Measurement 131 (2019) 173–182

Contents lists available at ScienceDirect

Measurement

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

Sparse regularization for traffic load monitoring using bridge response measurements

Huanlin Liu[a], Ling Yu[a,b,*]

[a] School of Mechanics and Construction Engineering, Jinan University, Guangzhou 510632, China
[b] MOE Key Lab of Disaster Forecast and Control in Engineering, Jinan University, Guangzhou 510632, China

ARTICLE INFO

Keywords:
Traffic load monitoring (TLM)
Moving force identification (MFI)
Redundant dictionary
l_1-Norm regularization
Analytical model
Wavelet functions

ABSTRACT

Traffic load monitoring (TLM) is one of important issues in bridge structural health monitoring (SHM), but there still exist such problems as lack of accuracy and efficiency for the existing methods. In this study, a sparse regularization approach is proposed for TLM based on analytical model and redundant dictionary. Firstly, an unknown moving traffic load is deemed as a combination of static and time-varying components so that a redundant dictionary can be established to independently express them. The static component is expressed by a basis vector whose elements are identical, and the time-varying one by wavelet functions for their good multi-resolution analysis characteristics. Then, the TLM problem is converted to determine a coefficient vector of dictionary, and the l_1-norm regularization technique is adopted to obtain a sparse solution to the coefficient vector. Finally, a series of experimental studies on a hollow steel beam bridge under crossing a moving model car are conducted in laboratory to assess the effectiveness of the proposed method. Furthermore, comparative studies are carried out for assessing the effect of different measurement parameters, such as moving car speeds, car weights, strain and acceleration response data, redundant dictionaries as well as selection of regularization parameters, on the proposed method. The illustrated TLM results show that the dictionary used for TLM in this study can independently distinguish the static and time-varying components of moving traffic loads. The proposed method can effectively identify the total weight of moving traffic loads with a higher accuracy, which provides a great potential for monitoring moving vehicle loads on bridges.

1. Introduction

Moving traffic loads are foundations for the life-cycle design of highway bridges. It is important to control and monitor traffic loads which contribute to the bridge design code. However, it is difficult to obtain time histories of traffic loads directly because they are functions in both time and space. Therefore, as indirect methods, moving force identification (MFI) is proposed for traffic load monitoring (TLM) [1]. Indirect methods consider traffic loads as moving forces and obtain time histories of moving forces from measured structural responses with inherent characteristics of structures.

As one of important issues in bridge structural health monitoring (SHM) [2,3], MFI has been widely studied in the past decades. In early studies, most of the methods focus on establishment of MFI equations, which can be divided into two kinds of methods, one is based on analytical model and another one is based on numerical model. A review of these methods can be found in Ref [4]. Methods based on analytical model include time domain method (TDM) [5], interpretive method II [6], frequency-time domain method [7], state space method [8], method of moments [9,10] and influence line method [11]. Methods based on numerical model include interpretive method I [12], optimal state estimation approach [13], updated static component technique [14,15]. After discretization processing, the discrete identification equations about time-varying moving force and structural responses are given by these methods.

The MFI problem is a typical inverse problem so that the identified results are always sensitive to noise. Under the environmental noise, the real time-varying moving force cannot be identified accurately. Moreover, for boundary conditions, response sensitivity to moving force is related to locations of moving force, as a result, when a moving force approaches to the structural boundary, the identified results are worse by directly solving the identification equation [5]. Therefore, regularization techniques, such as Tikhonov regularization [16], sparse regularization [17–19] and so on, are usually introduced to improve the ill-posedness of MFI problem.

The classical Tikhonov regularization has been widely used to

* Corresponding author at: School of Mechanics and Construction Engineering, Jinan University, Guangzhou 510632, China.
E-mail address: lyu1997@163.com (L. Yu).

https://doi.org/10.1016/j.measurement.2018.07.044
Received 22 April 2018; Received in revised form 14 July 2018; Accepted 16 July 2018
Available online 17 July 2018
0263-2241/ © 2018 Elsevier Ltd. All rights reserved.

obtain an improved MFI results in several studies [20–22]. The classical Tikhonov regularization can effectively improve the ill-posedness of original MFI problem, for example, Law et al. [20] introduced classical Tikhonov regularization into TDM, better identified results can be obtained even with noisy measurements. But the identified results are overfitting because the Tikhonov matrix is selected as a unity matrix. Therefore, some improved methods have been proposed: Chen and Chan [21] selected the matrix as double diagonal matrix and tri-diagonal matrix; Pan et al. [22] selected the Tikhonov matrix based on the concept of moving average, which can effectively obtain static component of moving force.

These methods use only one class set of basis vectors obtained from singular value composition (SVD) of discrete linear operator; as a result, these vectors cannot express the unknown moving traffic loads completely and suitability. To overcome this shortcoming, Pan et al. [23] proposed a MFI technique based on a redundant concatenated dictionary and sparse regularization. Compared with only one class set of basis vectors, the redundant concatenated dictionary is more suitable to express the unknown moving forces. Meanwhile, sparse regularization can extract main features of moving forces from the given dictionary. However, the concatenated dictionary in Ref [23] consists of trigonometric and rectangular functions, and the trigonometric functions cannot adapt to signal analysis of time-frequency. Meanwhile, a finite element model updated by structural frequencies, damping ratios and mode shapes is used for MFI, so it should be obtained by a large number of sensors due to application of mode shapes. Moreover, the applicability of this method for TLM has not been studied yet in detail.

In this study, an analytical model is used for TLM and it is updated only by structural frequencies and damping ratios. Then, a redundant dictionary is established to independently express static and time-varying components of moving forces. The static component is expressed by a basis vector whose elements are identical, and the time-varying one by wavelet functions for their good multi-resolution analysis characteristics. Finally, a series of experimental data of bridge responses caused by crossing traffic vehicle loads are measured and used to assess the effectiveness of the proposed method. Comparative studies on different vehicle axle weights, moving vehicle speeds, strain and acceleration response data, redundant dictionaries and selection of regularization parameter are carried out for TLM.

This paper is organized as follows: The Section one is devoted to literature review, containing state of art of MFI for TLM problems and some related MFI methods. The basic theories of MFI are briefly introduced for TLM in Section two. A series of experimental studies on TLM in laboratory is described in Section three. Comparative studies about effect of different parameters on the proposed method are illustrated in Section four. Several conclusions are drawn in Section five.

2. Basic theory

2.1. Time domain method (TDM)

TDM is a typical MFI method. It is based on the analytical model and gives the relations between unknown moving forces and structural responses. Here, a brief introduction is given and more details about TDM can be seen in Ref [5].

The bridge is simplified as a simply supported beam, and it is subjected to a moving force $f_1(t)$, as shown in Fig. 1. EI, ρ, C, l are flexural stiffness, mass per unit length, viscous damping and span of the beam, respectively. The constant value c represents the moving speed of moving force $f_1(t)$.

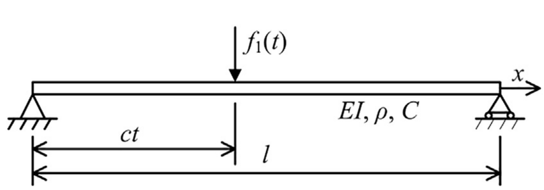

Fig. 1. A simply supported beam subjected to a moving force.

Based on modal superposition principle, structural bending moment and acceleration responses can be obtained:

$$m(x,t) = \sum_{n=1}^{\infty} \frac{2EI\pi^2 n^2}{\rho l^3 \omega_n'} \sin\frac{n\pi x}{l} \int_0^t e^{-\xi_n\omega_n(t-\tau)} \sin\omega_n'(t-\tau) \sin\frac{n\pi c\tau}{l} f(\tau)d\tau \tag{1}$$

$$\ddot{v}(x,t) = \sum_{n=1}^{\infty} \frac{2}{\rho l}\sin\frac{n\pi x}{l}\left[f(t)\sin\frac{n\pi ct}{l} + \int_0^t \ddot{h}_n(t-\tau)f(\tau)\sin\frac{n\pi c\tau}{l}d\tau\right],$$
$$\ddot{h}_n(t) = \frac{1}{\omega_n'}e^{-\xi_n\omega_n t}\{[(\xi_n\omega_n)^2-\omega_n'^2]\sin\omega'_n t-(2\xi_n\omega_n\omega_n')\cos\omega'_n t\} \tag{2}$$

where, $\omega_n = (n^2\pi^2/l^2)\sqrt{EI/\rho}$, $\xi_n = C/(2\rho\omega_n)$, $\omega_n' = \omega_n\sqrt{1-\xi_n^2}$ are the nth modal frequency, the nth modal damping and the nth damped modal frequency, respectively.

If the sampling duration is [0, ti] and the sampling time interval is Δt, the number of sampling points for structural response is $m = \lfloor ti/\Delta t + 1\rfloor$, where $\lfloor\cdot\rfloor$ is the floor function in mathematics. Similarly, the moving force is only considered in the time interval [0, T], the number of sampling points for moving force is $n = \lfloor T/\Delta t + 1\rfloor$ ($n \le m$). After discretization processing, Eqs. (1) and (2) can be simply expressed as:

$$\mathbf{H}_{11}\mathbf{f}_1 = \mathbf{b}_1 \tag{3}$$

where, $\boldsymbol{H}_{11} \in \boldsymbol{R}^{m\times n}$ is the transfer matrix; $\mathbf{f}_1 \in \boldsymbol{R}^{n\times 1}$ is the moving force vector; $\mathbf{b}_1 \in \boldsymbol{R}^{n\times 1}$ is the structural response vector.

2.2. Function expansion method using dictionaries

As a regularization strategy, the function expansion method expresses unknown moving force by using basis functions, so a moving force can be expressed by basis $\boldsymbol{\varphi}_i$ in a Hilbert space [24]:

$$\mathbf{f}_1 = \sum_{i=1}^{\infty}\alpha_i\varphi_i \approx \sum_{i=1}^{M}\alpha_i\varphi_i \tag{4}$$

where, M is the truncation number.

Then, a matrix-vector form of Eq. (4) can be expressed as follows:

$$\mathbf{f}_1 = \varphi\alpha_1 \tag{5}$$

where, $\boldsymbol{\alpha}_1$ is a vector of representation coefficients; $\boldsymbol{\varphi} = [\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \ldots, \boldsymbol{\varphi}_M]$ is a redundant dictionary to express the moving force vector.

By substituting Eq. (5) into Eq. (3), letting $\mathbf{A}_{11} = \mathbf{H}_{11}\boldsymbol{\varphi}$, the following equation can be obtained:

$$\mathbf{A}_{11}\alpha_1 = \mathbf{b}_1 \tag{6}$$

So the MFI problem is reformulated to Eq. (6) for determining the coefficient vector $\boldsymbol{\alpha}_1$ in the redundant dictionary $\boldsymbol{\varphi}$.

As mentioned above, it should be noted that the MFI results are partly determined by the selection of dictionary $\boldsymbol{\varphi}$. It can be selected as Legendre polynomials and Fourier series in Ref [9], or trigonometric functions and rectangular functions in Ref [23]; furthermore, spline functions and wavelets can also be chosen [24].

Because the time-varying components of moving force usually fluctuate around axle weight due to inertia of vehicle and surface roughness of bridge [22], the redundant dictionary is set as a combination as $\boldsymbol{\varphi} = [\boldsymbol{\varphi}_1, \mathbf{W}]$ in this study.

Here, $\boldsymbol{\varphi}_1$ is a basis vector used to represent static component of a moving force. The static component does not vary with the time; hence, each element of $\boldsymbol{\varphi}_1$ is identical, i.e., $\varphi_{1j} = 1/\sqrt{n}$ $(j = 1, 2, \ldots, n)$.

The time-varying components of the moving force is represented by $\mathbf{W}$, $\mathbf{W} = [\boldsymbol{\varphi}_2, \ldots, \boldsymbol{\varphi}_M]$. For the complexity of time-varying components, some simple basis vectors may not be suitable for describing the features of time-varying components, e.g. the mode shapes of simply supported beam. As a signal analysis technology, wavelet analysis has

Download English Version:

https://daneshyari.com/en/article/9953654

Download Persian Version:

https://daneshyari.com/article/9953654

Daneshyari.com