



Extraction of bridge fundamental frequency from estimated vehicle excitation through a particle filter approach

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ABSTRACT

A bridge's natural frequencies are important dynamic properties reflecting the structural condition of the bridge. Numerous studies have been conducted in the field to extract a bridge's natural frequencies from responses of passing vehicles. The bridge frequency peaks are, however, not easily observed, because pavement roughness often influences the spectra of vehicle responses. In this research, a method that extracts the fundamental frequency of a bridge from the responses of an ordinary vehicle with its parameters calibrated in advance is proposed. The method is based on the idea that the vehicle passing across a bridge is excited by two sources, i.e., pavement roughness and bridge vibration. The excitation inputs to the vehicle, i.e., displacement inputs at the front and rear tire locations, are estimated from vehicle responses using a particle filter method. The estimated displacement inputs at the front and rear tires are then subtracted from each other after shifting by a wheel–base distance to eliminate the roughness influence, which commonly appears in both signals. The signal after the subtraction contains only the bridge vibration influence and is used to extract the fundamental frequency of the bridge. This indirect method of bridge frequency extraction is investigated through numerical simulations. A field measurement was also conducted, and it showed that the bridge's fundamental frequency was successfully extracted with a good accuracy for several driving-speed cases.

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1. Introduction

The demand for monitoring a bridge's structural condition has increased worldwide in recent years [1]. Among various bridge dynamic properties, the fundamental frequency is an important indicator to reflect the actual conditions of a bridge [2,3]. From the structural-health-monitoring point of view, it is necessary to keep monitoring the bridge's fundamental frequency. The conventional methods, also known as direct methods, install sensors on the bridge to measure bridge responses under various loads, including ambient vibration, traffic loads, and seismic motion [4–9]. The measured bridge responses are then used to obtain the bridge's dynamic properties of interest. However, it is usually not practical to install sensors on a large number of bridges, because the installation procedure is always costly and time consuming with site-specific technical difficulties [10,11].

However, the idea of indirect methods, which uses a moving vehicle as both the exciter and the receiver of the bridge vibration, was first proposed by Yang et al. [12]. It has been investigated by many researchers in recent years for different

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purposes [13], including bridge frequency extractions [14–18] and bridge damage detection [19–24]. However, the effectiveness of these indirect methods is often influenced by pavement roughness, whose frequency components are distributed over a wide frequency range, making the bridge vibration components unnoticeable in the vehicle responses, which may lead to the failure of indirect methods [25]. To eliminate the influence of the bridge pavement roughness, Kong et al. proposed the idea of “shifting and subtracting” by using sensors on two trailers after a tractor [26,27]. The recorded responses of the trailers were subtracted from each other considering the time shift between the two signals; the bridge frequencies were then obtained by frequency analysis of the subtracted signal. Although the proposal of this shift-and-subtraction approach has been shown to be effective through simulation, the method has not been experimentally verified through field measurements. The complexity of the tractor-and-trailer system, which limits the applicability to real cases, is preferably eliminated.

In this paper, a method to extract the bridge fundamental frequency using the responses of a single ordinary vehicle with calibrated vehicle parameters passing over the bridge is proposed. The idea of shifting and subtracting is adopted. The method is based on the idea that the excitation to the vehicle consists of two parts: pavement roughness and bridge vibration. The excitation inputs to the vehicle, i.e., displacement inputs at the front and rear tire locations, are identified using a particle filter method. One of the excitation inputs is shifted to account for the wheel–base distance and then subtracted from the other input. Because the influence from the pavement roughness commonly appears in both input signals, the subtracted signal contains only the bridge vibration component and is used to extract the fundamental frequency. Although the estimation of vehicle excitation from vehicle responses has been proposed with different algorithms and investigated numerically [28–30], these approaches, to the authors' knowledge, have not been experimentally validated; the uncertainties in the vehicle models and drive speeds, as well as sensor setup, are among the typical difficulties in implementing vehicle–bridge-interaction (VBI)-related experiments. The feasibility of the proposed method is validated through a numerical analysis and field measurement.

2. Vehicle and bridge models

2.1. Vehicle model

A half-car vehicle model, which has four degrees of freedom, namely, vehicle body vertical movement u_b , two axle movements u_f and u_r , and vehicle pitch motion θ , is employed herein and shown in Fig. 1 [31].

The equation of motion describing the half-car model is expressed as

$$\mathbf{M}_v \ddot{\mathbf{U}}(t) + \mathbf{C}_v \dot{\mathbf{U}}(t) + \mathbf{K}_v \mathbf{U}(t) = \mathbf{P}(t) \quad (1)$$

where $\mathbf{M}_v$, $\mathbf{C}_v$, and $\mathbf{K}_v$ are mass, damping, and stiffness matrices of the half-car model, whose detailed definitions are in Ref. [31]. $\mathbf{P}(t)$ is the excitation force of the vehicle system and $\mathbf{U}(t)$ is the vehicle response as

$$\mathbf{U} = [u_b \quad \theta \quad u_f \quad u_r]^T, \mathbf{P} = [0 \quad 0 \quad h_f k_{tf} \quad h_r k_{tr}]^T \quad (2)$$

The definition of each variable in Eq. (2) is in Fig. 1. m_b , m_f , m_r are vehicle body mass, front tire mass, and rear tire mass, respectively. k_t and k_r are the front and rear stiffness of the suspension system, respectively. k_{tf} and k_{tr} are front and rear tire stiffness, respectively. c_f and c_r are the front and rear damping coefficients, respectively, of the suspension system. h_f and h_r are the input displacements at the front and rear tires, respectively, including bridge roughness and bridge deflection. I_y is the moment of inertia of the vehicle body.

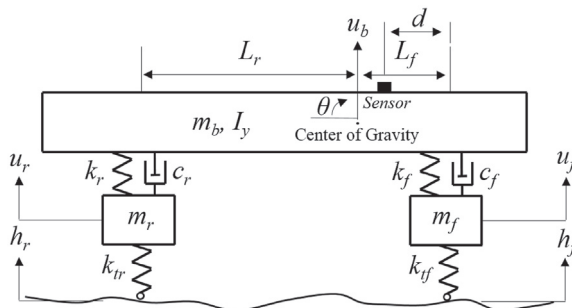


Fig. 1. Half-car model.

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