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Stability assessment method for railroad bridges using acceleration and strain in combination

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ABSTRACT

The stability of a railway bridge is mainly governed by level of acceleration, vertical displacement, and twist. While acquiring acceleration is relatively easy task in the data measurement respective, displacement and twist are very challenging due to lack of appropriate sensors. Furthermore, as most existing displacement sensors are confined to measuring single displacement, twist which is obtained from multiple displacements requires instrumentation of multiple displacement sensors, which are costly and labor-intensive. To address these issues, this study proposes an indirect multiple displacement estimation method based on the measurement of acceleration and strain; therefore, acceleration, displacements and twist for stability of a railway bridge can be obtained at a time. The proposed method was numerically and experimentally validated. Then, stability evaluation of a railway bridge was then carried out with a high-speed train speeding at three cases: 280km/h, 300km/h and 400km/h. The acceleration, vertical displacement and twist were successfully obtained and compared with the design limit.

1. INTRODUCTION

Railway design codes generally provide a guideline for allowable response levels of a railway bridge for traffic safety as well as passenger's comfort. For example, Eurocode (1990) provided by European Committee for Standardization specifies maximum acceleration, deflection, and twist. While the criteria are considered in the design stage of railway bridges, actual verification after construction is difficult in practice. Acceleration of the bridge due to a train passage can be conveniently measured by a few accelerometers on the bridge; measuring deflection and twist in practice is quite restricted as there are few sensors that meet measurement needs.

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The twist that indicates the torsional deflection is even more challenging to measure as it requires four displacement measurements at every 3 m. Thus, dense displacement sensing in an efficient manner is a key to the practical safety assessment of railway bridges.

Knowing that direct displacement measurement approaches is challenging and inappropriate for dense displacement sensing, a promising alternative is indirect displacement estimation using other physical quantities such as velocity, acceleration, and strain (Gindy et al., 2008; Lee et al., 2010; Park et al., 2013a; Shin et al., 2014; Kim et al., 2014). Data fusion using acceleration and strain (Park et al., 2013b; Cho et al., 2014; Cho et al., 2015; Cho et al., 2016) is seen to be particularly useful in the railway bridge because it is reference-free and able to capture both quasi-static and dynamic components in the displacement which is typically observed under the heavy train loading. However, knowing the fact that the data fusion algorithm is in need of an acceleration response at the same location of the desired displacement, the multiple displacement estimations required to obtain the twist at every 3 m over an entire bridge is costly and impractical.

This study illustrates a safety assessment strategy tailored to railway bridges based on the multisensor data fusion algorithm, which was described in Park et al. (2016) in detail. To address the aforementioned issues, this study employs the modal expansion (Friswell et al., 1995) in conjunction with the data fusion algorithm to enable the estimation of all displacements required for twist calculation. In addition, the wireless sensing system is adopted for multisensor data acquisition with the enhanced performance and efficiency from the practical point of view. The proposed approach is both numerically and experimentally validated using a simply supported beam model with a moving mass to simulate the train loading. Subsequently, the safety evaluation of a railway bridge located in South Korea is carried out with high-speed trains running at different speeds.

2. SAFETY ASSESSMENT STRATEGY FOR RAILWAY BRIDGES

This study introduces a safety evaluation strategy that combines (1) the expanded data fusion algorithm based on modal expansion for dense displacement information and (2) the wireless sensor system for multisensor data acquisition.

Expanded Data Fusion Algorithm for Dense Displacement Estimation

The multisensor data fusion algorithm described in the previous section can only output estimated displacements where accelerations are measured. Herein, the algorithm is expanded to be able to obtain displacements at arbitrary locations based on the modal expansion.

A displacement vector of a structure can be divided into two parts corresponding to known and unknown displacements; the total displacement vector can be expressed in the modal coordinates as:

$$u_t = \begin{bmatrix} u_k \\ u_u \end{bmatrix} = \begin{bmatrix} \Phi_k \\ \Phi_u \end{bmatrix} q \tag{5}$$

where u_k and u_u are known and unknown displacements, respectively; Φ_k and Φ_u are corresponding mode shapes; q is the modal coordinate. The modal coordinate q can be written in terms of the pseudo inverse of the known mode shape Φ_k and the known displacement u_k as:

$$q = \Phi_k^+ u_k \tag{6}$$

Subsequently, the unknown displacement u_u can be obtained as:

$$u_u = \Phi_u q = \Phi_u \Phi_k^+ u_k \tag{7}$$

As u_k can be determined by the data fusion-based indirect estimation method (Park et al., 2013b), the total displacement vector can be written as:

$$u_t = \begin{bmatrix} I \\ \Phi_u \Phi_k^+ \end{bmatrix} u_k = \begin{bmatrix} I \\ \Phi_u \Phi_k^+ \end{bmatrix} \begin{pmatrix} C_a \Delta t^2 & C_\varepsilon \end{pmatrix} \begin{pmatrix} \overline{a} \\ \overline{\varepsilon} \end{pmatrix} \tag{8}$$

where I is the identity matrix. Note that the number of modes cannot exceed the number of known displacements. The minimum number of known displacements is determined in the numerical simulation in the following section. The total displacement leads to the dense twist information necessary for checking the safety criteria.

Multimetric Wireless Sensor

The traditional wired sensor system needs a complex sensor and equipment configuration including accelerometers, strain gauges, signal conditioners, data loggers, and data and power cables. For full-scale civil engineering structures, installation of the traditional wired system can be costly and inefficient. The wireless smart sensor (WSS) is a powerful solution to these issues. Indeed, WSS-related developments and their full-scale applications for civil infrastructure monitoring have been increasing in the field of structural health monitoring (Lynch and Loh, 2006; Spencer et al., 2011; Park et al., 2013c; O'Connor et al., 2014; Spencer et al., 2016).

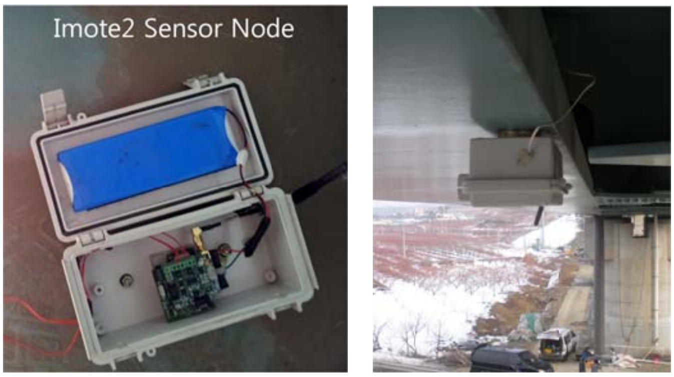
The multimetric wireless sensors enables (1) multimetric sensing capability of time-synchronized strain and acceleration, (2) enhanced applicability to field testing through the wireless communication, and (3) high-precision strain sensing. Wireless sensors are intrinsically versatile for multimetric sensing due to MEMS technology. MEMSIC's Imote2 smart sensor platform used in this study has strain and acceleration sensor boards (SHM-S and SHM-A, respectively) stacked on top of Imote2 as shown in Fig. 2 (Rice et al., 2010; Jo et al., 2012). Imote2 with SHM-S and SHM-A provides with synchronized strain and acceleration that are required in the data fusion algorithm for displacement estimation (Park et al., 2014). Furthermore, the wireless communication removes costly and labor-intensive cabling to connect each sensor to a data logger. This is particularly advantageous for strain sensing because strain gauges are susceptible to noise caused by the long wire connection before digitization.

3. FIELD APPLICATION OF THE SAFETY ASSESSMENT STRATEGY

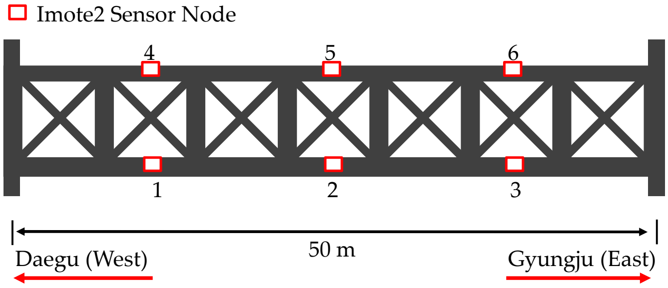
The proposed method is applied for safety evaluation of the Gaya Bridge located between two cities of Daegu and Gyungju in Korea (see Fig. 1). The Gaya Bridge is a single-span steel plate girder bridge, and 50 m in length and 4.9 m in height. The Gaya Bridge is designed to serve for the Korea Train Express (KTX) trains running up to 300 km/h. Recently, a newer express train, HEMU-430X, is developed to be able to run up to 430 km/h, and thus railway bridges designed according to the old standard need to be examined to ensure the railway safety. Because the KTX line has a number of railway bridges, an efficient and practical solution is demanded; the proposed approach is thus employed to evaluate the safety of the Gaya Bridge.

Fig. 1. The Gaya Bridge

To measure strain and acceleration during the passage of the train, six Imote2 sensor nodes are installed as shown in Fig. 2; three sensor nodes are instrumented at each side. Each sensor node is installed underneath with magnets to maximize the wireless communication quality with the gateway node located under the bridge. The sensor nodes are set to measure 30,000 data points with the sampling rate of 100 Hz.



(a) (b)



(c)

Fig. 2. Sensor deployment: (a) Imot2 sensor node, (b) installed sensor, (c) sensor location (plan view)

All three types of responses required for the safety check (i.e., acceleration, displacement, and twist) are obtained from the multisensor wireless DAQ system and the subsequent data processing using the data fusion algorithm. By combining acceleration and strain, displacement is calculated as shown in Fig. 3. Note that only three responses are shown to avoid complexity.

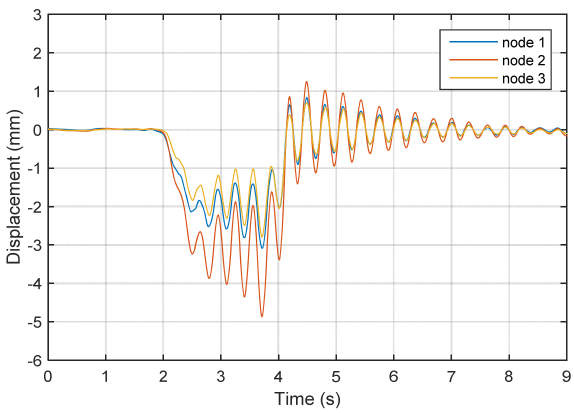


Fig. 3. Estimated displacements (270 km/h)

The multimetric responses of acceleration, displacement, and twist are used for safety evaluation of the Gaya Bridge. (1) The allowable acceleration for bridges with concrete tracks is 500 mg, while the maximum measured acceleration at the speed of 280 km/h is 68.25 mg; the bridge is evaluated to be stable in terms of acceleration. (2) The vertical displacements limit for safety and comfort are 83.3 mm and 22.7 mm, respectively. The maximum displacement of 4.44 mm occurred at the speed of 280 km/h, satisfying both safety and comfort criteria. (3) The twist per 3 m obtained by the expanded data fusion method exhibits the maximum of 0.116 mm/3m at the speed of 370 km/h that is also smaller than 1.2 mm/3m defined in the design criteria. This safety check is summarized in Table 1. As the design criteria is shown to be met, the Gaya Bridge is found to be stable for the operation of HEMU-430X.

Table 1. Safety evaluation of the Gaya Bridge

Criteria	Allowed	Measured			Evaluation
		280km/h	370km/h	400km/h	
Acceleration (mg)	500	68.316	43.782	48.423	Stable
Vertical Deflection (mm)	Safety: 83.3 Comfort: 22.7	4.862	3.192	2.008	Stable
Twist (mm/3 m)	1.2 mm/3 m	0.044	0.072	0.045	Stable

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