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Integrated monitoring scheme for a maglev guideway using multiplexed FBG sensor arrays

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ABSTRACT

In the structural monitoring of maglev guideways, electromagnetic interference (EMI) can be a significant problem, as the maglev train is powered by high-voltage electric feeding systems. Recently, researchers have successfully applied fiber optic sensors to modern railway structures, mainly because they offer EMI immunity. This study presents an integrated monitoring scheme for a maglev guideway using wavelength division multiplexing (WDM)-based fiber Bragg grating (FBG) sensors. The physical quantities such as strains, curvatures, and vertical deflections are measured in field tests. The strains are directly measured from multiplexed FBG sensors at various locations on a test bridge followed by curvature calculations based on the plane section assumption. Vertical deflections are then estimated using the Bernoulli beam theory and regression analyses. Frequency information obtained from the proposed method is compared with those from a conventional accelerometer. Verification tests were conducted on a newly developed Korean maglev test track at different vehicle speeds.

1. Introduction

Most traditional railway bridges are more than 50 years old and obsolete, and are carrying loads much heavier than originally anticipated. Railway bridges are commonly inspected at routine intervals until significant damage is noted. This time-based visual monitoring is inefficient not only because it requires considerable resources but also because it fails to minimize downtime of the railway bridge. Under these circumstances, there is growing attention on developing railway bridge monitoring systems for preventive maintenance purposes, since in many cases a relatively modest expenditure on preventive maintenance can circumvent much greater expenditures induced by a major structural failure. Information on structural bridge health is important not only for aging railway bridges but also for modern railway bridges such as maglev guideways.

The urban maglev train developed in Korea adopts an electromagnetic suspension (EMS) system for levitation. EMS maglev systems levitate and propel a transport vehicle by inducing magnetic forces of attraction between vehicle-mounted electromagnets and steel rails on a guideway, as can be seen in Fig. 1. The intensity of an electromagnet is continuously controlled by a gap sensor to maintain a constant air gap of approximately 8 mm. Propulsion and braking are provided by a separate linear induction motor (LIM) system. In the structural monitoring of maglev structures, electromagnetic interference (EMI) can be a significant problem, as the maglev train is powered by high-voltage electric feeding systems [1]. EMI refers to the disruption of an electronic device operation when the device is in the vicinity of an electromagnetic field. Under this condition, equipment and systems in their normal environment interfere with one another [2]. Thus, an EMI-free monitoring system is highly recommended for gathering meaningful information on the condition of maglev guideway health.

There has been growing recognition of the potential use of fiber Bragg grating (FBG) sensors for structural monitoring of engineering structures [3], such as pressure vessels, bridges, tunnels, and slopes. FBG sensors have significant advantages compared with conventional sensors, including multiplexing capability, immunity from EMI, absolute measurement, high temperature endurance, and they are suitable for being embedded directly into materials. Recently, researchers have successfully applied FBG sensors to monitoring systems for highway bridges [4–8] and railway bridges [1,9,10].

The ISIS project in Canada also focuses on the development of FBG-based monitoring systems in a number of bridges [4,6]. An FBG sensing system has been also successfully integrated in the structural health monitoring system of the Tsing Ma Suspension Bridge to monitor several key spots including hanger cables and truss girders [9]. Several researchers developed packaged FBG sensors for application in bridge structures under harsh conditions. Moyo et al. [7] proposed the use of packaged FBG sensors

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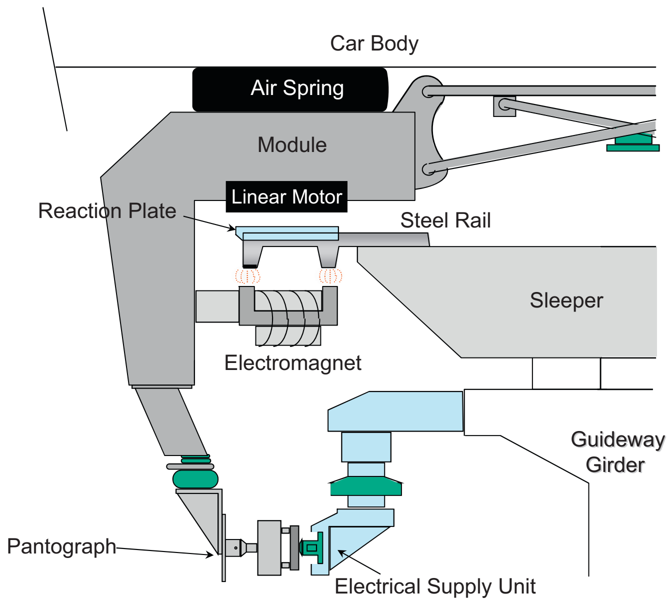

Fig. 1. Maglev system.

between layers of carbon composite laminate to measure strains and temperature. Kister et al. [8] also proposed strategies for the protection and bonding of optical sensors to perform reliable long-term monitoring of a composite bridge. Chung and Kang [10] successfully embedded multiplexed FBG sensors into a steel rebar for the measurement of a full-scale railway concrete girder under static and dynamic loads.

The majority of previous research on the application of FBG sensors to bridge monitoring system focused on the measurement of strains and temperatures. However, little attention has been paid to integrated monitoring systems, including several key parameters such as strains, curvatures, vertical deflections, and frequencies.

This study presents an integrated monitoring scheme for a maglev guideway using wavelength division multiplexing (WDM)-based fiber Bragg grating sensors. The proposed scheme is able to obtain local and global responses of the maglev guideway using two FBG sensor arrays with several sensors for each array. The local quantities are based on the strains directly measured from the FBG sensors and the global quantities are calculated curvatures, deflections, and frequencies of the guideway. The proposed FBG sensing system shows promise of overcoming the EMI problem in maglev guideway monitoring.

Present practice involves the use of individual conventional sensors such as electrical strain gauges, displacement transducers, and accelerometers to monitor the required quantities. For monitoring of vertical displacement, it is common practice that additional scaffolds are installed under the guideway to support the conventional displacement transducers. Thus, the measurement of vertical displacement has been restricted to discrete points along the guideway structure. However, the proposed monitoring scheme is able to estimate vertical displacement at any longitudinal position using multiplexed FBG sensor arrays. Thus, in practical terms, it is more effective than the traditional monitoring system.

Among several information on the structural health, vertical displacement and frequency information of the guideway are two key factors that are most important. Monitoring of vertical displacement is widely used for assessing the structural safety and evaluating the serviceability of the maglev guideway. For a maglev train system, the frequency contents of the guideway should be monitored in order to avoid the frequency range of the levitation control system. The voltage of electrical power to the electromagnet is controlled by the levitation control system so as to ensure stable levitation. If the fundamental frequency of the control system coincides with that of the guideway structure, the levitation system will suffer from resonance. Thus, the monitoring system should be able to provide reliable frequency information under the moving load of the maglev train.

To verify the applicability of the proposed methodology, a field test was conducted on a maglev test track guideway in Korea. The test trains passed over the bridge at different speeds ranging from 10 to 40 km/h, the maximum speed employed in performing the test. A conventional displacement transducer and an accelerometer were also installed to provide references for comparing the performance and accuracy of the proposed monitoring scheme.

2. FBG sensing system

FBG sensors for this study were produced using the phase mask method devised by Hill et al. [11]. When an ultraviolet ray is introduced to the phase mask, a particular interference pattern is formed inside the core of an optical fiber—this pattern is called a fiber Bragg grating. This grating reflects part of the incident light in a very narrowband, called the Bragg wavelength, $\lambda_B = 2n_e\Lambda$, where n_e is the effective refractive index of the fiber core and Λ is the grating period. A Bragg wavelength reflected under the Bragg condition is a function of the effective refractive index and grating interval. When external disturbances are applied to the grating part, the grating period is changed. Consequently, the Bragg wavelength also changes. The Bragg wavelength change can be determined from

$$\Delta\lambda_B = \lambda_B\{(\alpha_f + \xi_f)\Delta T + (1 - p_e)\varepsilon\} \quad (1)$$

where ε is the strain, ΔT is the temperature change, α_f is the coefficient of thermal expansion, ξ_f is the thermo-optic coefficient, and p_e is the strain-optic coefficient. Assuming there is no temperature change, the strain can be directly determined from the wavelength shift, as shown in Eq. (1).

Multiplexing capability is the most practical advantage of the FBG sensing system in terms of application to distributed measurements. Multiplexing enables the use of several FBG sensors in a single optical fiber in series. In other words, multiplexed arrays of FBG sensors allow for measurement of strains at discrete locations on a given structure. The wavelength-encoded nature of the source spectrum facilitates wavelength division multiplexing by allowing each sensor to be assigned a different part of the available source spectrum. This makes the overall sensor system simple and optimal to use in contrast with conventional electronic strain gauge systems, which require individual connections between every strain gauge and the data acquisition system via expansion of the acquisition channel.

Various interrogation schemes are used to detect the wavelength shift of the Bragg wavelength. In this study, an interrogation system with a wavelength-swept fiber laser (WSFL) [12] is used. The WSFL has a scanning tunable filter to sweep the laser output wavelength in time continuously and repeatedly over a range of a few tens of nanometers. The interrogation system manufactured by FiberPro [13] includes a WSFL as a broadband light source and has advanced characteristics, such as a wide wavelength range with high output power and a high resolution of measurement. The resolution of the sensing module is less than 1 pm ($0.83\mu\varepsilon$) and the wavelength measurement accuracy is typically less than ±5 pm (4.15$\mu\varepsilon$). The maximum sampling rate is 200 Hz.

3. Integrated monitoring scheme

This paper proposes an integrated monitoring scheme to measure several key responses of a maglev guideway using a single monitoring unit. The integrated monitoring scheme takes advantage of wavelength division multiplexed (WDM) FBG sensor arrays.

First, the local strain can be directly measured from the WDM-based FBG sensors. Under the assumption that the plane cross-sections of a beam remain plane under pure bending and FBG sensors are installed parallel to the neutral axis at the same longitudinal location, the curvature κ_i for an instrumented section is approximated by

$$\kappa_i = \frac{\varepsilon_i^{bot} - \varepsilon_i^{top}}{h} \tag{2}$$

where ε_i^{bot} and ε_i^{top} are the bottom strain and top strain of the ith longitudinal location, respectively, and h is the vertical distance between FBG sensors. It will have the same sign as the moment for the section.

Meanwhile, the curvature function can be expressed as the nth order polynomial of the lengthwise position as

$$\kappa(x) = a_0 + a_1x + a_2x^2 + \cdots + a_nx^n \tag{3}$$

where $a_0, a_1, \ldots, a_n$ are the coefficients of the curvature function and x is an arbitrary longitudinal position along the structure. The polynomial order of the curvature function for the test is chosen as $(n-1)$th degree, since curvatures are measured at n longitudinal positions. The coefficients of the curvature function are determined via a regression analysis using κ_i from the experiment.

The vertical deflection of the maglev guideway can be determined from the geometric relationship between the curvature and deflection in a simple beam, which is given by

$$\kappa(x) = \frac{d^2w(x)}{dx^2} \Bigg/ \left[1 + \left(\frac{dw}{dx}\right)^2\right]^{3/2} \tag{4}$$

where w is the vertical deflection of the maglev guideway. Eq. (4) is independent of the properties of the material since it is derived solely from the geometry of the deformed beam. If the displacement is small and the strain is infinitesimal, the denominator of Eq. (4) becomes unity. The expression can be simplified as

$$\kappa(x) \approx \frac{d^2w(x)}{dx^2} \tag{5}$$

Curvature from Eq. (3) can then be entered into Eq. (5) and the vertical deflection can be obtained from double integration as

$$w(x) = c_0 + c_1x + \iint \kappa(x)\,dx\,dx \tag{6}$$

The integral constants c_0 and c_1 can be determined by applying the boundary conditions, which are given as the vertical deflection being zero at both supports. At a specific time step, the integrated monitoring scheme can be systematically achieved using the flowchart shown in Fig. 2.

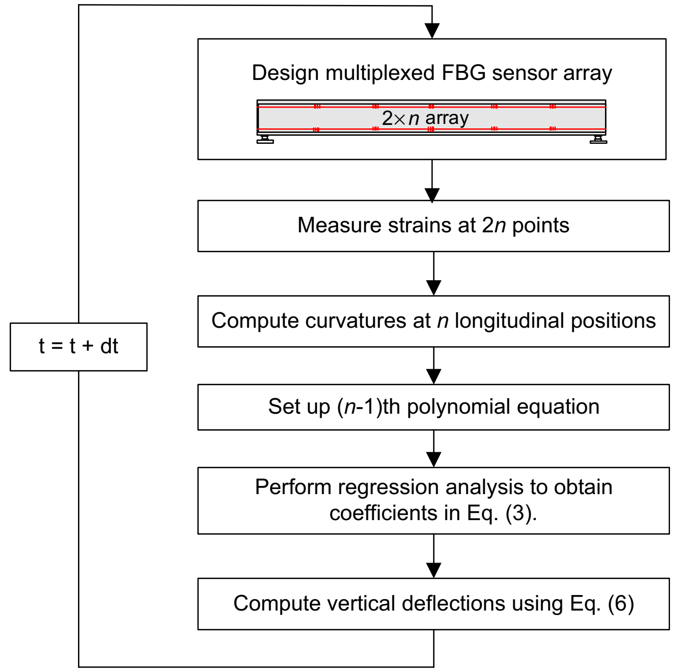

Fig. 2. Flowchart for integrated monitoring scheme.

Kim and Cho [14] proposed a method to extrapolate the vertical displacement curve of a bridge based on the linear regression of measured strains at the bottom surface. This method showed good correlation to the test results for steel beams in the linear elastic region. However, this method is not applicable if the neutral axis changes. In order to overcome these limitations, Chung et al. [15] utilized mean curvatures to extrapolate the vertical deflection using long-gauge fiber optic sensors that are based on the principle of low-coherence interferometry. Kuang et al. [16] also employed intensity-based fiber optic sensors to monitor the vertical displacement in concrete beams. However, all previous researches were limited insofar as they were conducted only for static load cases. For this reason, this study describes an integrated monitoring scheme of dynamic displacement using multiplexed FBG sensors.

4. Field test verification

A maglev guideway is an elevated structure that supports maglev trains. The maglev test track in Korea utilizes conventional prestressed concrete (PSC) box girders topped by transverse steel sleeper beams, which in turn support the steel rails. Various tests are being conducted on the test track in Korea. Fig. 3 shows the maglev test track located in Daejeon, South Korea.

The tested guideway is a simple span girder with a length of 25 m. The dimensions of the cross-section are 1410 mm (W) by 1900 mm (H). As shown in Fig. 4, five FBG sensors are multiplexed in a single optical fiber and installed in parallel pairs along the entire length of the bridge by surface attachment, with one set at the top portion (Channel 1) and the other at the bottom portion (Channel 2) of the maglev guideway. The distance between two multiplexed FBG sensor lines is 1600 mm. FBG sensors are directly attached to the side surface of the structure using epoxy glue. In addition to the FBG sensors, a conventional displacement transducer and an accelerometer are installed at the mid-span of the bridge for comparison, as shown in Fig. 4(b).

The maglev train is levitated through the attractive force between the electromagnets of the maglev vehicle and the steel rail located in a guideway. The electromagnets use feedback control to maintain the train at a constant gap from the track. In this procedure, the train requires a large amount of voltage to keep it levitating under precise control. The monitoring of the guideway steel rail using conventional strain sensors is highly

Fig. 3. Korean maglev test track (Daejon, South Korea).

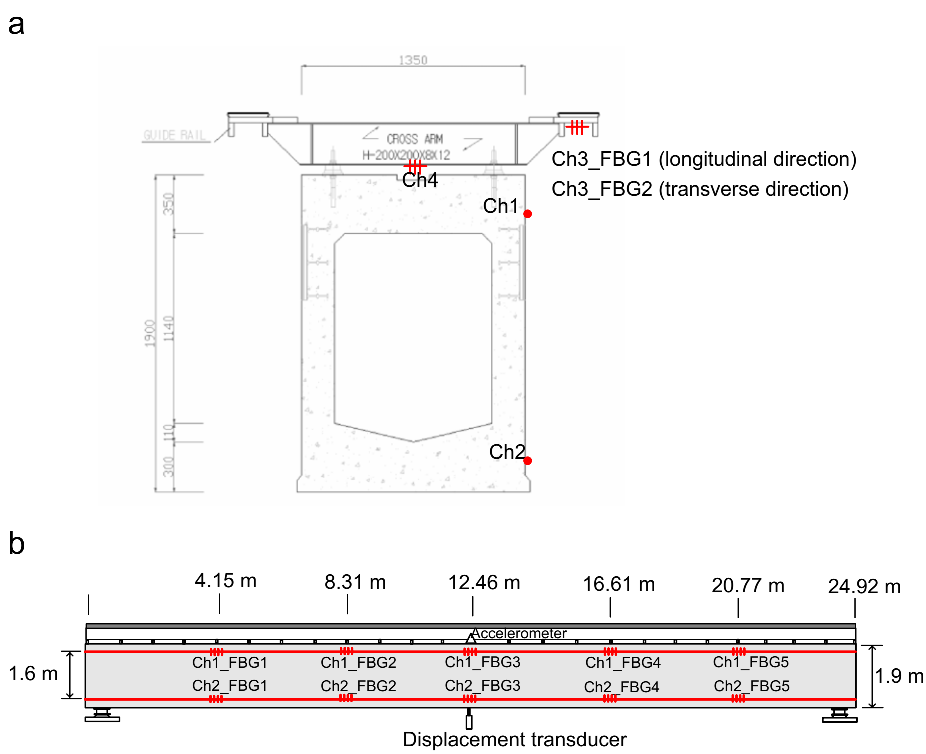

Fig. 4. The layout of sensor locations: (a) cross-section and (b) front view.

susceptible to EMI. In order to avoid the EMI problem, FBG sensors are installed on the steel rail in both the longitudinal the and transverse directions (Channel 3), and on the cross beam in the transverse direction (Channel 4), as shown in Fig. 4(a).

The FBG sensors continuously monitor strain-induced wavelength shifts throughout the entire experiment. Fig. 5 shows the reflected wavelength spectrum for the multiplexed FBG sensors at Channel 1 and Channel 2. For instance, strain-induced wavelengths in Channel 2 are shifted to the positive direction if the structures are in a state of tension.

As described earlier, five FBG sensors are multiplexed in each sensor array. Figs. 6(a) and (b) show the measured strains of the tensile region when the train passed the bridge at speeds of 20 and 40 km/h, respectively. It is clear that the passing train induces

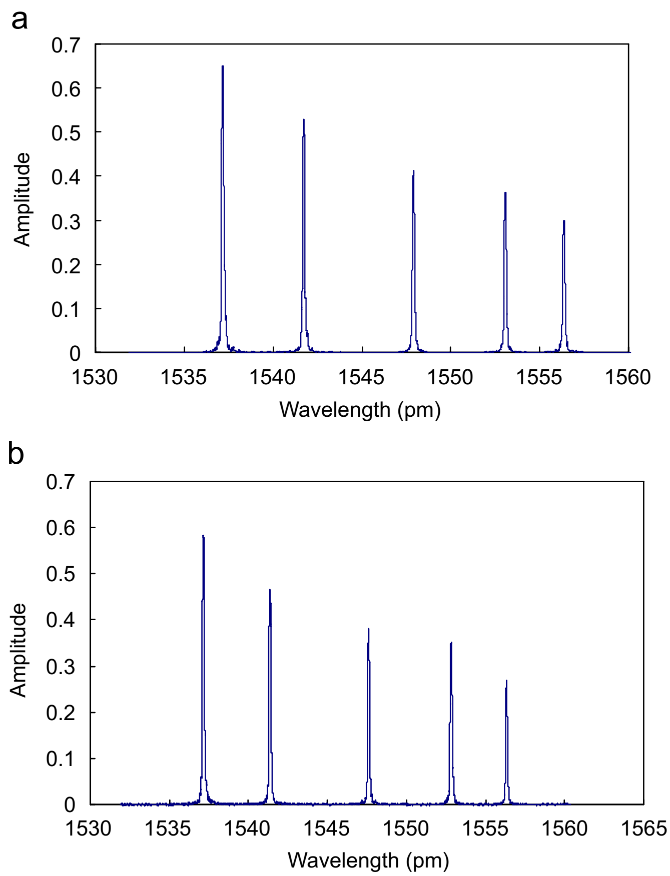

Fig. 5. The spectrum of reflected wavelength signals for FBG sensor arrays: (a) channel 1 and (b) channel 2.

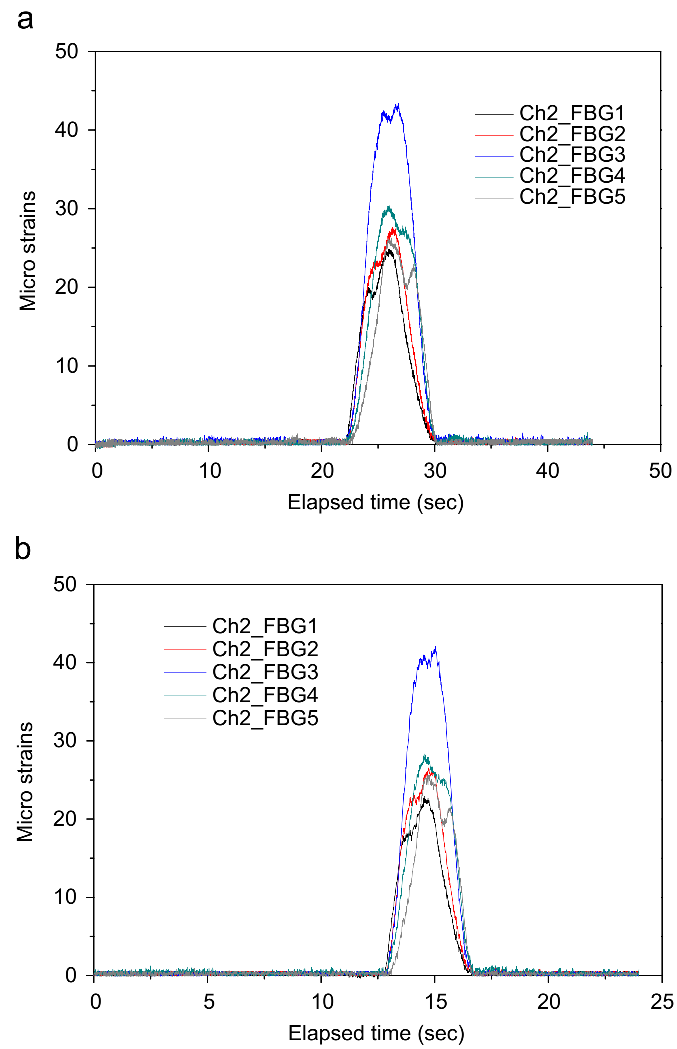

Fig. 6. Time history of bottom strains measured from guideway girder: (a) maglev speed = 20 km/h and (b) maglev speed = 40 km/h.

the maximum tensile strains at the mid-span (FBG 3 of Channel 2). Figs. 7(a) and (b) show the local strains measured from the steel rail and the cross beam at the mid-span when the maglev train passes the guideway with speeds of 20 and 40 km/h, respectively. It is observed that the bottom surface of the steel rail is under compressive strain in both directions. In the transverse strain results, two peaks are typically observed, since the test maglev train consists of two cars, each composed of three modules. For this reason, the measured transverse strains have three local peaks per single global peak, because the sensors attached on the steel rail are able to capture the impact of the passing three modules in each car.

Fig. 8 shows the computed curvatures at different longitudinal locations when the train passed the guideway at a speed of 30 km/h. The curvatures at the measured points can be determined based on the Bernoulli conservation law and regression analyses, as discussed earlier. The correlation coefficients (R^2) in the regression analyses fell between 0.96 and 1.0 for all the cases.

The estimated deflection at any longitudinal location can be determined by the aforementioned experimental scheme. Fig. 9 presents comparisons of the deflections estimated from the proposed experimental technique with those measured from a displacement transducer at the mid-span when the maglev train passed the guideway with speeds of 20, 30, and 40 km/h. Good agreement between the measured deflection and the estimated deflection is achieved. The maximum difference between two peak displacements is 3.5%.

The frequency contents obtained from the proposed method were compared with those obtained using the accelerometer, as shown in Fig. 10. Even though there is a discrepancy in terms of frequency amplitude, the frequency contents of the two systems are almost identical for all cases. The correlations between the two sensing systems are very good overall. This confirms that the experimental technique using FBG sensors is capable of tracing the dynamic behavior of the maglev guideway with acceptable accuracy. It should be noted that the levitation system can be unstable due to resonance between the levitation controller and guideway if the natural frequency of the levitation controller is larger than 6 Hz, as can be inferred from the results of Fig. 10.

5. Summary and conclusions

This paper presents an integrated monitoring system for a maglev guideway using WDM-based FBG sensor arrays. The measured parameters include both local and global quantities of the guideway response, such as stains, curvatures, vertical deflections, and frequencies. The local strains are directly measured from multiplexed FBG sensors at various locations of the guideway followed by curvature calculations based on the plane section assumption. Vertical deflections are then estimated using the Bernoulli beam theory and regression analyses. Frequency contents obtained from the proposed method are compared with those from a conventional accelerometer.

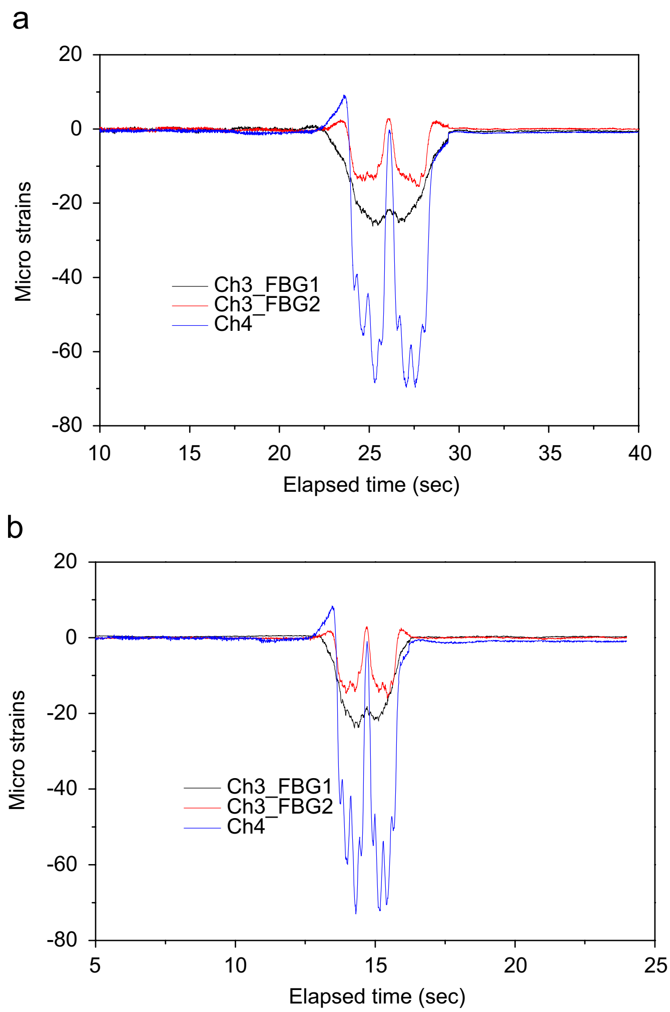

Fig. 7. Time history of strains measured from guideway track: (a) maglev speed = 20 km/h and (b) maglev speed = 40 km/h.

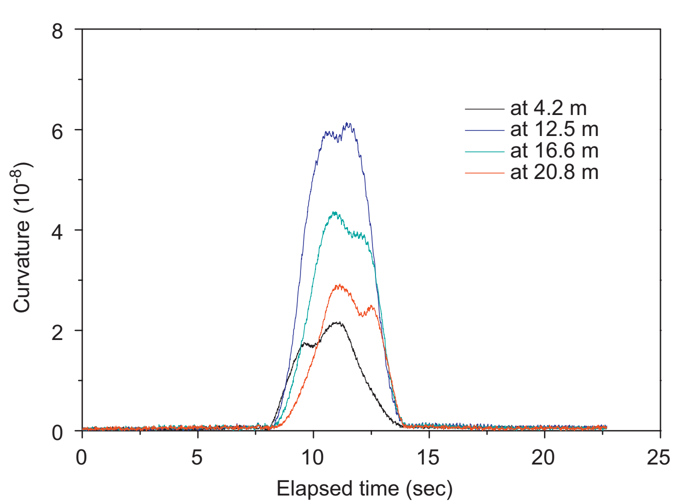

Fig. 8. Time history of computed curvatures at several longitudinal locations (maglev speed = 30 km/h).

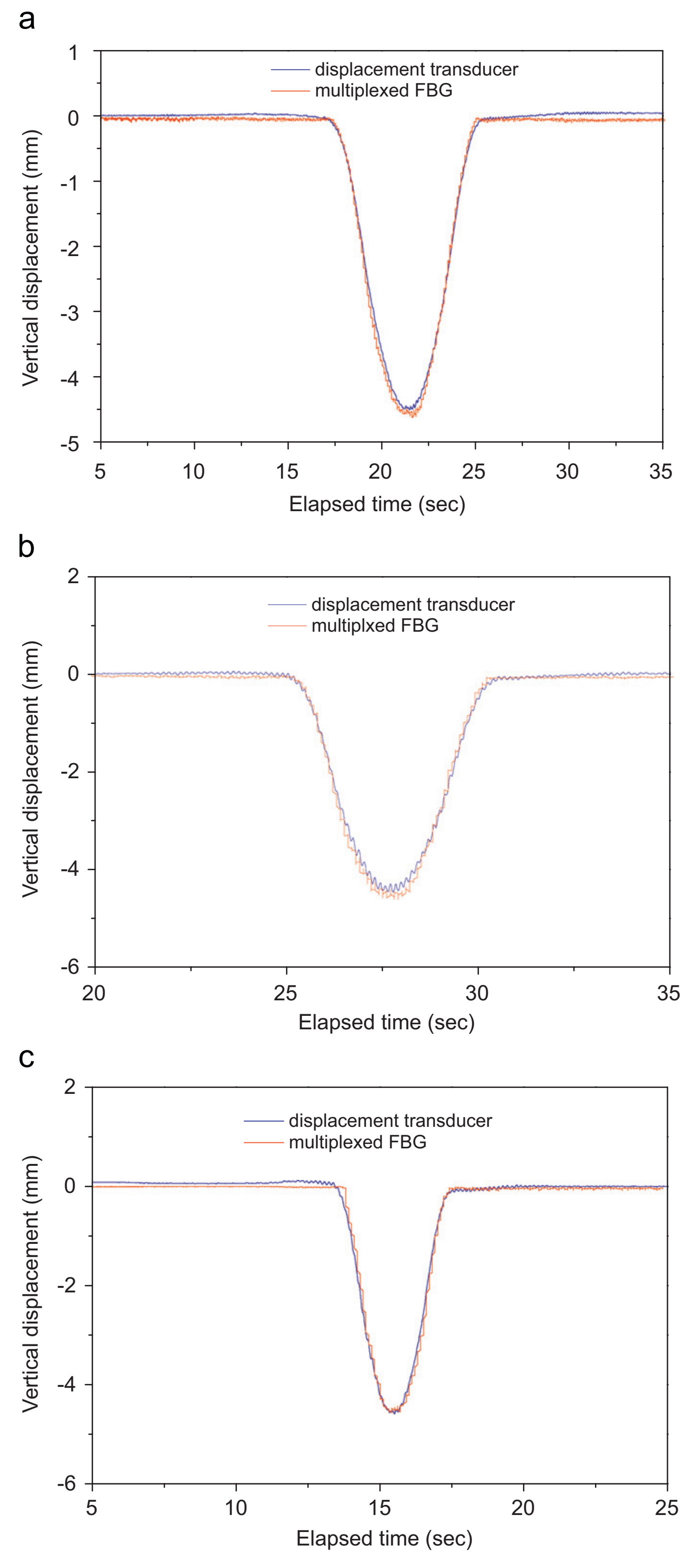

Fig. 9. Comparisons of vertical displacements at mid-span: (a) maglev speed = 20 km/h, (b) maglev speed = 30 km/h, and (c) maglev speed = 40 km/h.

Verification tests were conducted on the newly developed Korean maglev test track. From the test results, it has been shown that good agreement between the measured deflection and the estimated deflection is achieved. The difference between the two displacements was 3.5% at maximum and the correlations between data from the two sensing systems are very good overall. Good correlations on frequency results were also obtained between the proposed system and traditional system for all test cases. This confirms that the proposed technique is capable of tracing the dynamic behavior of the maglev guideway with

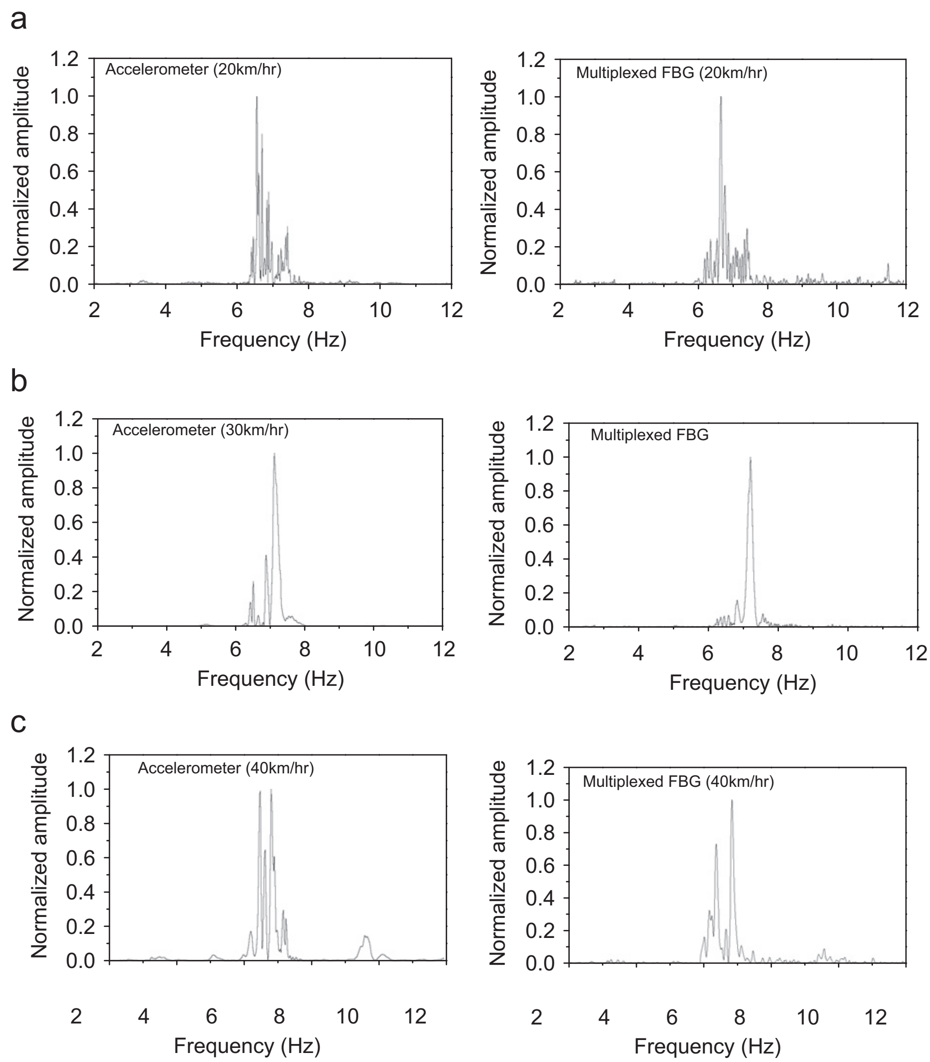

Fig. 10. Comparisons of frequency analysis results. (a) maglev speed = 20 km/h, (b) maglev speed = 30 km/h, and (c) maglev speed = 40 km/h.

acceptable accuracy. It is expected that the proposed scheme will provide an effective tool for monitoring the behavior of maglev guideway structures without electromagnetic interference.

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