Mechanical Systems and Signal Processing 98 (2018) 32–49

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Moving force identification based on redundant concatenated dictionary and weighted l_1-norm regularization

Chu-Dong Pan [a,b], Ling Yu [a,b,c,*], Huan-Lin Liu [a], Ze-Peng Chen [a], Wen-Feng Luo [a]

[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
[c] College of Civil Engineering and Architecture, China Three Gorges University, Yichang 443002, China

A R T I C L E I N F O

Article history:
Received 27 October 2016
Received in revised form 24 February 2017
Accepted 24 April 2017
Available online 2 May 2017

Keywords:
Moving force identification
Redundant concatenated dictionary
Weighted l_1-norm regularization
Structural health monitoring (SHM)

A B S T R A C T

Moving force identification (MFI) is an important inverse problem in the field of bridge structural health monitoring (SHM). Reasonable signal structures of moving forces are rarely considered in the existing MFI methods. Interaction forces are complex because they contain both slowly-varying harmonic and impact signals due to bridge vibration and bumps on a bridge deck, respectively. Therefore, the interaction forces are usually hard to be expressed completely and sparsely by using a single basis function set. Based on the redundant concatenated dictionary and weighted l_1-norm regularization method, a hybrid method is proposed for MFI in this study. The redundant dictionary consists of both trigonometric functions and rectangular functions used for matching the harmonic and impact signal features of unknown moving forces. The weighted l_1-norm regularization method is introduced for formulation of MFI equation, so that the signal features of moving forces can be accurately extracted. The fast iterative shrinkage-thresholding algorithm (FISTA) is used for solving the MFI problem. The optimal regularization parameter is appropriately chosen by the Bayesian information criterion (BIC) method. In order to assess the accuracy and the feasibility of the proposed method, a simply-supported beam bridge subjected to a moving force is taken as an example for numerical simulations. Finally, a series of experimental studies on MFI of a steel beam are performed in laboratory. Both numerical and experimental results show that the proposed method can accurately identify the moving forces with a strong robustness, and it has a better performance than the Tikhonov regularization method. Some related issues are discussed as well.

1. Introduction

The dynamic moving forces are important in the field of bridge structural health monitoring (SHM), as they contribute to live load components in the bridge design code [1,2]. However, it is difficult to directly measure the interaction forces between the vehicles and a bridge, because the change in moving forces occurs in time and space simultaneously. Therefore, it would be beneficial to develop some indirect identification methods. The indirect method means that the moving forces are calculated according to the known dynamic properties of bridges and dynamic responses measured in actual situation. Compared to the cost of direct methods, the indirect identification methods are inexpensive.

* Corresponding author at: School of Mechanics and Construction Engineering, Jinan University, 601 West Huangpu Avenue, Guangzhou 510632, PR China.

E-mail address: lyu1997@163.com (L. Yu).

http://dx.doi.org/10.1016/j.ymssp.2017.04.032
0888-3270/

The problem of dynamic force reconstruction has been widely studied and lots of effective methods have been proposed. The force reconstruction methods are divided into three classes, i.e. direct methods, regularization methods and probabilistic/statistical methods, in a review work made by Sanchez and Benaroya [3]. Actually, the moving force identification (MFI) is a special problem in force reconstruction. The main feature of moving forces is that the positions of unknown forces will vary with time. The MFI theory has been developed greatly in the past decades and a lot of effective methods have been proposed [4]. Yu and Chan [5] made a complete study about four basic MFI methods, i.e. interpretive method I (IMI), interpretive method II (IMII), time domain method (TDM) [6] and frequency–time domain method (FTDM) [7]. Wu and Law [8] proposed a MFI technique based on a statistical system model. With the superposition principle and influence surface concept, Deng and Cai [9] proposed a MFI method for estimating the vehicular axle loads. Yu et al. [10] used the wavelet analysis to extract the axle information from the global responses.

As a second kind of inverse problem, the MFI problem is a typical ill-posed problem, which means that at least one point among existence of solution, uniqueness and stability cannot be satisfied. Therefore, the discrete MFI equations are always ill-conditioned and the identified results are sensitive to the noise. The regularization methods are widely used to improve this drawback, e.g. basis function method (BFM), Tikhonov regularization method, sparse regularization method and so on.

The BFM is a special regularization technique, which has been widely used in force reconstruction [11–13]. Actually, the BFM employs basis functions, e.g. trigonometric functions, orthogonal polynomials or spline functions, to express the unknown moving forces, which can be approximately expressed as the sum of a set of weighted basis functions. Therefore, the purpose of BFM is to identify the coefficients of basis functions. It must be emphasized that the existing BFMs always use single class set of basis functions. However, in practical engineering, the moving forces are very complex in the vehicle-bridge coupling system. They not only include slowly-varying harmonic components during the overall time history, but also contain the local impact components. Therefore, it is hard to express the moving forces completely and sparsely by using one class set of basis function only. This is the main shortcoming of the existing BFMs for MFI problems.

The classical Tikhonov regularization method is one of the most famous regularization techniques, and it has been fully studied in MFI [14,15]. In most cases, the solution of classical Tikhonov regularization method can be analyzed in a special way via the singular value decomposition (SVD). The biggest advantage of SVD-based method is that the complex MFI problem can be decoupled to simple problems. In fact, the SVD of a discrete linear operator is a factorization of the form $\boldsymbol{U}\sum\boldsymbol{V}^{\mathrm{T}}$, where $\sum$ is the singular value matrix and $\boldsymbol{U}$, $\boldsymbol{V}$ are two orthogonal matrixes, respectively. For the SVD-based methods, the unknown moving forces are decomposed by the columns of matrix $\boldsymbol{V}$, which can be regarded as a set of basis vectors. The MFI results by the SVD-based methods, e.g. classical Tikhonov regularization method, are mainly composed of the front part of the basis vectors in $\boldsymbol{V}$, since the contributions of basis vectors corresponding to small singular values are neglected. Therefore, it should be note that the SVD-based method can be regarded as one of the BFMs, and it has the same shortcoming of the existing BFMs for the MFI problems. Furthermore, the Tikhonov regularization method belongs to one of l_2-norm regularization methods. The results obtained by the Tikhonov regularization method are smooth. However, in some cases, especially for redundant dictionary, the results are preferred to contain a large number of zero components, i.e. the results are sparse. Therefore, it is better to use the sparse regularization method.

Unlike the existing BFM and Tikhonov regularization methods, the study of sparse regularization method in the MFI field seems not so much. Sparse regularization, in the mathematical inverse problem field, refers to a process of introducing additional sparse constraint information in order to solve an ill-posed problem. A sensible sparsity constraint is the l_0-norm, defined as the number of non-zero elements in estimated vector. Solving a l_0-norm regularized problem has been demonstrated to be non-deterministic polynomial hard (NP-hard) [16]. Therefore, l_1-norm constraint can be used to approximate the optimal l_0-norm via convex relaxation. Herein, l_1-norm constraint is defined as the sum of absolute values of elements in estimated vector. Obviously, the l_1-norm constraint is different from l_2-norm regularization method, in which the constraint is defined as a l_2-norm of the estimated vector. Qiao et al. [17,18] used the l_1-norm regularization method to identify both the impact force and harmonic force. Rezayat et al. [19] proposed a group-sparsity based method to identify both the unknown time history and unknown position of the dynamic force. The above methods are focused on the force reconstruction of fixed position. Bao et al. [20] used the l_1-norm regularization method for solving the distribution of moving heavy vehicle loads on cable-stayed bridges, however, only the time invariant forces are studied in this work. The biggest advantage of sparse regularization is for solving problem of feature extraction. As a convex optimization problem, the l_1-norm regularization is one of the most commonly used sparse regularization methods. However, the l_1-norm regularization always fairly penalizes all the components of unknown inputs. To overcome this draw, weighted l_1-norm regularization method is proposed in this study.

Unlike the stability of solution, the signal features of the complex moving forces are rarely considered in the existing MFI methods as stated above. Therefore, the existing MFI methods are difficult to extract these main features from the structural responses accurately, although their solutions are not sensitive to noise. In this study, an alternative method is proposed for MFI problems based on redundant concatenated dictionary and weighted l_1-norm regularization method. The redundant dictionary consisting of trigonometric functions and rectangular functions is adopted for matching the main features of the complex moving forces. Sparse regularization method can be used for extracting these main features from the structural responses. Therefore, the weighted l_1-norm regularization method belonging one of the sparse regularization methods is introduced for formulation of the MFI equations, and the fast iterative shrinkage-thresholding algorithm (FISTA) is employed for solving the MFI problems.