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Ambient Vibration-Measurement of Real Building Structure by Using Fiber Optic Accelerometer System

Dae-Hyun Kim

Abstract Vibration-based structural health monitoring is one of non-destructive evaluation (NDE) techniques for civil infrastructures. This paper presents a novel fiber optic accelerometer system to monitor civil engineering structures and a successful application of the novel sensor system for measuring ambient vibration of a real building structure. This sensor system integrates the Moiré fringe phenomenon with fiber optics to achieve accurate and reliable measurements. The sensor system is immune to electromagnetic (EM) interference making it suitable for difficult applications in such environments involving strong EM fields, electrical spark-induced explosion risks, and cabling problems, prohibiting the use of conventional electromagnetic accelerometers. A prototype sensor system has been developed, together with a signal processing software. The experimental studies demonstrated the high-performance of the fiber optic sensor system. Especially, the sensor was successfully used for monitoring a real building on UCI (University of California Irvine, USA).

Keywords: Structural Health Monitoring, Vibration-Based NDE, Fiber Optic, Accelerometer

1. Introduction

Extensive research has recently been performed to study structural integrity using structural vibration data measured by in-structure sensors such as accelerometers (Feng and Kim, 1998; Feng and Bahng, 1999). However, one of the major obstacles preventing sensor-based monitoring is the unavailability of reliable, easy-to-install, and cost-effective sensors. Civil engineering structures place unique demands on sensors. Besides accuracy, sensors and their cables are expected to be reliable, low in cost, lightin weight, small in size, resistant to EM interference, and long in service life. They are required to with stand harsh environments, be moisture-, explosion-, lightning-proof, and corrosion-resistant. Civil engineering structures are usually very large, demanding easy cabling of the sensors. It is very difficult, if not impossible, for the currently available electric-type sensors to satisfy these demanding requirements. For instance, these sensors use electric cables for signal transmission and power supply, which may act as large antennae picking up various kinds of noise, creating ground loops, and are susceptible to lightning strikes.

Emerging fiber optic sensor technologies have shown great potential to overcome the difficulties associated with the conventional sensors. They are immune to EM noise and electric shock and thus can be used in explosion-prone areas. Several kinds of fiber optic sensors have been developed over the last two decades to take advantage of these merits (Udd et al, 1995; Lee, 2003). There have also been many field applications of fiber optic sensors for health monitoring of civil engineering

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Received: October, 10, 2006, Accepted: November 25, 2006. Department of Mechanical Engineering, Seoul National University of Technology, Seoul 139-743, Korea (E-mail: dkim@snut.ac.kr)

structures (Li et al. 2004; Ansari, 2005; Moerman et al., 2005) However, very few optical fiber sensors, particularly dynamic sensors (e.g. accelerometers, dynamic strain gauges, and pressure sensors) have been successfully commercialized for monitoring civil engineering structures (Kim et al., 2004a; Kim, et al., 2004b; Kageyama et al, 2005)

In this paper, we present a novel fiber optic accelerometer for monitoring large-scale civil infrastructure such as utility lifelines, highway bridges, and buildings. In the fiber optic sensing system, the sensor head uses the optic phenomenon of Moiré fringeas the mechanism to measure displacement. Optic energy is sent, though multimode optic fibers, to the sensor head where the physical measurand is modulated into light signals via the Moiré phenomenon (Feng and Kim, 2006). Usually, Moiré phenomena have a long history being used for engineering measurement (Post et al., 1994). Therefore, the fiber optic sensor takes advantage of this well-established and reliable measurement technique and integrates it with the fiber optics in a novel way. Aprototype has been developed and tested to measure the physical parameters such as the natural frequency and the damping ratio. Finally, we monitored ambient vibration of a real building on UCI (University of California Irvine, USA) campus as an application of the prototype and then performed FFT analysis of the ambient vibration signal to find a natural frequency of the building.

2. Moiré-Fringe-Based Fiber Optic Accelerometer

2.1 Principle of the Work

The fiber optic accelerometer head contains apendulum that can be modeled as a single-degree-of-freedom dynamic system with a mass m, a spring stiffness k and a damper c, as shown in Fig. 1.

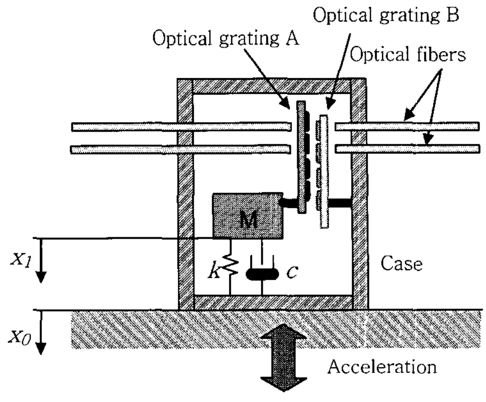


Fig. 1 Conceptual design of Moiré fringe-based fiber optic accelerometer

The equation of motion for the pendulum system is simply expressed as follows:

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_o \tag{1}$$

where $x=x_1-x_0$, the relative displacement between the pendulum mass and the sensor casing (i.e., the pendulum support) and $\ddot{x}_o$ is the acceleration imparted to the sensor (i.e., the "excitation acceleration") that is to be measured.

Equation (1) can be rewritten in terms of the damping ratio ζ and the natural frequency of the pendulum ω_n:

$$\ddot{x} + 2\omega_n\zeta\dot{x} + \omega_n^2 x = -\ddot{x}_o \tag{2}$$

where $\omega_n = \sqrt{\frac{k}{m}}$ and $\zeta = \frac{c}{2m\omega_n}$.

Assuming that $\ddot{x}_o = A_{excite}e^{i\omega t}$, where ω is the frequency of the excitation acceleration, then the steady state response should be $x = D_{response}e^{i\omega t}$. In theory, the ratio of $D_{response}$ to A_{excite} should satisfy the following relation:

$$\frac{D_{response}}{A_{excite}} = \frac{-1}{\omega_n^2 - \omega^2 + 2i\omega_n\omega\zeta} \tag{3}$$

Thus, if one sets $r = \frac{\omega}{\omega_n}$, then the deformation response factor (i.e., transmissibility) R can be expressed as follows:

$$R = \left| \frac{D_{response}}{A_{excite}} \right| \cdot \omega_n^2 = \frac{1}{\sqrt{(1-r^2)^2 + (2r\zeta)^2}} \qquad (4)$$

where $r = \frac{\omega}{\omega_n}$.

One can carefully design a system with a pendulum of mass m and spring stiffness k such that the natural frequency ω_n is much larger than ω. As ω_n increases, the ratio r approaches zero, and in turn the deformation response factor, R approaches unity. In this condition, Equation(4) demonstrates that the relative displacement, x is directly proportional to the excitation acceleration, $\ddot{x}_o$. Consequently, one can derive the acceleration of the sensor simply by gauging the relative displacement, x between the pendulum mass and the sensor casing. In this paper, the fiber optic accelerometer system applies a Moiré fringe technique via gratings and optical fibers to reliably measure the relative displacement, x.

As shown in Figure 1, the fiber optic accelerometer contains a pairs of parallel optical grating panels, one fixed to the mass of the pendulum and the other to the sensor casing. As a result, the relative displacement of the two optical gratings is the same as the displacement between the mass and the sensor casing. Because one optical grating is fixed to the mass while the other is fixed to the sensor casing, the relative displacement of the two optical gratings is the same as the displacement between the mass and the sensor casing. When two optical gratings consisting of alternating parallel transparent and opaque strips (i.e. "rulings") are overlaid, light will either be transmitted (when the transparent regions coincide) or be obstructed (when they do not coincide). If the rulings on one grating are aligned at a small angle relative to those on the other, then the loci of their intersections will be visible as dark Moiré fringes running approximately perpendicular to the rulings as shown in Figure 2.

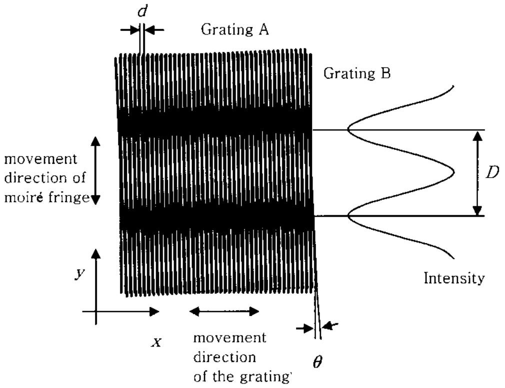


Fig. 2 Moiré fringes for displacement amplification

As the two parallel grating panels move with respect to each other in the X direction, the Moiré fringes will move in the Y direction. The Moiré fringes will shift by one pitch distance D in the Y direction when the two gratings shift in the X direction by one grating pitch d. The Moiré fringe pitch D can be designed using the relation $D = d/\theta$ where is an angle subtended by the rulings of the two gratings. If one lets θ approach zero in the relation, the ratio D/d (i.e. the "displacement amplification") can become very large. Consequently, if a small θ is chosen, one can considerably amplify a small grating movement d into a large Moiré fringe movement D. One would facilitate accurate displacement measurement by designing a small θ and thus a large D.

The relative displacement between the two gratings can be measured by tracking the Moiré fringes as they pass through one point. However, observing the Moiré fringes at only one point yields no information regarding the direction of their movement, which is necessary to determine the direction of the relative movement of the two gratings. Fortunately, one can determine the direction as well as the amplitude of the displacement by tracking the fringes at two points which are separated by a quarter of the fringe width *D* across the fringe profile. In order to observe the Moiré fringe at two different points, two pairs of optical fibers are placed perpendicular to the optical grating panels, as illustrated in Figure 1.

2.2 Sensing Mechanism

The light intensity signals at the two observing points are sinusoidal function of displacement with a phase difference of π/4 with respect to each other. When superposed on a DC component, the light intensities at these two observing points can be expressed as follows:

$$s_1(t) = C_1 \sin\left(\frac{2\pi x(t)}{d}\right) + C_2$$
$$s_2(t) = C_3 \sin\left(\frac{2\pi x(t)}{d} + \frac{\pi}{4}\right) + C_4 = C_3 \cos\left(\frac{2\pi x(t)}{d}\right) + C_4 \quad (5)$$

where $x(t)$ is the relative displacement ($u_o(t)-u_i(t)$) and C_1, C_2, C_3 and C_4 are constants. The above expressions can be normalized as follows;

$$\bar{s}_1(t) = \frac{s_1(t) - C_2}{C_1} = \sin\left(\frac{2\pi x(t)}{d}\right)$$
$$\bar{s}_2(t) = \frac{s_2(t) - C_4}{C_3} = \cos\left(\frac{2\pi x(t)}{d}\right) \quad (6)$$

The relative displacement $x(t)$ can be obtained by unwrapping the two signals as follows;

$$x(t) = \frac{d}{2\pi} unwrap\left(\arctan\left(\frac{\bar{s}_1(t)}{\bar{s}_2(t)}\right)\right) \quad (7)$$

By tracking two fringes, $\bar{s}_1(t)$ and $\bar{s}_2(t)$, the direction of the displacement can be determined as well as its amplitude. Finally, the measured relative displacement can be converted into the sensor's acceleration by using Equation (4).

2.3 Fiber Optic Accelerometer Sensor System

A prototype of the fiber optic accelerometer sensor was developed as shown in Figure 3. The prototype is composed of a mass, a spring and a damper inside the case. Two glass gratings (Quartz, pitch=200 μm) are used as the mass. To drive light sources and photo detectors, an electric circuit system was also manufactured. Finally, an algorithm and signal processing software was developed to determine the direction as well as the amplitude of the displacement based on viewing the fringes at two points apart across the fringe profile by a quarter of the fringe width *D*.

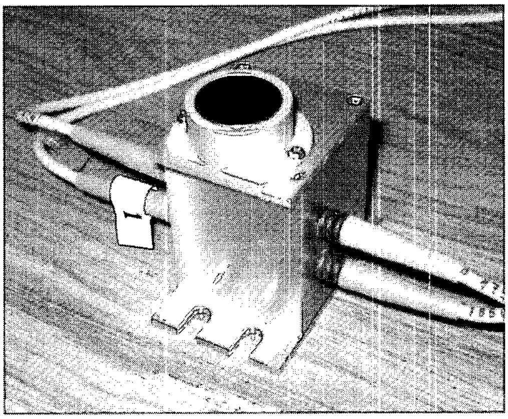


Fig. 3 The prototype of the fiber optic accelerometer

Figure 4 shows a light control unit developed in this study for driving one sensor head and processing the sensor signals. It provides the light source to the sensor head through the two optical fibers (multimode fiber 62.5/125 μm) and detects the intensity variation of the light transmitted through the two optical gratings. Totally two LEDs (AMP Co., 1300 nm) and two photo diodes (AMP Co., InGaAs) are used in this unit. A battery is included in the unit for portability. The control unit has a simple structure and the cost is much lower than many of the existing fiber optic sensor systems.

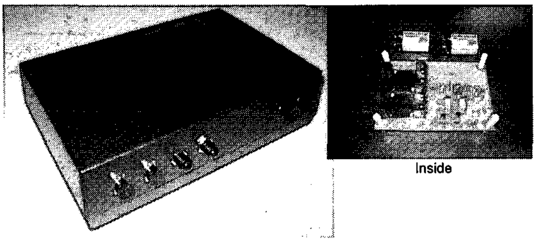


Fig. 4 Light control unit including LED and PD

3. Characterization of the Prototype Sensor Head

We need to characterize the developed fiber optic accelerometer to use the fiber optic accelerometer for measuring a structural vibration. Above all, its natural frequency and its damping ratio are the most important parameters. In this section, the physical features were determined by the acquisition of responses to external acceleration made by a shaking table (APS Dynamics, Inc. APS-113). A reference accelerometer (Kinematrics, FBA-11) was used for verifying the developed fiber optic accelerometer.

Because of the difficulty in obtaining the static sensor response using vibrator generator, the natural frequency and the damping ratio were determined by obtaining the frequency response curve experimentally. The shaking table was operated at selected frequencies, the response was observed until the transient part damps out, and the amplitude of the steady state acceleration was measured. The frequency of the shaker was adjusted to new value and the measurements were repeated. The forcing frequency was varied over a range that includes the natural frequency of the system. A frequency response curve in the form of transmissibility versus frequency ω was plotted directly from the measured data as shown in Figure 5. The transmissibility is defined as a ratio between a measured acceleration and an excited acceleration. Natural frequency (ω_n) and damping ratio (ζ) can be determined as 21.8 Hz and 0.121 respectively by the half-power bandwidth methodfrom the frequency response curve. Theoretical transmissibility can be also calculated by these two parameters and Equation (4) in the section 2.1. As shown in Figure 5, the measured transmissibility has a good agreement with the theoretical one.

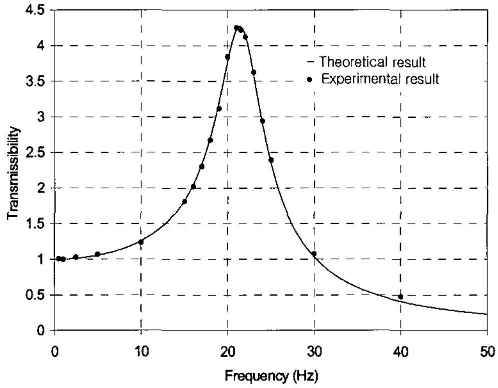


Fig. 5 Comparison of measured and theoretical transmissibility

4. Monitoring of Ambient Vibration of Cal-(IT)^2 Building

UCI (University of California Irvine, USA) has a special building that is Cal-(IT)^2 building. It has totally 32 accelerometers on the floors, the ceilings even under the soil to monitor its structural health. We applied the fiber optic accelerometer to the building to measure the ambient vibration of the building as shown in Figure 6.

In this section, it is made comparison of the signals obtained from two different accelerometers installed in the same point of the building. One is our fiber optic accelerometer while the other is a conventional servo accelerometer (AS-3257, Tokyo Sokushin Co.).

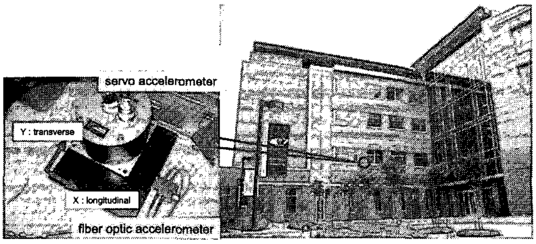


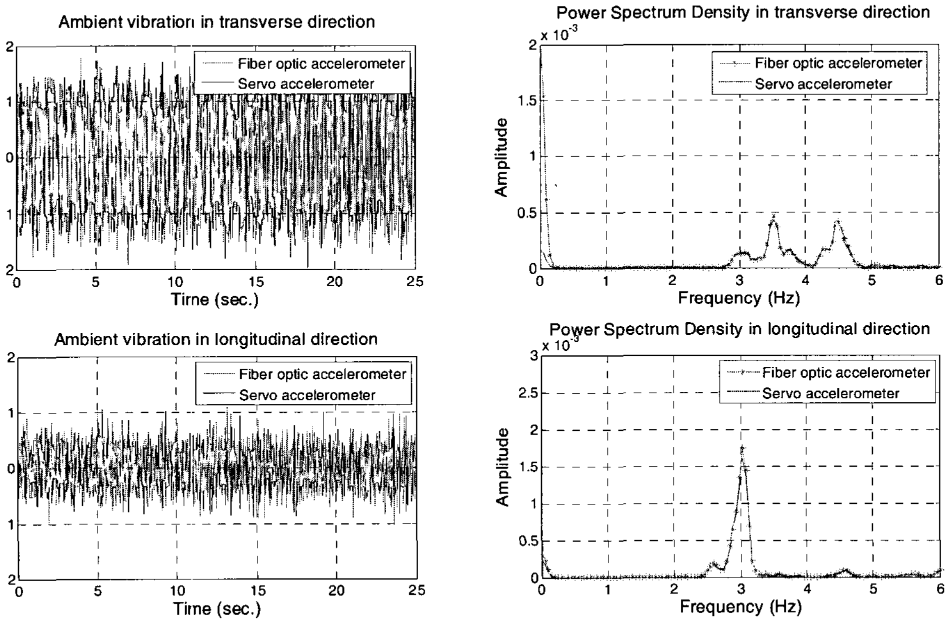
Fig. 6 Installation of two sensors to measure an ambient vibration of the Cal-(IT)^2 building

The X and Y-directional ambient vibrations were recorded for about seven minutes respectively. These two directional vibrations indicate the in-plane vibration of the building. The measured acceleration agrees well with the acceleration measured by the reference as shown Figure 7(a). To analyze the real goodness of the fiber optic acceleration, the power spectrum density also results to be a nice way of comparison of two sensor systems as shown in Figure 7(b).

As shown in the time history of Figure 7(a), the acceleration of the measured ambient vibration is under about 0.2 mg. The result shows that the fiber optic accelerometer system can measure the small acceleration successfully. The upper FFT result also shows that the fiber optic accelerometer has higher S/N ratio than the reference accelerometer. And the lower FFT result presents that the building has the first natural frequency of 3 Hz in longitudinal direction of the building.

5. Conclusions

This paper presented a novel fiber optic accelerometer for the structural health monitoring of civil structures. The prototype including a sensor head as well as a light control unit was manufactured and tested for measuring physical parameters that were necessary for signal processing. Moreover, the fiber optic accelerometer was successfully used for monitoring the Cal-(IT)^2 real building on UCI campus. In this experiment, the fiber optic accelerometer gave a signal and results that were completely comparable with that coming out from the different commercialized type. In the power spectrum analysis, the featured frequencies are also well caught by two accelerometers, individuating the frequency peaks. Finally, the fiber optic accelerometer successfully measured the ambient vibration of which magnitude was about 0.2 mg and the spectrum analysis presented that the building had the first natural frequency of 3 Hz in longitudinal direction of the building. Additionally, we could monitor the building structure to detect damage in real time by using the fiber optic accelerometer system.



(a) Acceleration (b) Power spectrum of the acceleration

Fig. 7 Acceleration and power spectrum of ambient vibration in X and Y-direction

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