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Innovative cable force monitoring of stay cables using piezoelectric dynamic strain responses

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Key Words : stay cable, tension force, piezoelectric strain, wireless sensor.

ABSTRACT

This study presents a method to monitor cable force of a long-span cable-stayed bridge using a smart piezoelectric sensor system. The following approaches are implemented in order to achieve the objective. Firstly, the method to utilize piezoelectric materials for the health monitoring of stay cables is presented. For strain measurement of a stay cable, a PZT-embedded smart skin is designed to overcome the difficulties of bonding PZT sensors directly on stay cables. Secondly, a piezoelectric strain monitoring system for stay cables is designed. For the operation of the sensor board, the Imote2 sensor platform is used to provide the computation, wireless communication and power supply units. The feasibility of the proposed monitoring system is then evaluated on a full-scale cable of a cable-stayed bridge.

1. Introduction

For cable supported bridges, cable systems carry most of the loads of decks and transfer those loads to foundations through pylons. However, cables are very flexible components, and they are subjected to various repeated load conditions such as vehicle traffic, wind and temperature variation. As a result, stress relaxation in cables due to loosening of cable anchorages can be strongly occurred and that may lead to significant reduction of loading capacity of the structures. Therefore, health monitoring of stay cables is very essential to ensure the structural integrity and operational safety of the cable-stayed structures.

Over the last two decades, piezoelectric materials have been widely adopted for SHM applications. The piezoelectric materials are commonly used for active monitoring of critical structural members (Park et al. 2001, Bhalla and Soh 2003, Nguyen and Kim 2012a). For vibration-based cable force monitoring in which only dynamic parameters of cables are needed (Zui el al. 1996), piezoelectric materials can be used as dynamic strain sensors. One of the advantages of piezoelectric strain sensors is that the piezoelectric strain acquisition systems are very simple since they need to measure only voltage induced by strain of the sensors. Also, piezoelectric strain sensors do not need power supply, which is very beneficial for wireless sensor applications. Additionally, PZT strain sensors are very cheap (about $1) compared with accelerometers (more than $10).

In this paper, a tension force monitoring system for stay cables using wireless piezoelectric strain sensors is developed. Firstly, the cable force monitoring method utilizing piezoelectric materials is presented. For strain measurement of a stay cable, a PZT-embedded smart skin is designed to overcome the difficulties of bonding PZT sensors directly on stay cables. Secondly, a piezoelectric strain monitoring system for stay cables is designed. For operation software, software for the automated tension

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estimation of stay cables is programmed for the sensor node. The advantages of the monitoring system are simple, energy-efficient and cost-efficient. Finally, the feasibility of the proposed monitoring system is evaluated on a stay cable of the Hwamyung cable-stayed Bridge in Korea.

2. Piezoelectric materials for health monitoring of stay cables

The principle of piezoelectric materials (PZT) as strain sensors is shown in Fig. 1. As direct effect of the materials, an electrical displacement (related directly to electrical current) is induced since a mechanical stress (or strain) is applied to a piezoelectric sensor. The strain-charge relation for the piezoelectric material can be expressed as follows (Sirohi and Chopra 2000):

$$D_3 = e_{33}^{\sigma} E_3 + d_{31}\sigma_1 \tag{1a}$$

$$\varepsilon_1 = \frac{\sigma_1}{Y^E} + d_{31}E_3 \tag{1b}$$

where D_3 is the electric displacement; e_{33}^{σ} is the dielectric constant of piezoelectric wafer; E_3 is the applied external electric field in direction-3 at zero stress; d_{31} is the piezoelectric coupling constant; σ_1 is the stress in direction-1, ε_1 is the strain in direction-1, Y^E is the Young's modulus of the material at zero-electric field. If the PZT patch is surface-bonded on a host structure, the strain of the PZT patch can be expressed in terms of voltage measured from its terminals as:

$$\varepsilon_1 = \left(\frac{e_{33}^{\sigma}}{d_{31}t_p Y^E}\right) V = k_p V \tag{2}$$

where V is the output voltage across the terminals of the PZT patch; t_p is thickness of the PZT patch; k_p is the scale factor between strain and voltage which depends on the characteristics of the PZT patch.

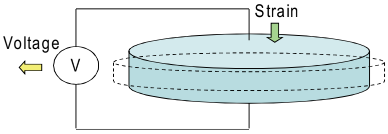


Fig. 1 Direct piezoelectric effect

In real cable-stayed bridges, it is not allowed to bond PZT sensors directly on stay cables. Also, bonding condition between the PZT sensors and cable surfaces which are made of polyethylene (PE) is not well maintained. In order to overcome those difficulties, a PZT-embedded smart skin is designed as shown in Fig. 2. A PZT sensor is bonded on a skin plate which tightly covers the cable. The deformation of the smart skin is secured by the static friction in the interface between the skin and the cable. For design specification, the skin plate should be flexible and low mass in order not to affect response of the cable. Also, its thickness should be small enough compared with the cable section and its surface should have large frictional coefficient in order to guarantee the accuracy of strain measurement.

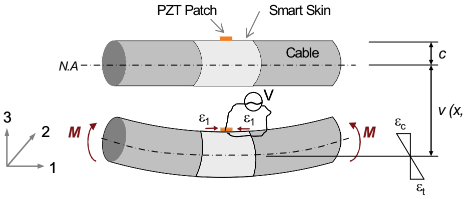


Fig. 2 Schematic of PZT-cable interaction

3. Wireless monitoring system for stay cables

3.1 Design of piezoelectric strain sensor nodes

The interest on developing wireless smart sensor nodes for efficient SHM systems has been increasing recently. The advantages of wireless sensor systems over conventional cabling sensor systems have been discussed by many researchers (Spencer et al. 2004, Lynch and Loh 2006, Kim et al. 2011). Figure 3 shows the block diagram of a piezoelectric strain sensor node. The core component of the sensor node is the digital filter QF4A512 ADC for signal conditioning with customizable sampling rates. The digital filter is used to convert the analog signal (strain-induced voltage) from a PZT sensor to digital signal. The Imote2 sensor platform is used to provide onboard computation, wireless communication and power supply. The Imote2 platform is integrated with a low power, high speed X-scale processor, PXA27x, and a wireless radio, CC2420. It also has 256 kB of SRAM, 32MB of external SDRAM, and 32 MB of program flash memory.

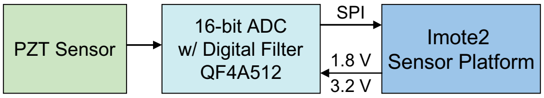


Fig. 3 Design schematic of piezoelectric strain sensor node

According to the proposed design schematic, in this study, the SHM-A sensor board developed by the University of Illinois at Urbana-Champaign, USA (Rice et al 2010) is utilized to measure piezoelectric strain responses. Since the SHM-A is also integrated with a digital filter QF4A512, a PZT sensor can be hooked up to the external channel which is used for an analog input. To distinguish from the original SHM-A, the sensor board used to measure acceleration and PZT strain is named as SHM-A(S).

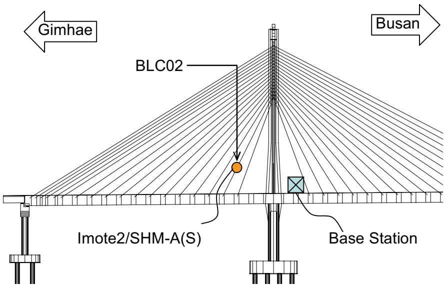
3.2 Automated cable force estimation software

The software for the sensor node is programmed according to the UIUC ISHMP Toolsuite and PKNU SSeL SHM Tools (Kim et al. 2011). For cable strain sensing, *Remotesensing* component from ISHMP Toolsuite is implemented. After finishing measuring, the strain signal is transformed to the power spectral density (PSD) using to Bartlett's procedure, in which a Hanning window with the number of FFT of 2048 is used.

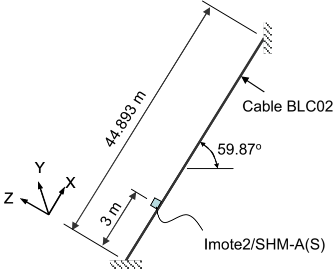
Subsequently, natural frequencies are extracted by a peak-picking method (Nguyen and Kim 2012b). In this approach, the entire frequency range is divided into *N* equal sub-frequency ranges. The interval of each range is selected to be smaller than the reduced fundamental frequency of the cable which has 20% of the design cable tension. The reduced fundamental frequency of the cable is calculated based on the string theory as: $(f_1)_{20} = \sqrt{T_{20}/(4mL^2)}$, in which T_{20} is taken as 20% of the design tension. In each sub-frequency range, the natural frequency is recognized if its magnitude is the largest and at least five times larger than the magnitude mean in that range. Once natural frequencies are determined, the cable tension force is estimated using the practical formulas of Zui et al. (1996).

4. Experimental evaluation

The feasibility of the proposed system was evaluated on a stay cable of the Hwamyung cable-stayed Bridge in Korea, as shown in Fig. 4. The bridge consists of three spans (a 270-m mid span and two 115-m side spans) which are supported by 72 multi strain-type stay cables. Among the 72 cables, a short cable BLC02 at the span toward Gimhae side was selected for the evaluation test of the monitoring system. The selected cable is comprised of 49 stainless steel 1x7 strands. It has the length of 44.89 m, the nominal area of 7350 mm^2, and the mass per length of 67.54 kg/m.



(a) Hwamyung Bridge



(b) Cable BLC02

Fig. 4 Sensor layout on the Hwamyung Bridge

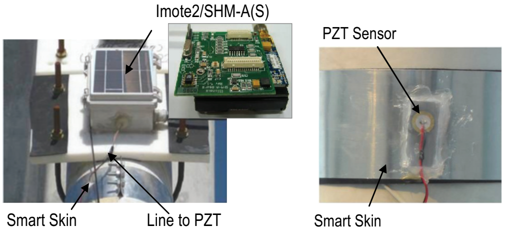
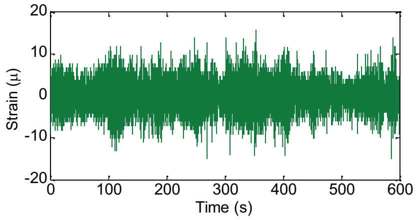


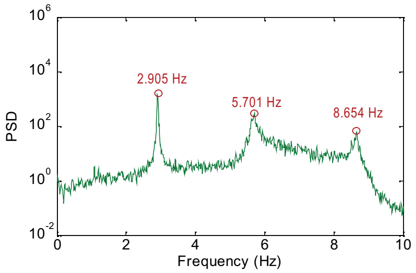
Fig. 5 Experimental setup for cable BLC02

A PZT sensor (FT-35T-2.8A1) was bonded to the cable through a smart skin at location of 3 m from the cable end as shown in Figs. 4(b) and 5. The PZT sensor was connected to an Imote2/SHM-A(S) for strain monitoring. Here the smart skin was designed as an aluminum tube which had the thickness of 0.4 mm and covered tightly the cable through bolt connections. The sensor node was powered by a Li-ion polymer rechargeable battery (Powerizer 3.7V, 10000mAh). A solar panel (SPE-350-6) was mounted on the sensor box to harvest the solar energy and recharge the battery. The sensor node was automatically activated every two hours, and measured dynamic strain in 10 minutes with a sampling rate of 25 Hz and a cut-off frequency of 10 Hz. The environmental temperature was also measured by the SHT11 temperature and humidity sensor in the SHM-A(S) sensor board.

Figure 6 shows the dynamic strain signal and the corresponding PSD measured from the PZT sensor. Sharp peaks indicating resonant responses of the cable can be clearly seen from the power spectral density. Natural frequencies of the cable were extracted by the automated peak-picking process. The reduced fundamental frequency of the cable with 20% of the design force was found to be 1.33 Hz. Hence, for picking natural frequencies, 8 sub-power spectral densities with 1.25 Hz intervals were made from the original one.



(a) Time history response



(b) Frequency response

Fig. 6 PZT dynamic strain response of cable BLC02

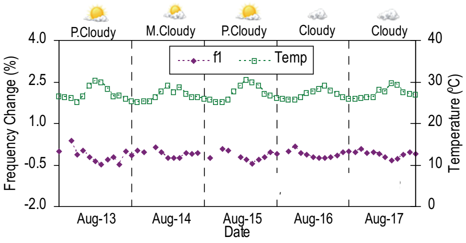
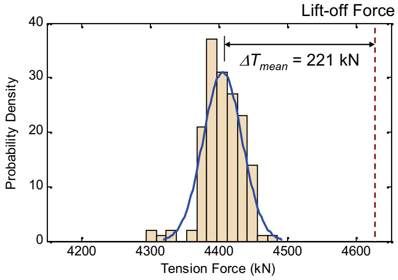


Fig. 7 Changes in 1st natural frequency due to temperature variation on cable BLC02

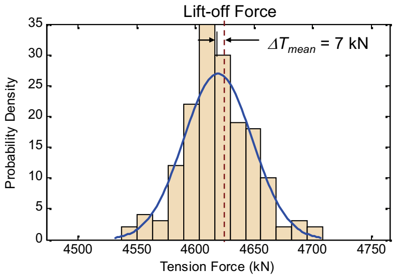
The relative changes in the first natural frequency versus temperature change over five-day monitoring are shown in Fig. 7. The natural frequency decreases as the temperature goes up, and vice versa. This implies axial stress of the cable is partially released when temperature increases and vice versa. In order to compensate the effect of temperature variation on vibration responses of cable BLC02, linear relationship between the temperature and the first natural frequency was made as follows:

$$\Delta f_1^s = -0.0023\Delta t \tag{3}$$

The distribution density of the estimated tension force of cable BLC02 without temperature compensation is shown in Fig. 8(a). It is found that the mean value of estimated force is found to be 4405 kN which has about 4.8% difference from the value of the lift-off test. Note that the tension force was estimated at the temperatures varied from 21.9°C to 44.7°C, while the tension force from the lift-off test was measured at -2°C. In order to improve the accuracy of the estimation, the values of the 1st natural frequency were fine-tuned by the difference of the measured temperatures with regard to -2°C. Thus, the compensation process was also embedded to the sensor node using Eq. (3). Figure 8(b) shows the distribution of the estimated tension force with temperature compensation. As shown in the figure, the accuracy of estimation is improved significantly by considering the difference in temperature. The mean value of estimated force after temperature compensation is found to be 4619 kN which is very close to the value obtained from the lift-off test by about 0.15% difference.



(a) Temperature-independent estimation



(b) Temperature-compensated estimation

Fig. 8 Distribution of estimated cable tension force

5. Conclusions

In this study, a method of monitoring health status of stay cables by wireless piezoelectric sensing systems was developed. The principle of PZT-embedded smart skins for dynamic strain sensing was first presented. Utilizing the piezoelectric materials for strain measurement of stay cables, a vibration-based monitoring method for cable was presented. Then the design of an autonomous health monitoring system for stay cables using the Imote2/SHM-A(S) sensor nodes and PZT sensors was described. The feasibility of the monitoring system was evaluated on a stay cable of the Hwamyung cable-stayed Bridge in Korea.

From the experiment results, the following conclusions have been made. Vibration responses of the cable were sensitively measured by the PZT sensor embedded on the smart skin. The cable tension forces were successfully estimated and monitored by the wireless piezoelectric sensing system. The differences between the estimated forces after temperature compensation and the value obtained from the lift-off test are reasonably small.

Acknowledgements

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