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Identification of bridge mode shapes using Short Time Frequency Domain Decomposition of the responses measured in a passing vehicle

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ABSTRACT

This paper processes the signals from accelerometers mounted on a vehicle travelling over a bridge. Short Time Frequency Domain Decomposition (STFDD) is used to estimate bridge mode shapes from the dynamic response of the vehicle. In Frequency Domain Decomposition (FDD), several segments are defined on the bridge and the measurement is performed using two instrumented axles. Here, the FDD method is employed in a multi-stage procedure applied to the bridge segments in sequence. A rescaling process is used to construct the global mode shape vector. The performance of the proposed method is validated using numerical case studies. In other indirect bridge identification methods, the road profile may excite the vehicle, making it difficult to detect the bridge modes. This is addressed using two concepts: applying external excitation to the bridge and subtracting signals in the axles of successive trailers towed by the vehicle. The results obtained from the numerical investigation demonstrate that the proposed method can estimate the bridge mode shapes with acceptable accuracy. Sensitivity of the method to added white noise is also investigated.

1. Introduction

There is a long history of the use of natural frequency as an indicator of structure and bridge health [1,2]. Damping ratios [3,4] and mode shapes [5] have also been used as indicators of health and damage. The dynamic properties of bridges continue today to be a useful evaluation tool in non-destructive damage assessment. The principle is that damage in a bridge leads to some loss of stiffness and consequently to changes in its dynamic properties [6,7]. In most vibration-based bridge health monitoring techniques, large numbers of sensors are installed on the structure to monitor the dynamic properties. Then, conventional modal testing methods [6] or output-only modal methods [8] can be used to process the measured signals. These approaches, in which sensors are installed directly on the bridge, are known as direct methods [9].

The idea of an indirect approach, in which the natural frequencies of bridge structures are extracted from sensors in a passing vehicle, was first proposed by Yang et al. [10,11]. In this approach, a vehicle is instrumented and dynamic properties of the bridge are extracted by processing the dynamic response of the moving vehicle to the bridge. Through interaction between bridge and vehicle, the moving vehicle can be considered as both exciter and receiver. The measured vehicle response needs to include high levels of bridge dynamic response. The feasibility of this method in practice was experimentally confirmed by Lin and Yang [12] by passing an instrumented vehicle over a highway bridge in northern Taiwan. In the case that only bridge frequency is required, the indirect approach showed many advantages in comparison with direct methods in terms of equipment needed, specialist personnel on site, economy, simplicity, efficiency and mobility.

Bu et al. [13] also proposed a bridge condition assessment method based on the dynamic response of a passing vehicle. Yang and Chang [14] applied a pre-processing approach to the measured vehicle response using empirical mode decomposition (EMD) to enhance the resolution of the approach. The effect of several key parameters on the dynamic response of the vehicle passing over the bridge was studied in [15]. It was demonstrated that, unsurprisingly, a larger bridge/vehicle acceleration amplitude ratio results in better accuracy in identifying the bridge frequencies.

McGetrick et al. [16] demonstrated that with a road profile, better accuracy can be obtained at lower vehicle speed. At higher speeds, the road profile's influence on the vehicle vibration

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dominates the spectrum, hiding the bridge frequency. They showed that changes in bridge damping could be efficiently monitored using the proposed instrumented vehicle. Chang et al. [17] showed that the existence of road surface roughness results in the appearance of vehicle frequencies which cannot be neglected in practice. The feasibility of using an instrumented vehicle to detect the natural frequency and changes in structural damping of a model bridge was investigated by Kim [18,19] through a scaled laboratory moving vehicle experiment. Yang et al. [20] used two connected vehicles to eliminate the blurring effect of road surface roughness when identifying bridge frequencies.

A novel method for the identification of the damping ratio of a bridge using acceleration measurements from a moving vehicle is proposed in [21]. The appearance of vehicle frequencies in the sensor acceleration spectrum can be a problem, especially when they are close to the bridge first natural frequency [16]. Yang et al. [22] propose some filtering techniques to remove vehicle frequency from the spectrum but these are not always effective. Several types of model test carts were designed and used to improve the experimental accuracy of identifying bridge frequencies from vehicle response in [23]. Keenahan et al. [24] propose a subtraction idea to remove the effect of road profile in the measured response of the vehicle. The obtained results were used to detect the damping changes in the bridge.

Zhang et al. [25] propose a damage index that is based on the squares of the bridge mode shapes, extracted from the acceleration of a passing vehicle applying controlled dynamic forces. The method gives an estimate of the mode shapes. Zhang et al. [26] extended this concept to find the operating deflection shape curvature of the bridges. An optimization method is proposed in [27] to identify bridge frequencies as well as bridge stiffness indirectly using a passing vehicle. Recently, vehicle-based measurement has been extended to construct the mode shapes of bridges theoretically [28]. The instantaneous amplitude history of the bridge component response was obtained using a Hilbert transform of the response measured in the passing vehicle. Although the method worked well when a smooth road profile was used, the accuracy was less in the presence of road roughness. The sensitivity of the method to measurement noise was not considered.

In recent years, several researchers have developed methods to identify the bridge frequency from the acceleration signal in a passing vehicle [10,11,22,23] and to improve the accuracy of the results. In addition, some authors obtained the damping ratio of the bridge using indirect approaches [21,24], but very few [28] have obtained mode shapes of the bridge indirectly. Estimation of bridge mode shape is very important in a dynamic investigation of a bridge. For instance, there are discontinuities at the damage points in the mode shapes of a damaged bridge, including slope discontinuities at cracks [29,30]. Furthermore, the bridge mode shape can be used as an important tool in model updating of a bridge [31].

In this paper a novel Short Time Frequency Domain Decomposition (STFDD), using multi-stage measurements, is proposed to obtain bridge mode shape indirectly from accelerations in two connected passing axles. The proposed method is based on the Frequency Domain Decomposition (FDD) method that is an output-only modal testing method. This was first proposed by Brincker et al. [32] to obtain modal parameters of a structure from direct measurements. The proposed method involves two main parts. In the first part, several segments are defined in the bridge and then a multi-stage measurement procedure is done based on the defined segments. The FDD method is applied to the time history acceleration responses from the two following axles in each stage. As a result, local mode shape elements are estimated in each stage in the first part of the method. In the second part, a correction procedure is performed to construct the global mode shape vectors of the bridge from the local estimated mode shape elements.

Numerical case studies are investigated using Finite Element (FE) models of vehicle bridge interaction (VBI) to validate the effectiveness and performance of the proposed method. As noted by many authors [16,17,20] the presence of road roughness causes the dominance of vehicle frequencies. Therefore, in the present study, two concepts are tested to address this problem: (a) excitation of the bridge by traffic other than the test vehicle and (b) subtraction of signals measured on following axles. The simulations confirm the capability of the proposed method to identify the mode shapes of a bridge using signals from passing vehicles. Only one accelerometer is assumed on each of the two axles so the proposed method is more efficient than traditional modal testing methods, which usually require the installation of several sensors on the structure.

2. Finite element modelling of vehicle bridge interaction

In recent years, much research has been carried out on the modelling of vehicle bridge interaction (VBI) [33–36]. González [37] carry out a comprehensive review of coupled and uncoupled VBI models in the literature. A Finite Element (FE) VBI model similar to that used by Keenahan et al. [24] is used here for the numerical investigation of the proposed method. In this model, VBI is modelled as a coupled system in which the solution is calculated at each time step. The vehicle and bridge models and the iterative VBI procedure employed in this paper are set out in the following sub-sections.

2.1. Vehicle model

The two-quarter-car model shown in Fig. 1 illustrates many of the important characteristics of VBI [38]. This is used here to represent a 2-axle vehicle and, not connecting quarter-cars is a deliberate simplification. Each quarter-car has two independent degrees of freedom corresponding to the translational displacements of body bounce, y_s and axle hop, y_u. The vehicle body and axle component masses are represented by m_s and m_u (sprung and unsprung). The axle mass connects to the road surface via a spring with linear stiffness k_t which represents the tyre. The equations of motion of the vehicle model are obtained by imposing equilibrium of all forces and moments acting on the masses and expressing them in terms of the degrees of freedom:

$$M_v\ddot{y}_v + C_v\dot{y}_v + K_v y_v = f_{int} \tag{1}$$

where M_v, C_v and K_v are the respective mass, damping and stiffness matrices of the vehicle and $\ddot{y}$, $\dot{y}_v$ and y_v are the respective vectors of nodal acceleration, velocity and displacement. f_{int} is the time-varying dynamic interaction force vector applied to the vehicle degrees of freedom.

2.2. Bridge model

A simply supported beam of total span length L is modelled using the FE method to represent the bridge (Fig. 1). The model consists of discretised beam elements with 4 degrees of freedom (2 per node) which have constant mass per unit length, m, modulus of elasticity E and second moment of area J.

The response of the beam model to a series of moving time-varying forces is given by the system of equations:

$$M_b\ddot{y}_b + C_b\dot{y}_b + K_b y_b = f_{int} \tag{2}$$

where M_b, C_b and K_b are global mass, damping and stiffness matrices of the beam model, respectively and $\ddot{y}_b$, $\dot{y}_b$ and y_b are the vectors of nodal bridge accelerations, velocities and displacements, respectively.