Mechanical Systems and Signal Processing 24 (2010) 707–720

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Extracting modal parameters of high-speed railway bridge using the TDD technique

Byeong Hwa Kim [a], Jungwhee Lee [b], Do Hyung Lee [c,*]

[a] Department of Civil Engineering, Kyungnam University, 449, Masan 631-701, Republic of Korea
[b] Department of Civil and Environmental Engineering, Dankook University, 126, Jukjeon-dong, Suji-gu, Yongin, Gyeonggi 448-701, Republic of Korea
[c] Department of Civil Environmental and Railroad Engineering, PaiChai University, Yonja 1 gil (439-6 Doma 2 dong), Seo-gu, Daejeon 302-735, Republic of Korea

ARTICLE INFO

Article history:
Received 21 August 2008
Received in revised form
20 November 2009
Accepted 28 November 2009
Available online 11 December 2009

Keywords:
Modal testing
Modal analysis
Railway bridge
High-speed train
Mode shapes
Ambient modal analysis

ABSTRACT

In case the excitation frequency induced by a high-speed train passage coincides with the natural frequency of a railway bridge, a resonance of the bridge occurs. In addition, if the train is passing through the bridge very quickly, measurable time samples can be of limited numbers and thus modal parameters of the bridge can hardly be obtained. To get over this, effective technique for the extraction of modal parameters is proposed in the present study. With the cross correlations among free vibration responses immediately after the train passes, mode shapes are obtained by TDD (time domain decomposition) technique while temporal modal parameters are extracted by the proposed sensitivity-updating system identification technique. A two-span steel composite girder bridge, which is of typical Korean high-speed railway bridge system, is employed to verify the proposed approach. Comparative studies reveal that the predictions of the proposed approach agree well with those by the well-known existing methods. It is thus postulated that the present approach is promising in terms of both accuracy and applicability.

1. Introduction

Most bridges on the KHST (Korean high-speed train) system are in general two-span continuous prestressed concrete box girder bridges with the individual span length of 40 m. Other types of the KHST bridge are also available. There are, a simply supported steel composite bridge with span length of 50 m, a simply supported prestressed concrete box bridge with span length of 40 m, a two-span continuous steel composite bridge with individual span length of 50 m, and a three-span continuous prestressed concrete box bridge with center span length of 50 m and side span length of 33 m. Generally, the lowest natural frequencies of a two-span continuous prestressed concrete box and a steel composite bridge are 4.35 and 3.0 Hz, respectively, while those of a simply supported prestressed concrete box and a steel composite bridge are 3.8 and 4.0 Hz, respectively [1]. For the three-span continuous prestressed concrete box bridge, the lowest natural frequency is 4.30 Hz. In all, the lowest natural frequency of most bridges for the KHST system lies in the range of 3.0∼4.35 Hz.

Meanwhile, the nth excitation frequency induced by the train can be obtained by [2]

$$f_n = n\frac{v}{d} \tag{1}$$

* Corresponding author. Tel.: +82 42 520 5571; fax: +82 42 525 7486.
E-mail addresses: bhkim@kyungnam.ac.kr (B.H. Kim), jwhee2@dankook.ac.kr (J. Lee), dohlee@pcu.ac.kr (D.H. Lee).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2009.11.010

where $n(=1, 2, 3, \dots)$ denotes a positive integer. ν and d represent a train velocity and a distance between two compartment centers, respectively. A feature of such crossing frequency is very narrow band since train velocities at a specific bridge are rather distributed. With the compartment center distance of $d=18.7$ m, the 2P+18T KHST, which is comprised by two locomotives at both extremities connected to 16 passenger coaches by means of two motorized cars, is regularly passing through the bridge with the velocity of 220∼300 km/h (61.1∼83.3 m/s). For such velocities, the first excitation frequency can be obtained as $f_1=3.3\sim4.5$ Hz from Eq. (1). This frequency is well overlapped with that of most bridges for the KHST system and thus a strong possibility of resonance exists on such bridges.

For the modal parameter extraction of the high-speed railway bridge, several salient features should be taken into account. Firstly, use of free vibration responses immediately after a train is passing can be the most effective way for the identification of the modal parameter. This is mainly due to the fact that such responses possess natural frequencies only. Secondly, since the train is passing very rapidly through the bridge, measurable time responses are of limited small numbers. Moreover, a lot of both cost and time are required for the acquisition of the repeated sets of dynamic responses on such bridge, due to relatively long time interval between train passages. This is true for the KHST system. Whereas the system has excitation duration in between 4.5 and 6.2 s, the duration of free vibration is less than 6 s. Lastly but by no means at least, special care should be taken into account for closely placed modes in the extraction of temporal modal variables. This is due to the fact that two-lane system is widely installed on a railway bridge and thus closely placed torsinal modes are often obtained in near of bending modes.

Recently, full scale modal test for the high-speed railway bridge has been dramatically increased [1,3,4,5] for the purpose of design checks imposed by codes. For the extraction of modal parameters from the field data, however, the peak-picking (PP) technique [6] is frequently adopted. While the application of the PP technique is very straight forward, it is well known that the accuracy of the estimated modal parameters relies highly on the frequency resolution [7]. To improve the frequency resolution and remove in-band noise in frequency domain, the collection of a large amount of time samples is required. To resolve such drawback, many outstanding research works have been conducted. Representative works among many others are ITD (Ibrahim time domain) technique [8], ERADC (eigensystem realization with data correlation) technique [9], SSI (stochastic subspace identification) technique [10], FDD (frequency domain decomposition) technique [11], NExt (Natural excitation technique) [12], and TDD (Time Domain Decomposition) technique [13].

For a small amount of time samples, the frequency resolution in the spectrum becomes very poor and thus employment of the FDD method [11] is not appropriate. Unlike time domain method, the accuracy of frequency domain method such as the FDD method depends inherently on the number of measured time samples that affect on the frequency resolution in the spectrum. It is worth noting that increasing sampling frequency does not improve the frequency resolution in the range of the low frequency for a particular set of the short excitation of a high-speed train passage. To improve the frequency resolution for such case, it is required to collect the long time history containing low frequency contents. In addition, the FDD method requires computationally extensive SVD procedures with respect to all the individual frequencies for a specific inspection frequency band. For the TDD approach, however, only one time of the SVD procedures for the same specific inspection frequency band is required in time domain. This is due to the fact that the FDD method is a frequency domain decomposition while the TDD method is a time domain decomposition. Meanwhile, for the case of the ERADC method [9] and the stochastic subspace identification method [10], the size of the SVD target matrix depends on the number of sensors, time samples and the correlation time lags. Accordingly, the TDD technique is computationally efficient when a large number of sensors are involved. While the NExt method [12] utilizes cross correlations instead of measured responses, systematic algorithm for the extraction of natural frequency and damping ratio has not been developed since the reference [12]. Idea of the NExt method is to use of the cross correlations instead of measured responses. This leads that the NExt method can typically be used to combine with other modal parameter extraction methods such as the ERADC [14].

In view of the above discussion, the TDD technique is employed in the present study since it is suitable for the railway bridge in terms of both simplicity and applicability. As discussed, the acquisition of a large amount of time samples is very limited on the high-speed railway bridge. This leads both statistical reliability loss and poor noise reduction on the signals. This limitation however can be circumvented by increasing the number of sensors and using their cross correlations. It is worth noting that random error is inversely proportional to the square root of the number of records or record length [6]. For p sensor locations, p sets of the p cross correlations can be generated with respect to the p reference locations. This implies that the number of available signals is increased to p^2. It is also noted that the generated cross correlations have the same form as the free vibration responses [15]. Thus, use of the resulting large number of cross correlations with respect to increased number of sensors may have a favor to reduce the random error. Subsequently, when a large number of sensor locations are involved in the modal tests, the TDD technique is the most efficient method among the various modal parameter extraction techniques [13]. Since the fundamental idea of the TDD technique lies in the well-known principle of the separation of variables, spatial and temporal variables are independently extracted in terms of the TDD technique. Whereas the temporal variables include natural frequency and damping ratio, the spatial variables denote mode shapes. For the extraction of mode shapes, the computationally intensive SVD procedures in the TDD technique are required only one time for a considered resonance mode, while the FDD technique requires many times of SVD procedures for a considered resonance mode. Moreover, the size of SVD matrix in the TDD technique is only associated with the number of sensors, unlike the ERADC method and SSI method whose sizes of SVD matrix are associated with not only the number of sensors, but also the number of time samples and correlation time lag. Thus, the TDD technique can significantly save a