Engineering Structures 153 (2017) 57–70

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Identification of moving vehicle parameters using bridge responses and estimated bridge pavement roughness

Haoqi Wang, Tomonori Nagayama *, Boyu Zhao, Di Su

The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

ARTICLE INFO

Article history:
Received 5 March 2017
Revised 1 October 2017
Accepted 3 October 2017

Keywords:
Vehicle-bridge interaction
Particle filter
Pavement roughness estimation
Weigh-in-motion

ABSTRACT

Passing vehicles cause bridge deformation and vibration. Overloaded vehicles can result in fatigue damage to, or even failure of, the bridge. The bridge response is related to the properties of the passing vehicles, particularly the vehicle weight. Therefore, a bridge weigh-in-motion system for estimating vehicle parameters is important for evaluating the bridge condition under repeated load. However, traditional weigh-in-motion methods, which involve the installation of strain gauges on bridge members and calibration with known weight truck, are often costly and time-consuming. In this paper, a method for the identification of moving vehicle parameters using bridge acceleration responses is investigated. A time-domain method based on the Bayesian theory application of a particle filter is adopted. The bridge pavement roughness is estimated in advance using vehicle responses from a sensor-equipped car with consideration of vehicle-bridge interaction, and it is utilized in the parameter estimation. The method does not require the calibration. Numerical simulations demonstrate that the vehicle parameters, including the vehicle weight, are estimated with high accuracy and robustness against observation noise and modeling error. Finally, this method is validated through field measurement. The resulting estimate of vehicle mass agrees with the measured value, demonstrating the practicality of the proposed method.

1. Introduction

When a vehicle passes over a bridge, vibration occurs as a result of the dynamic forces generated by the vehicle [1]. Unpleasant bridge vibration is highly correlated with the vehicle parameters, including high vehicle mass and vehicle speed. This traffic-induced response may cause fatigue problems if the dynamic response is large and/or if the fatigue design is not appropriately performed [2,3]. Therefore, a bridge weigh-in-motion (BWIM) system is important for at least two reasons [4]. First, from the point of view of structural design, the accurate estimation of passing vehicle loads helps to evaluate the real dynamic load on existing bridges, providing information for future designs. Second, by monitoring passing vehicle loads, the overload conditions present on the bridge can be determined, which enables the transportation network to take corresponding action [5]. However, the determination of vehicle load in motion is not usually easy because the dynamic force created by a passing vehicle depends on both time and space. Even when a bridge is well equipped with sensors, the dynamic response of the structure is only obtained at a limited number of points. Therefore, the problem of obtaining vehicle parameters from bridge response data presents an important and challenging issue for research [6].

The identification of vehicle parameters from bridge dynamic responses is an inverse dynamic problem and has drawn much attention in recent years [7–9]. At first, most researchers focused on the use of strain data to identify dynamic load, due to the simplicity and accuracy of this approach. The concept of BWIM was first proposed by Moses [10], using a system in which the moving load is estimated from the strain in the main girders and their influence lines calibrated by a known weight vehicle. Later, Connor and Chan [11] proposed a BWIM system for identifying both static and dynamic loads, which also relied on measuring bridge strain data. Attempts to improve the estimation accuracy of strain-based systems by including accelerometers were made by some researchers. The time domain method was first proposed by Law et al. [12], combining bending moments determined by measured strain data with acceleration measurements, to give axle load. A frequency domain method was also proposed by Yu et al. [13], in which the load and bridge response are related in the frequency domain, and the load is obtained by using an inverse Fourier transform. A Bayesian analysis of time domain signals, which is represented by the Kalman filter [14], is another method for vehicle parameter determination. Hoshiya and Maruyama [15] combined an extended Kalman filter with a weighted global iteration (WGI)

* Corresponding author.
E-mail address: nagayama@bridge.t.u-tokyo.ac.jp (T. Nagayama).

https://doi.org/10.1016/j.engstruct.2017.10.006
0141-0296/

technique to simultaneously identify both a moving force on a simply-supported beam and the beam parameters. Chen and Lee [16] also used a Kalman filter to estimate the moving force on a bridge, while the vehicle-induced force was modeled as a sine wave. A significant development was achieved when the use of a particle filter was proposed by Gordon et al. [17]. Lalthlamuana et al. [18] used the particle filter method to identify vehicle parameters from bridge acceleration measurements. The method does not require the calibration process. However, the particle filter method assumes a pavement roughness measurement using a total station, which requires the closure of the bridge to obtain, thus limiting its applicability, especially for bridges that carry heavy traffic. Furthermore, while vehicle parameter estimation typically suffers from large measurement noise and modeling errors, these effects and the improvement of estimation accuracy against them have not been investigated.

In this paper, a two-step method for vehicle parameter identification using a particle filter with a simple and accurate response-based pavement roughness estimation is proposed, which does not need calibration with the known weight truck. This method relies upon the fact that the bridge pavement roughness is the main excitation source of the coupled vehicle-bridge system; when a vehicle crosses the bridge, the bridge pavement roughness causes vehicle vibration, which, in turn, leads to bridge vibration. Therefore, an accurate estimate of the pavement roughness is of great importance [19]. In the first step of the proposed method, the pavement roughness of the target bridge is estimated using a probe car with calibrated parameters. As the output of the vehicle-bridge coupled system, vehicle responses are measured through sensors installed on the probe car. The system input, i.e., the pavement roughness, is estimated through an inverse analysis. In the second step, accelerometers are installed on the bridge to measure the vehicle-induced vibration. Since the pavement roughness input has already been estimated in the first step, the parameters of the passing vehicle can then be identified using the system identification method. The flow chart for the proposed method is shown in Fig. 1. The particle filter method is used in both steps.

The structure of this paper is as follows. In Section 2, the vehicle and bridge model adopted in this study is described and the vehicle-bridge interaction is considered. In Section 3, the proposed method of vehicle parameter identification is explained in detail. Section 4 provides numerical examples testing the feasibility of this method. Section 5 describes the field measurements taken to verify the effectiveness of the proposed method. Conclusions are drawn in Section 6.

2. Vehicle and bridge model

2.1. Vehicle model and its responses

A half-car vehicle model, which represents an ordinary two-axle vehicle, is employed for analysis in this paper. The model has 4 degrees of freedom corresponding to the vehicle body vertical movement u_b, two axle movements u_f and u_r, and vehicle body rotation, θ, as shown in Fig. 2 [20].

The equation of motion of this half-car model is given by

$$M_v\ddot{U}(t) + C_v\dot{U}(t) + K_vU(t) = P(t) \tag{1}$$

where

$$M_v = \begin{bmatrix} m_b & 0 & 0 & 0 \\ 0 & I_y & 0 & 0 \\ 0 & 0 & m_f & 0 \\ 0 & 0 & 0 & m_r \end{bmatrix} \tag{2}$$

$$C_v = \begin{bmatrix} c_f + c_r & L_rc_r - L_fc_f & -c_f & -c_r \\ L_rc_r - L_fc_f & L_f^2c_f + L_r^2c_r & L_fc_f & -L_rc_r \\ -c_f & L_fc_f & c_f & 0 \\ -c_r & -L_rc_r & 0 & c_r \end{bmatrix} \tag{3}$$

$$K_v = \begin{bmatrix} k_f + k_r & L_rk_r - L_fk_f & -k_f & -k_r \\ L_rk_r - L_fk_f & L_f^2k_f + L_r^2k_r & L_fk_f & -L_rk_r \\ -k_f & L_fk_f & k_f + k_{tf} & 0 \\ -k_r & -L_rk_r & 0 & k_r + k_{tr} \end{bmatrix} \tag{4}$$

$$U = [u_b \quad \theta \quad u_f \quad u_r]^T, \quad P = [0 \quad 0 \quad h_fk_{tf} \quad h_rk_{tr}]^T \tag{5}$$

In Eqs. (2)–(4), M_v, C_v, and K_v are vehicle mass, damping, and stiffness matrices, respectively. In Eq. (5), $P(t)$ is the excitation force of the vehicle system and $U(t)$ is the vehicle response. The parameters in the matrices are shown in Fig. 2, including vehicle body mass m_b, vehicle tire mass m_f and m_r, moment of inertia I_y, suspension stiffness k_f and k_r, suspension damping c_f and c_r, and tire stiffness k_{tf} and k_{tr}.

2.2. Bridge model and its responses

An Euler–Bernoulli simply supported beam model is adopted as the bridge model for its simplicity. When the bridge is excited by the vehicle load, the equation of motion of the bridge is expressed as

$$\bar{m}\frac{\partial^2 y(x,t)}{\partial t^2} + c_b\frac{\partial y(x,t)}{\partial t} + EI\frac{\partial^4 y(x,t)}{\partial x^4} = L(x,t), \tag{6}$$

in which $\bar{m}$ is the mass per length, c_b is the viscous damping parameter, EI is the flexural stiffness, $y(x, t)$ is the time- and space-dependent displacement response, and $L(x, t)$ is the moving dynamic load on the bridge [21]. To solve this equation numerically, modal decomposition analysis is used, yielding

$$M_b\ddot{q} + C_b\dot{q} + K_bq = F_b, \tag{7}$$

where M_b, C_b, and K_b are the diagonal modal mass, damping, and stiffness matrices, respectively, q contains the bridge displacement

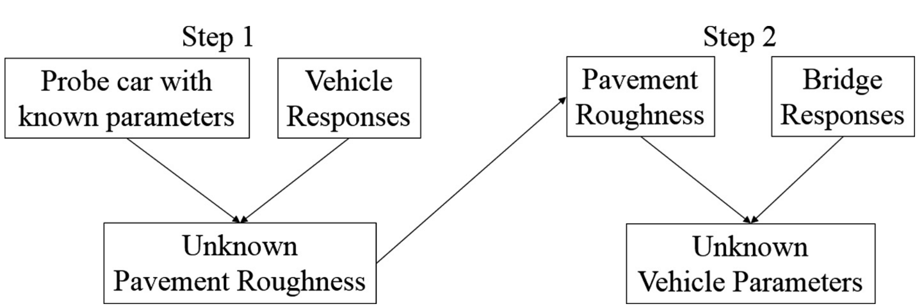

Fig. 1. Flow chart of the proposed method for determining vehicle parameters.