Computers and Structures 157 (2015) 76–88

Contents lists available at ScienceDirect

Computers and Structures

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

Simultaneous identification of bridge structural parameters and vehicle loads

Dongming Feng [a,*], Hao Sun [b], Maria Q. Feng [a]

[a] Department of Civil Engineering & Engineering Mechanics, Columbia University, New York, NY 10027, United States
[b] Department of Civil & Environmental Engineering, MIT, Cambridge, MA 02139, United States

ARTICLE INFO

Article history:
Received 7 December 2014
Accepted 11 May 2015
Available online 4 June 2015

Keywords:
Vehicle axle loads
Moving forces
Vehicle–bridge interaction
Output-only identification
Bayesian regularization
Damped Gauss–Newton optimization

ABSTRACT

Most of the existing methods for identification of vehicle axle loads are based on a model with known system parameters. In this study, a new method is proposed to simultaneously identify bridge structural parameters and vehicle dynamic axle loads of a vehicle–bridge interaction system from a limited number of response measurements. As an inverse output-only identification problem, the estimation of unknown axle loads is incorporated in the framework of an iterative parametric optimization process, wherein the objective is to minimize the error between the measured and predicted system responses. A Bayesian inference regularization is presented to solve the ill-posed least squares problem for input axle loads. Numerical analyses of a simply-supported single-span bridge and a three-span continuous bridge are conducted to investigate the accuracy and efficiency of the proposed method. Effects of the vehicle speed, the number of sensors, the measurement noise, and initial estimates of structural parameters on the accuracy of the identification results are investigated, demonstrating the robustness and efficiency of the proposed algorithm. Finally, it is shown that the bridge dynamic response can be accurately predicted using the identified axle load histories and structural parameters.

1. Introduction

Repeated operational traffic loads over time can lead to the deterioration of bridge structures. It is therefore important to measure the operational vehicle axle loads or the moving dynamic forces for evaluation and maintenance bridge structures. From bridge design point of view, it is also desirable to measure the vehicle axle loads [1]. Weigh-in-motion (WIM) systems [2] have been developed, which measure the bridge strains caused by moving vehicles to estimate the equivalent static axle loads [3,4]. However, the accuracy of the WIM systems often depends on the road surface condition and the results are reliable only when the vehicle speed is low and bridge pavement surface is smooth [5]. In fact, the dynamic effects of the moving vehicle cause much larger bridge responses, especially when unfavorable road roughness exists, by increasing the average surface damage two to four times compared to that from the static axle forces [5]. In view of this, it would be beneficial if the dynamic axle forces of the operational traffic vehicles as well as the structural parameters could be identified. Such information is of particular importance for the purpose of deck and pavement design, management, maintenance, safety assessment as well as fatigue estimation [5,6].

Consequently, there has been a considerable amount of research efforts towards identification of dynamic vehicle axle loads or moving forces from measured bridge responses including strain, displacement, acceleration, and bending moment [1–13]. For example, Law et al. [7] introduced a regularization method in the ill-posed inverse problem to provide bounds to the identified moving forces. Based on the finite element formulation, a generalized orthogonal function approximation was developed by Zhu and Law [8] to obtain the derivatives of the bridge modal responses, and moving forces were identified using the regularized least-squares method in the time domain. Zhu and Law [12] further studied the effects of vertical and rotational support stiffness on the identification results based on an elastically supported multi-span continuous bridge deck. González et al. [4] developed a moving force identification method using the first-order Tikhonov regularization applied to a two dimensional orthotropic plate bridge from 21 strain measurements. Deng and Cai [5] presented a moving force identification technique using the superposition principle and the influence surface to deal with the bridge structure, and effects of factors such as the vehicle speed, the road

* Corresponding author. Tel.: +1 917 834 4717.
E-mail addresses: df2465@columbia.edu (D. Feng), haosun@mit.edu (H. Sun), mqf2101@columbia.edu (M.Q. Feng).

http://dx.doi.org/10.1016/j.compstruc.2015.05.017
0045-7949/

surface condition, and the traveling route, were numerically studied. Asnachinda et al. [13] carried out laboratory experiments by using two scaled two-axle vehicles running on a scaled three-span continuous bridge, and successfully identified the multiple axle forces using an updated static component technique. Besides the above numerical and laboratory experimental validations, Chan et al. [11] carried out field measurements of an existing prestressed concrete bridge for moving force identification. Dynamic axle forces and the gross vehicle weight were obtained with an acceptable error. In general, all these methods can identify moving axle forces with an acceptable accuracy.

However, in the above studies, the force identification is based on the prerequisite that the system parameters, e.g., the flexural stiffness of the bridge structure, are completely known in advance, which would limit practical implementations of these approaches. There have been a few attempts for simultaneous identification of both the structural parameters and vehicle parameters or axle loads. For example, Zhu and Law [14] developed an iterative procedure to identify the unknown moving forces and system parameters from measured bridge responses with a full sensor placement. Lu and Liu [15] presented a response sensitivity-based finite element model updating approach to identify both damages in a bridge and the vehicular parameters, where acceleration measurements from both the bridge and vehicle were used.

In summary, existing extensive vibration-based bridge system identification methods can be categorized as follows: (1) studies focusing on identification of bridge parameters based on dynamic measurements due to ambient excitations [16–18], earthquake excitations [19–22] or traffic-induced bridge responses with known traffic loads [23–26]; (2) the identification of dynamic vehicle axle loads or moving forces by assuming known bridge parameters; and (3) identification of both bridge and vehicle parameters with a full sensor placement or using measurements from both the bridge and vehicle subsystems.

The major contributions of this study are: (1) we propose a new method to simultaneously identify bridge structural parameters and vehicle axle loads from only a limited number of sensors in the framework of an iterative parametric optimization process and (2) we present a Bayesian inference-based regularization approach to solve the ill-posed least squares problem for the unknown vehicle axle loads. This paper is organized as follows. Section 2 introduces the dynamics of the VBI system. Section 3 presents the basic identification formulation, including the system identification as an optimization problem as well as the force identification using the Bayesian inference regularization technique. Section 4 presents the iterative identification procedure. In Sections 5 and 6, numerical analyses of a single-span simply supported bridge and a three-span continuous bridge are conducted to demonstrate the accuracy and efficiency of the proposed method. Finally, Section 7 summarizes the results of this study.

2. Dynamics of the VBI system

As shown in Fig. 1, the vehicle–bridge interaction (VBI) system is modeled by a simply supported or continuous bridge subject to a moving vehicle which is represented by a four-degree-freedom system. Here, m_v and I_v are the body mass and the pitch moment of inertia, respectively; m_{t1} and m_{t2} are the front and the rear axle mass, respectively; K_{s1}, K_{s2}, C_{s1} and C_{s2} are the linear suspension stiffness and the viscous damping parameters of the front and rear axles, respectively; K_{t1}, K_{t2}, C_{t1} and C_{t2} are the linear tire stiffness and the viscous damping parameters, respectively; a_1 and a_2 are the axle distances with respect to the gravity center; ρ is the mass per unit length; *EI* is the flexural stiffness of the bridge, a product of Young's modulus *E* and the moment of inertia *I*.

2.1. Road surface roughness

The road surface condition distinctly affects the dynamic responses of both the bridge and vehicles [5]. According to the ISO-8606 specification [27], the road roughness is classified as five levels from 'Level A' (very good) to 'Level E' (very poor). By applying the inverse fast Fourier transformation, the road surface roughness in the spatial domain can be simulated from

$$r(x) = \sum_{k=1}^{N} \sqrt{4S(f_k)\Delta f} \cos(2\pi f_k x + \theta_k) \quad (1)$$

where $f_k = k\Delta f$ is the spatial frequency (cycle/m); $\Delta f = 1/(N\Delta)$, herein Δ is the distance interval between successive ordinates of the surface profile and N is the number of surface profile points; and θ_k is the random phase angel distributed uniformly between 0 and 2π. The general form of the PSD function of the road surface roughness can be given as

$$S(f_k) = S(f_0)(f_k/f_0)^{-2} \quad (f_l \leqslant f_k \leqslant f_u) \quad (2)$$

where $f_0 = 0.1$ (cycles/m) is the reference spatial frequency; f_l and f_u are the lower and the upper cut-off spatial frequencies, respectively. The roughness level of the road profile can be indicated by the value of $S(f_0)$.

2.2. Vehicle model

The equation of motion of the four-degree-freedom vehicle in Fig. 1 can be derived using dynamic equilibrium, given by

$$\begin{bmatrix} \mathbf{M}_{v1} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{v2} \end{bmatrix} \ddot{\mathbf{y}}_v + \begin{bmatrix} \mathbf{C}_{v11} & \mathbf{C}_{v12} \\ \mathbf{C}_{v21} & \mathbf{C}_{v22} \end{bmatrix} \dot{\mathbf{y}}_v + \begin{bmatrix} \mathbf{K}_{v11} & \mathbf{K}_{v12} \\ \mathbf{K}_{v21} & \mathbf{K}_{v22} \end{bmatrix} \mathbf{y}_v = \mathbf{P}_v \quad (3)$$

where $\mathbf{M}_{v1}, \mathbf{M}_{v2}, \mathbf{C}_{v11}, \mathbf{C}_{v12}, \mathbf{C}_{v21}, \mathbf{C}_{v22}, \mathbf{K}_{v11}, \mathbf{K}_{v12}, \mathbf{K}_{v21}$ and $\mathbf{K}_{v22}$ are respectively the vehicle mass, damping and stiffness sub-matrices, as given in Appendix A; $\mathbf{y}_v, \dot{\mathbf{y}}_v$ and $\ddot{\mathbf{y}}_v$ are respectively the vehicle

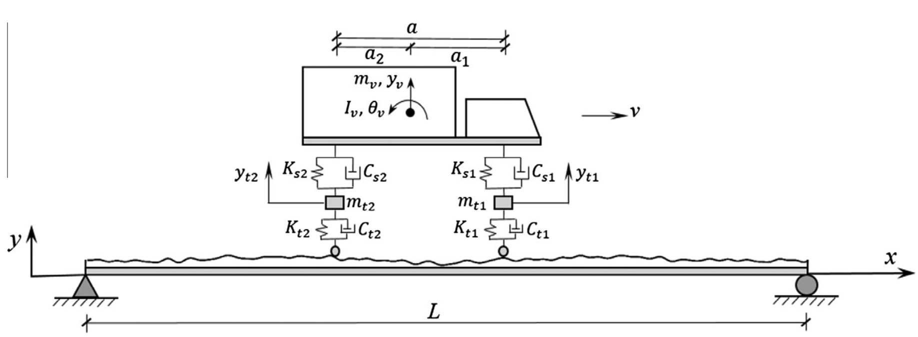

Fig. 1. VBI system considering road surface roughness.