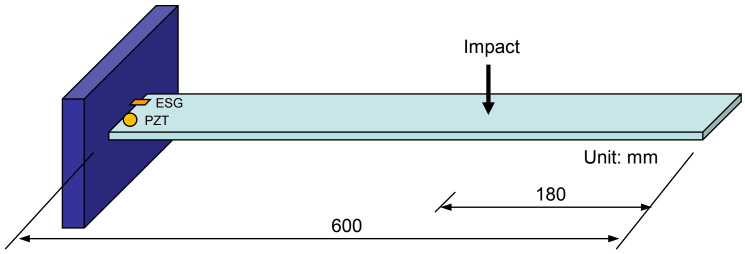
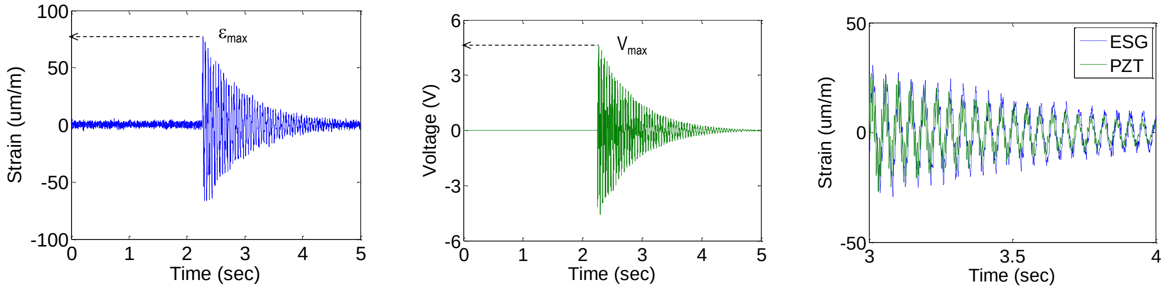


Fig. 2 Experiment setup for calibration of PZT's dynamic strain

Dynamic responses (i.e., PZT voltage and ESG strain) were measured at the same time with a sampling frequency of 1 kHz. Figure 3 shows the time history responses measured by the PZT sensor and the ESG. The maximum voltage measured by the PZT sensor was compared with the maximum strain measured by the ESG. The calibration factor for dynamic voltage of the PZT sensor is obtained as 17.5. As shown in Fig. 3(c), the calibrated signal from the PZT is well matched with the strain signal from the ESG.

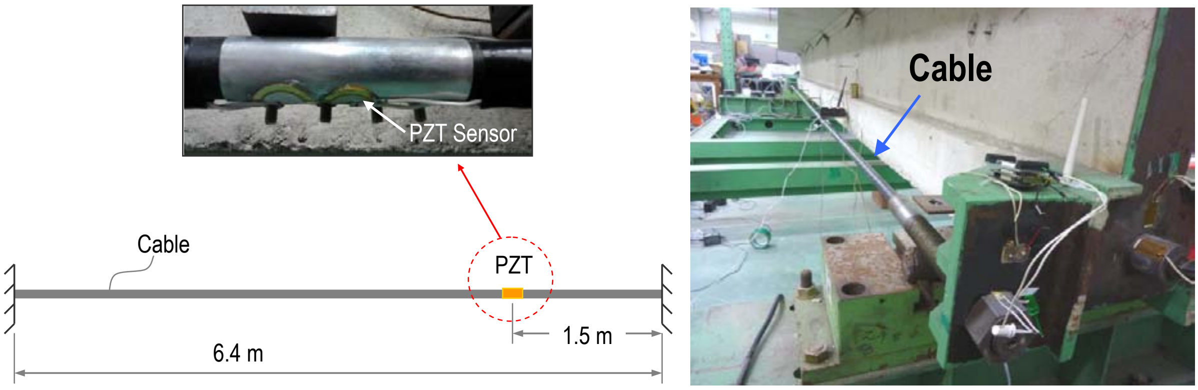


(a) ESG dynamic strain (b) PZT dynamic voltage (c) PZT strain after calibration

Fig. 3 Time history responses of PZT sensor and ESG

3.2 Dynamic stress monitoring of a lab-scale steel cable

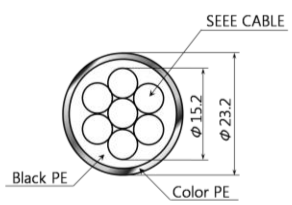
The feasibility of the proposed monitoring system was evaluated on a lab-scaled cable model as shown in Fig. 4. The cable is comprised of 7 stainless steel ropes (1x7 strand cable). The length of the cable is 6.4 m. The specifications of the cable are given in Table 1. At 1.5 m from the cable end, a PZT sensor (FT-20T-3.6A1) was bonded to the cable through an aluminum tube. The PZT sensor was connected to an Imote2/SHM-DAQ for strain monitoring as shown in Fig. 5. The data acquisition system was the same with that used for the calibration experiment on the cantilever beam. The measuring time was set as 60 second with a sampling rate of 500 Hz.



(a) Schematic of experimental setup (b) Lab-scale steel cable

Fig. 4 Experimental setup on lab-scale steel cable

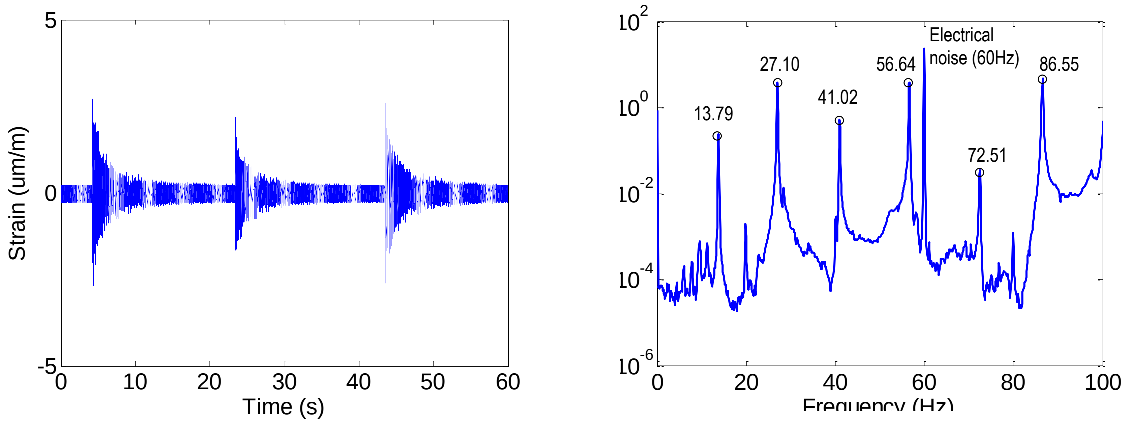
Table 1 Specifications of lab-scale cable

	Nominal diameter (mm)	15.2
	Nominal area (mm^2)	138.7
	Tensile strength (kN)	260
	Elastic modulus (kN/m^2)	190
	Unit mass (kg/m)	1.37

Monitoring of dynamic stress for different tension forces

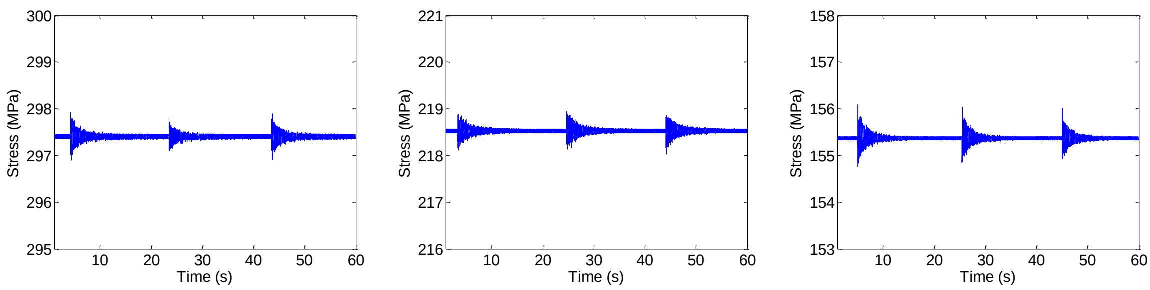
The first test was carried out in order to evaluate the performance of the proposed system on monitoring different cable force levels. Tension forces were introduced into the cable by a hydraulic jack as the cable were anchored at one end and pulled out at the other. Three levels of cable force T0-T2 (i.e., 41.2 kN, 32.4 kN, 21.6 kN) were consequently applied to the cable, in which T0 is considered as the design force. A load cell was installed at one of the cable anchorages to measure the applied tension forces. Hammer impacts were applied to the cable at the location of 2 m distanced from the cable end.

Figure 5 shows the strain variation signal measured by the PZT sensor and the corresponding power spectral density (PSD) at the design force (T0). Sharp peaks indicating resonant responses of the cable can be clearly seen from the PSD. However, the consistent noise of about 0.2 μ in magnitude is observed. This noise can be caused by the electrical effect of the PC, as a peak of 60 Hz is clearly detected in the PSD curve. As the future work, an amplifier should be designed for the PZT signal in order to reduce this effect. The dynamic stress at different cable forces is shown in Fig. 6. It is found that the estimated static stress component (297.40 MPa, 218.53 MPz and 155.37 MPa) are very close to the inflicted ones (i.e., 297.04 MPa, 219.18 MPa and 155.73 MPa).



(a) Time history response (b) Power spectral density

Fig. 5 Strain variation measured by PZT sensor at design force T0



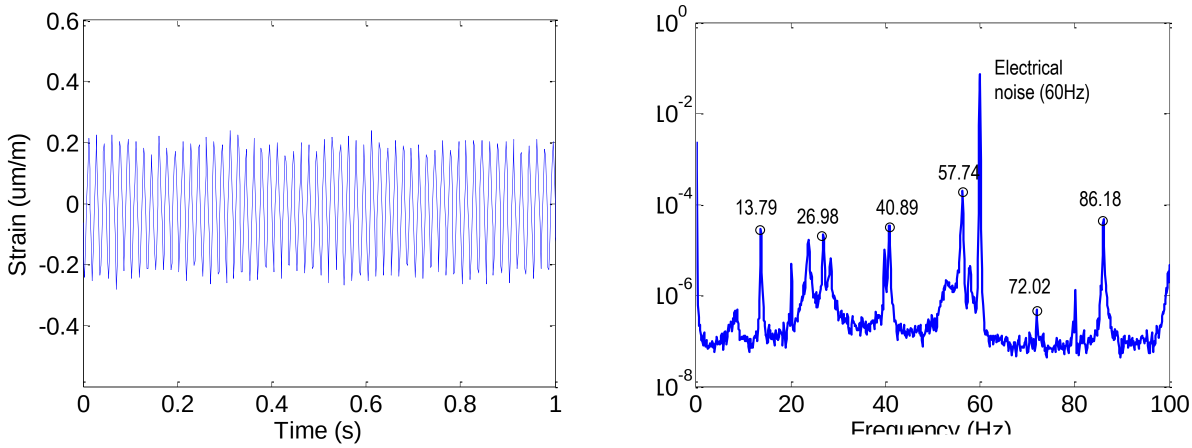
(a) T0: 41.2 kN (b) T1: 32.4 kN (c) T2: 21.6 kN

Fig. 6 Cable's dynamic stress monitoring results for three different tension forces

Monitoring of dynamic stress under different wind conditions

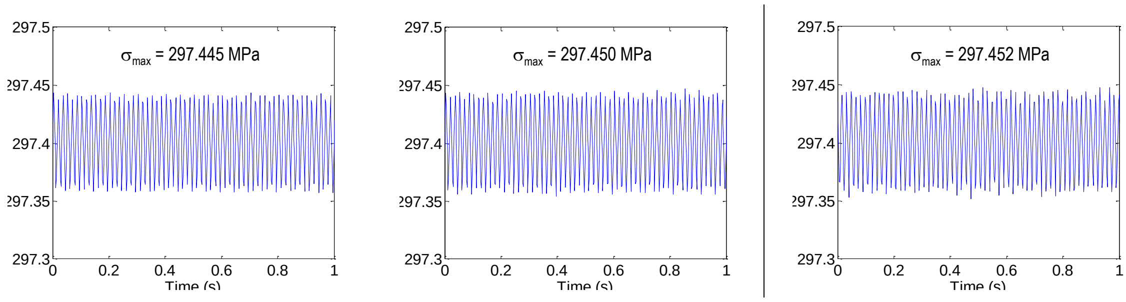
The second test was conducted in order to evaluate the performance of the proposed system on monitoring the variation of cable stress. The cable was tensioned to the design force of 41.2 kN. Vibration of the cable was excited by wind generated from two fans arranged along the cable. The simulated wind was in the direction horizontal and perpendicular to the cable. Three levels of wind speeds (i.e., 1.0 m/s; 2.2 m/s and 4.5 m/s) were consequently generated.

Figure 7 shows the strain variation signal measured in 1 second by the PZT sensor and the corresponding power spectral density (PSD) at the largest wind speed. The modal frequencies of the cable can be obtained as shown in Fig. 7(b). However, it is found that the influence of electrical noise is very significant since the measured signal is little larger than the noise level (0.2 μ in magnitude). The dynamic stress at different wind speeds is shown in Fig. 6. It is found that the estimated static stress components (all about 297.40 MPa) are very close to the inflicted ones (i.e., 297.04 MPa). Also, it is observed that the maximum stress variation becomes increasing when the wind speed increases.



(a) Time history response (b) Power spectral density

Fig. 7 Strain variation measured by PZT sensor at wind speed 4.5 m/s



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(a) Wind speed: 1.0 m/s (a) Wind speed: 2.2 m/s (a) Wind speed: 4.5 m/s

Fig. 8 Cable's dynamic stress monitoring results: wind speed 1.0m/s-4.5m/s

4. CONCLUSIONS

In this paper, a dynamic stress monitoring system for stay cables using piezoelectric strain sensors was proposed. First, a dynamic strain-based monitoring system to estimate cable stress in real-time manner was schematized. In this approach, the static stress of cable is estimated by using natural frequencies extracted from the dynamic piezoelectric voltage signal. Meanwhile, the dynamic stress component is estimated from magnitude of the signal. The signal of the piezoelectric sensor, which is strain-induced voltage, can be calibrated with the strain signal measured from a commercial electrical strain gauge. Next, the proposed monitoring system was evaluated by an experiment on a lab-scale steel cable. It was found that the estimated static stress components at different tension force cases were very close to the inflicted ones. Also, the stress variation magnitude measured by the monitoring system was found increasing reasonably when wind speed increased. In future, a signal amplifier will be designed in order to reduce the effect of electrical noise observed in the measured signal.

ACKNOWLEDGEMENTS

This research was supported by a grant from the Strategic Research Project (Development of smart prestressing system for prestressed concrete bridges) funded by the Korea Institute of Construction Technology.

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