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Vibration-Monitoring of a Real Bridge by Using a Moiré-Fringe-Based Fiber Optic Accelerometer

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Abstract This paper presents the use of a novel fiber optic accelerometer system to monitor ambient vibration (both wind-induced one and vehicle-induced) of a real bridge structure. This sensor system integrates the Moiré fringe phenomenon with fiber optics to achieve accurate and reliable measurements. A low-cost signal processing unit implements unique algorithms to further enhance the resolution and increase the dynamic bandwidth of the sensors. The fiber optic accelerometer has two major benefits in using this fiber optic accelerometer system for monitoring civil engineering structures. One is its immunity 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. The other is its ability to measure both low- and high-amplitude vibrations with a constantly high resolution without pre-setting a gain level, as usually required in a conventional accelerometer. The second benefit makes the sensor system particularly useful for real-time measurement of both ambient vibration (that is often used for structural health monitoring) and strong motion such as earthquake. Especially, the semi-strong motion and the small ambient one are successfully simulated and measured by using the new fiber optic accelerometer in the experiment of the structural health monitoring of a real bridge.

Keywords: Fiber Optic Accelerometer, Real-Bridge, Structural Health Monitoring, NDT

1. Introduction

Advanced sensors and monitoring technologies can play an important role in prioritizing the repair and rehabilitation process. They are also improving the cost-effectiveness of inspection and maintenance, and ultimately enhancing the longevity and safety of civil infrastructure systems such as bridges, highways, buildings and pipelines. Extensive research has recently been performed to study structural integrity using structural vibration data measured by in-structure sensors such as accelerometers (Feng, 1998). 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, light in weight, small in size, resistant to EM interference, and long in service life. They are required to withstand harsh environments, be moisture-, explosion-, and 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

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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). There have also been many field applications of fiber optic sensors for health monitoring of civil engineering structures (Li at al., 2004 and Ansari, 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 at al., 2004 and Kageyama et al., 2005).

This paper presents a new fiber optic accelerometer (FOA) for monitoring large-size structures such as civil infrastructures. The sensing mechanism of the sensor head is based on a novel integration of the moiré fringe phenomenon with fiber optics (Kim and Feng, 2005; Feng and Kim, 2006 and Kim and Feng, 2007). The proposed sensor takes the advantage of this well-established and reliable measurement technique by employing fiber optics in a novel way. Moreover, the accelerometer has another merit such as stability of the resolution. Usually, the resolution of a conventional type of accelerometer is affected by the measurable range of acceleration. The gain should be adjusted to the measurable range for high resolution. However, the proposed accelerometer can keep the high resolution in the whole measurable range without the adjustment of the gain.

In this paper, the fiber optic accelerometer was applied to monitor a real bridge in South Korea. In this experiment, the accelerometer successfully measured the large vibration induced by a heavy truck as well as small one without any adjustment of the gain. Even though the vibration induced by a heavy truck was not enough to simulate the strong motion, it is highly expected that the strong motion e.g. earthquake can also be measured along with the ambient vibration (traffic-induced vibration or wind-induced vibration) by using the accelerometer.

2. Novel Fiber Optic Accelerometer

2.1 Principle of Sensing Mechanism

The proposed accelerometer head contains a pendulum 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. The equation of motion for the pendulum system is simply expressed as follows,

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_o \tag{1}$$

where u is the relative displacement ($u = u_1 - u_0$ in Fig. 1) between the pendulum mass and the sensor case, $\ddot{u}_o$ is the acceleration imparted to the sensor (the "excitation acceleration") that is to be measured.

Equation (1) can be rewritten in terms of the damping ratio ζ_0 and the natural frequency of the pendulum ω_0:

$$\ddot{u} + 2\omega_0\zeta_0\dot{u} + \omega_0^2 u = -\ddot{u}_o \tag{2}$$

where $\omega_0 = \sqrt{\frac{k}{m}}$ and $\zeta_0 = \frac{c}{2m\omega_0}$.

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

$$\frac{D_{response}}{A_{excite}} = \frac{-1}{\omega_0^2 - \omega^2 + 2i\omega_0\omega\zeta_0} \tag{3}$$

Thus, *the deformation response factor* (R) and *the phase lag* (ϕ) can be expressed as follows;

$$R = \left|\frac{D_{response}}{A_{excite}}\right| \cdot \omega_0^2 = \frac{1}{\sqrt{(1-r^2)^2 + (2r\zeta)^2}} \qquad (4)$$
$$\phi = -\tan^{-1}\left(\frac{2\zeta r}{1-r^2}\right)$$

where $r = \dfrac{\omega}{\omega_0}$.

One can carefully design a system with a pendulum of mass m and a spring of stiffness k such that the natural frequency ω_0 is much larger than ω. By allowing ω_0 to increase without bound, the ratio of r approaches zero. In turn, allowing r to approach zero causes the deformation response factor (R) to approach unity. In this condition, the Equation (4) demonstrates that the relative displacement (u) is directly proportional to the excitation acceleration ($\ddot{u}_o$). Consequently, one can derive the acceleration of the sensor simply by gauging the relative displacement (u) between the pendulum mass and the sensor casing. In this paper, the proposed fiber optic accelerometer system applies a moiré fringe technique via gratings and optical fibers in order to reliably measure the relative displacement (u).

As shown in Fig. 1, the fiber optic accelerometer also consists of one mass, one spring and one damper as a single-degree-of-freedom system. Particularly, two optical grating panels are attached to the mass and to the sensor case respectively. Two pairs of optical cables are aligned perpendicular to the optical grating panels. Because one optical grating is attached to the mass of the sensor 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 (Kim and Feng, 2005; Feng and Kim, 2006 and Kim and Feng, 2007).

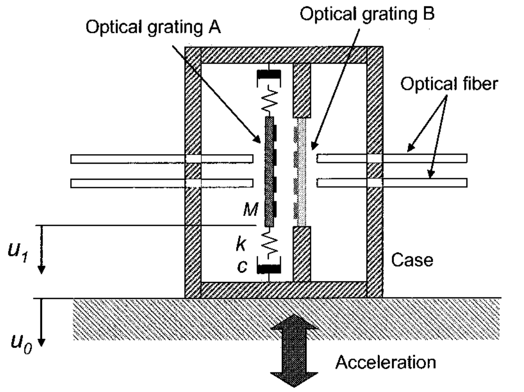


Fig. 1 Conceptual design of Moiré-fringe-based fiber optic accelerometer

In theory, 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, the direction can be determined 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.

2.2 Moiré-Fringe-Based Fiber Optic Sensor System

As shown in Fig. 2, a prototype fiber optic accelerometer system was successfully developed, which consists of a sensor head, a control unit for driving the sensor head and a signal processing unit.

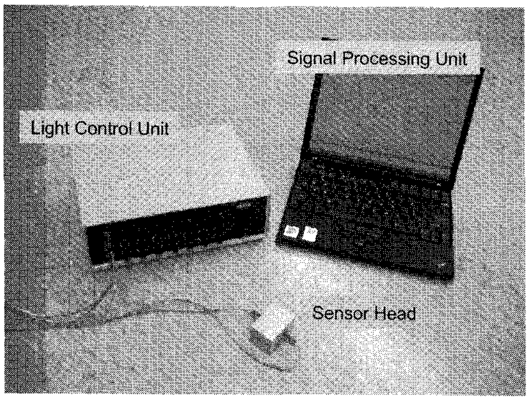


Fig. 2 Prototype of fiber optic accelerometer sensor system

The prototype sensor head has a dimension of 33*33*48 mm and a weight of 150 g. The sensor head consists of a pendulum with a mass, a spring, and a damper, together with two glass gratings and two pairs of optical fibers. The sensor head is linked to the control unit by the two optical fibers. The control unit provides the light source to each sensor head through two optical fibers and detects the intensity variation of the light transmitted through the two optical gratings. Totally sixteen LEDs and sixteen photo diodes are used in this unit. A rechargeable 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. Moreover, an unique algorithm is applied to the signal processing unit to convert the raw signals into acceleration (Kim and Feng, 2005 and Kim and Feng, 2007).

3. Structural Health Monitoring of a Real Bridge

3.1 Description of a Test Bridge

Korea Highway Corporation (KHC) built a test road to verify and enhance the pavement design guides based on the measured data from the real traffic and environmental conditions. The test road is an ordinary two lane expressway of 7.7 km long constructed along the Joongbu Inland Expressway in Korea, as shown in Fig. 3. There are 3 test bridges along the test road. Field verifications of the present novel fiber optic accelerometer were made on a concrete box girder bridge. The forced vibration tests due to running trucks and the ambient vibration tests were carried out on the Geumdang Bridge, which is a 3-span continuous bridge composed of concrete box girder and the length of each span is 38 m, 46 m, and 38 m, respectively.

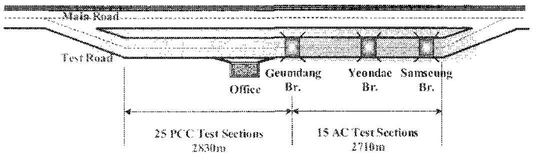


Fig. 3 KHC Test Road on Jungbu Inland Expressway in Korea

3.2 Vehicle Running Tests Using Fiber Optic Accelerometer

Vehicle running tests were carried out to verify the performance of the novel fiber optic accelerometer. Since only one FOA sensor head was available, roving tests were performed three times as shown in Fig. 4. Fig. 4 shows the geometry of the test bridge and the location of FOA at each test set.

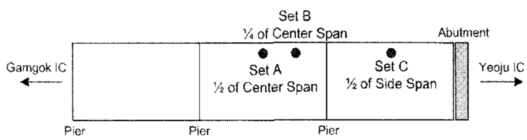


Fig. 4 Location of FOA at each test set

To suggest a reference, a vertical acceleration at the location of 1/2 of center span (set A) was measured by the conventional measurement equipments including the accelerometer (393B12, PCB electronics) and the AD converter with 12-bit resolution at the sampling rate of 200 Hz, independently (not simultaneously) with the

FOA. The vibration level was found to be 0.0005 g – 0.02 g as shown in Fig. 5. When vehicles run over the bridge, the vibration level reaches 100 times of the ambient vibration mainly due to wind. In addition, the wind speed has not been measured at the field tests, since the correlation analysis between the wind speed and the structure's vibration characteristics is beyond the scope of this study. To enhance the amplitude resolution, it is required to control the signal gain in the data acquisition equipment, when the commercial devices are utilized for measuring the signals with various response levels. Low signal gain needs to be set to measure high-amplitude responses without overload alarm, when vehicles are running over the test bridge; the ambient vibration due to wind with low amplitude requires a high gain value to make the signal readable, which may naturally cause frequent overload alarm. Setting up a proper gain value is a trade-off problem. This issue will be problematic when the accelerometer is utilized for measuring ambient vibration as well as strong motion such as earthquake. In this study, two different gain values of 1 and 10 were utilized for measuring the vehicle-induced vibration and ambient vibration, respectively.

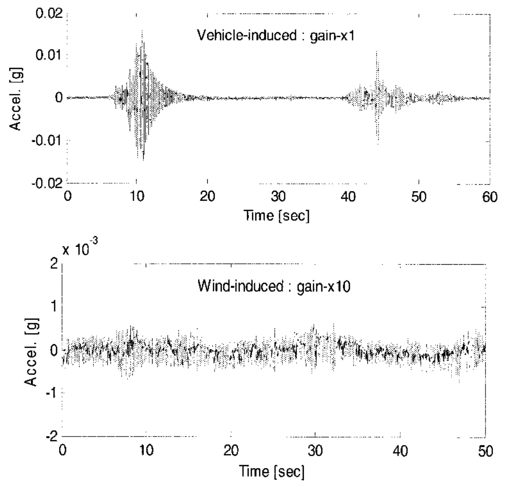


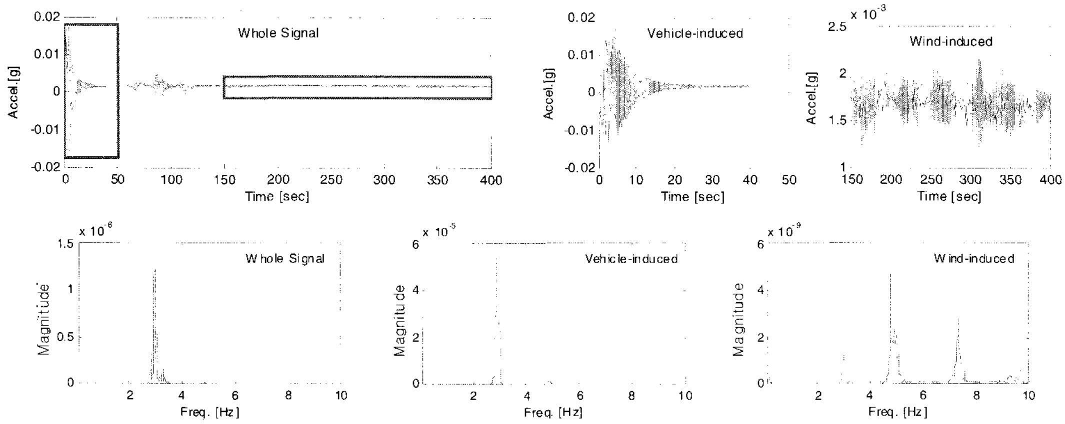
Fig. 5 Acceleration time histories obtained by the conventional accelerometer

Vehicle-induced vibration with high amplitude and ambient vibration with low amplitude were simultaneously measured without any adjustment of the gain using the novel FOA. Measured acceleration time histories were shown in Fig. 6. Fourier spectra were calculated using the whole measured signal, vehicle-induced vibration with high amplitude and ambient vibration with low amplitude, respectively as shown in Fig. 6. In addition, Fig. 7 has been suggested as a reference showing the results of experimental modal analysis using the conventional sensors (Yi et al., 2007). Finally, the obtained results can be summarized as follows;

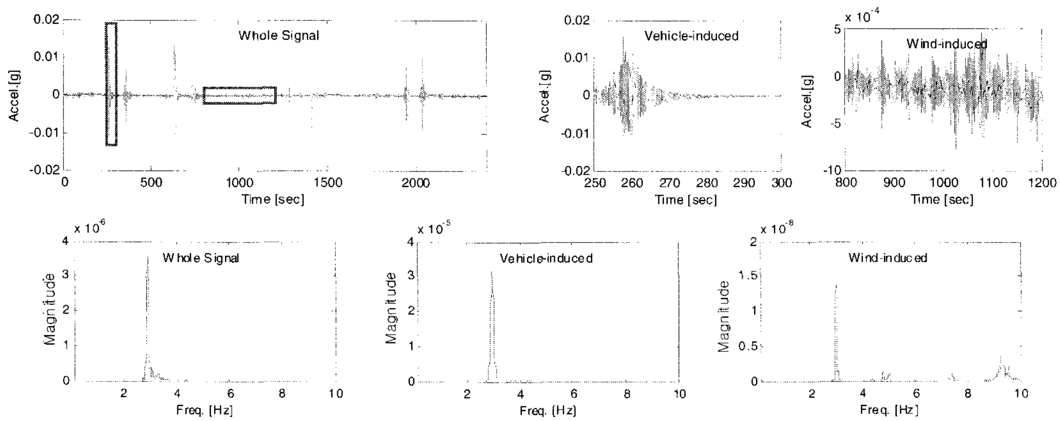
(1) Structural responses including high-amplitude vehicle induced vibration and low-amplitude ambient vibration were successfully measured simultaneously using the novel FOA developed.
(2) When the whole signal was utilized, the contribution of the vehicle induced vibration was found to be dominant, which amplifies structural responses of lower modes.
(3) Ambient vibration due to wind is widely distributed in frequency contents; the effects of lower and higher modes are equally reflected in the measured response. This emphasizes the effectiveness of the novel FOA.
(4) From the above results, it is highly expected that the strong motion e.g. earthquake can also be measured along with the ambient vibration (traffic-induced vibration and wind-induced vibration), when the developed FOA is utilized.

4. Conclusions

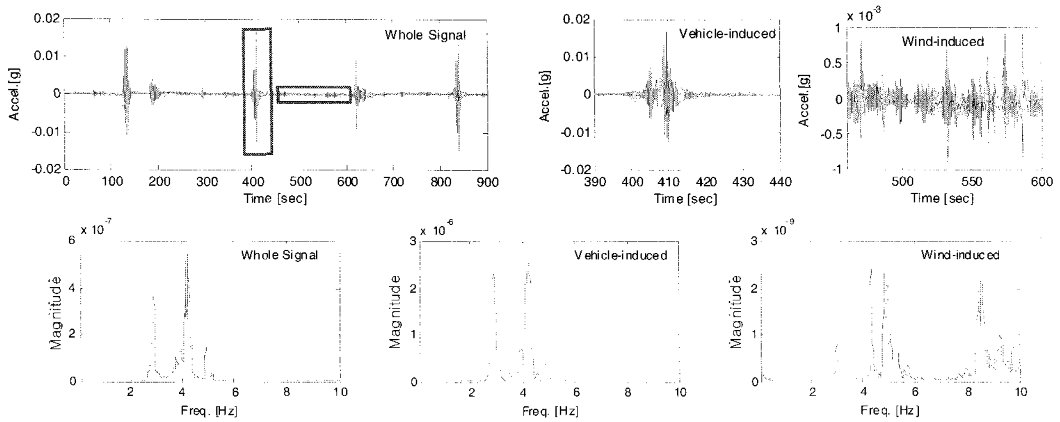
This paper presents a novel fiber optic accelerometer which is composed of moiré fringe panel and two optical fibers. It has a major benefit that is its ability to measure both low- and high-amplitude vibrations with a constantly high resolution without pre-setting a gain level,



(a) Set A

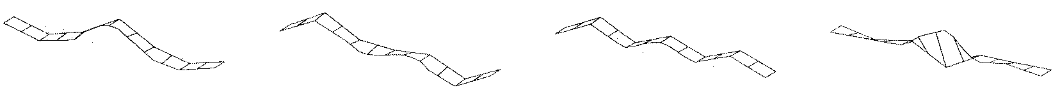


(b) Set B



(b) Set C

Fig. 6 Measured responses using a fiber optic accelerometer



1st mode (3.0 Hz) 2nd mode (4.4 Hz) 3rd mode (4.9 Hz) 4th mode(7.4 Hz)

Fig. 7 Estimated four lower modes from ambient vibration tests as usually required in a conventional accelerometer. In this paper, the accelerometer was utilized to measure the ambient vibration induced by wind and by a heavy truck coincidently. In this experiment, structural responses including high-amplitude vehicle induced vibration and low-amplitude ambient vibration were successfully measured simultaneously using the novel FOA developed. Even thought the vibration induced by a heavy truck was not enough to simulate the strong motion such as earthquake, it is highly expected that the strong motion e.g. earthquake can also be measured along with the ambient vibration (traffic-induced vibration and wind-induced vibration by using the accelerometer.

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