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Identification of wind loads on super-tall buildings by Kalman filter

Lunhai Zhi [a,b], Pan Yu [b], Qiu-Sheng Li [c,*], Bo Chen [d], Mingxin Fang [b]

[a] School of Civil and Hydraulic Engineering, Hefei University of Technology, Hefei 230009, China
[b] School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China
[c] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong
[d] Key Laboratory of Roadway Bridge and Structural Engineering, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

An inverse method based on the discrete time Kalman filter is developed to simultaneously estimate the unknown wind-induced responses and wind loads of high-rise buildings using limited response measurements. The accuracy and effectiveness of the presented estimation method are assessed based on both wind tunnel test results and field measurements of wind effects on a super-tall building. The wind-induced responses obtained by wind tunnel test are used to identify the wind loads on the super-tall building and evaluate the effects of crucial factors, such as covariance matrix of noise, initial estimation error, noise in measurements, modelling errors of structural dynamic properties and number of vibration modes, on the identification results. In addition, the wind loads are also estimated based on the field measured displacements during Typhoon Neoguri. Comparisons between the identified wind loads from the field measured displacements and the wind tunnel test results are made to verify the applicability of the inverse technique. The results of this study illustrate that the proposed inverse method is an efficient tool for predicting the wind loads on super-tall buildings from limited measurements of structural responses.

1. Introduction

In recent years, numerous super-tall buildings have been or are being built throughout the world. As modern high-rise buildings become higher and more flexible than those in the past, evaluation of wind loads is the key factor in their structural design. At present, wind tunnel testing is a relatively mature technique for estimating wind effects on buildings and structures. However, it is difficult to reproduce the exact field conditions such as incident turbulence and terrain characteristics as well as Reynolds number in wind tunnel tests. Field measurement is regarded as the most reliable way for evaluating the wind effects on prototype buildings and structures. Nevertheless, it is infeasible to directly measure the wind loads on a tall building by field measurements due to the facts such as high cost of force transducers or/required transducers might not even exist. Consequently, it would be beneficial if the wind forces could be determined indirectly using measured wind-induced responses of high-rise structures.

Force identification from measured dynamic responses of a structure is a typical inverse problem in structural dynamics. Usually, the inverse problem tends to be ill-posed, in the sense that a small amount of measurement noise in the measured responses may excite large excursion in the estimated input forces. For this reason, a suitable algorithm should be chosen to avoid ill-posed phenomena. There have been numerous studies on the ill-posed inverse problem. For instance, Bateman et al. [4] proposed two force identification methods, i.e., the sum of weighted acceleration and the deconvolution techniques to investigate impact problems. Law et al. [18] and Chan et al. [6] presented methods based on the system identification concept for moving force identification using a simply supported beam. Haung [11] utilized the conjugate gradient method (CGM) to identify the external forces for a single-degree-of-freedom system with displacement-dependent parameters. However, in most engineering applications, vibration systems can rarely be simplified as a single-degree-of-freedom system. Therefore, Huang [12] proposed an extended inverse identification technique to estimate the unknown external forces for a multiple-degree-of-freedom system with displacement-dependent parameters. Klinkov and Fritzen [16] used a nonlinear observer to identify the wind loads for a 5 MW wind energy plant. Zhang et al. [26] presented a Bayesian force identification approach based on the inversion of an uncertain model, and applied the method to identify the actual external forces acting on a laboratory beam structure.

Kalman filter is an effective tool for state estimation from noisy measurements [15,30]. Due to its relative simplicity and robust nature, the Kalman filter has been used for structural engineering

* Corresponding author.
E-mail address: bcqsli@cityu.edu.hk (Q.-S. Li).

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applications such as damage detection and system identification. To handle the inverse problem, Ma et al. [21] proposed an inverse method based on a combination of a Kalman filter and a recursive least squares algorithm to estimate the impulsive loads of lumped-mass systems. However, an important limitation of the estimator is the assumption that the state of all degrees of freedom of a structure are known, which might not be feasible in practice. Hwang et al. [13,14] presented a Kalman filtering based inverse approach for estimating wind loads. The technique allows identification of the wind forces based on limited measured responses. But, only modal loads (instead of real wind loads) acting on structures can be identified. Zhi et al. [27,28] extended the algorithm to simultaneously estimate the wind loads and entire wind-induced responses of tall buildings using only a limited set of measurements. Xu et al. [25] developed an inverse method based on an extended Kalman filter for the identification of pressure loading on structures. This method has been verified under quasi-static as well as dynamic impulse loading conditions using either strain or displacement measurements. Zhi et al. [29] proposed an inverse approach for identifying wind loads on supertall buildings based on the discrete time Kalman filter. But, the inverse algorithm is not applicable to the estimation of the wind loads using the acceleration response. Recently, several coupled estimators based on augment Kalman filter have been proposed [20,23]. These methods allow jointly estimating the input forces and states of a structure from structural response. However, the stability and accuracy of the identified results using the estimators based on acceleration measurements should be further verified and improved.

Review of the relevant works mentioned above shows that the research works on the identification of wind loads on structures are still limited. Especially, the indirect estimation for wind loads acting on complex structures such as super-tall buildings has rarely been reported in literature. Hence, it is required to conduct such a study, since the estimated wind loads using measured structural responses should be valuable for the wind-resistant design, structural health monitoring and control of super-tall buildings.

In this paper, a discrete time Kalman filtering based inverse method is developed for identification of the wind loads on super-tall buildings based on limited measurements of structural responses. The inverse technique is formulated in the state space to construct the unknown wind-induced responses and external wind loads. The proposed algorithm is applied to the estimation of wind loads on a super-tall building based on wind tunnel test results and field measurements. Through comparisons between the estimated and exact wind forces, the accuracy of the wind loading estimation technique is assessed. The paper has the following contents. The Kalman filtering based inverse algorithm is developed in Section 2. Then, the performance of the inverse procedure is examined using the wind tunnel test results of a super-tall building. In Section 4, the effectiveness and accuracy of the algorithm are further illustrated using field measured dynamic responses of the super-tall building. Finally, conclusions of this study are summarized in Section 5.

2. Identification of wind loads

2.1. Modal wind load identification using Kalman filter

A tall building with "n" floors is usually considered to be a "multiple"-degrees-of-freedom system. Therefore, the equations of motion for the structural system with external force $\boldsymbol{F}$ can be written in second order form as

$$\boldsymbol{M}\ddot{\boldsymbol{y}} + \boldsymbol{C}\dot{\boldsymbol{y}} + \boldsymbol{K}\boldsymbol{y} = \boldsymbol{F} \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are structural mass matrix, damping matrix and stiffness matrix, respectively. $\boldsymbol{y}$, $\dot{\boldsymbol{y}}$ and $\ddot{\boldsymbol{y}}$ are displacement vector, velocity vector and acceleration vector, respectively. $\boldsymbol{F}$ is wind excitation time history vector. Since the measurement of complete responses for all degrees of freedom is infeasible in practice and only displacement or acceleration responses are generally measured or available. The estimation of complete responses from limited measured responses is required. In this regard, the Kalman filter is employed to estimate the unknown responses in this study.

Assuming that the accelerations responses for all degrees of freedom are measured, the structural acceleration vector can be expressed by the following equation:

$$\ddot{\boldsymbol{y}}_{n\times 1} = \boldsymbol{\phi}_{n\times n}\ddot{\boldsymbol{U}}_{n\times 1} \tag{2}$$

where $\boldsymbol{\phi}_{n\times n}$ is the $n \times n$ mode shape matrix; n is the total node number of a structure. $\ddot{\boldsymbol{U}}_{n\times 1}$ is the modal acceleration response vector. Owing to the limitation of the number of sensors and identified mode shapes, a reduced-order representation of the measured acceleration responses is approximately given by

$$\ddot{\boldsymbol{y}}_{p\times 1} = \boldsymbol{\phi}_{p\times q}\ddot{\boldsymbol{U}}_{q\times 1}(1 \leqslant p \leqslant n, 1 \leqslant q \leqslant n) \tag{3}$$

where $\boldsymbol{\phi}_{p\times q}$ is the $p \times q$ mode shape matrix corresponding to the highest q vibration mode.

Using the pseudo-inverse of the modal transformation matrix $\boldsymbol{\phi}_{p\times q}$, the modal acceleration responses can be approximately calculated from the measured acceleration responses as follows

$$\hat{\ddot{\boldsymbol{U}}}_{q\times 1} = (\boldsymbol{\phi}_{p\times q})^{+}\ddot{\boldsymbol{y}}_{n\times 1} \tag{4}$$

in which $\hat{\ddot{\boldsymbol{U}}}_{q\times 1}$ is the estimated modal acceleration responses. The error between the exact and estimated modal acceleration responses can be minimized subjected to the condition that the number of sensors exceeds the number of modes governing the responses of the structure. In this study, the proper orthogonal decomposition (POD) technique is employed to determine the governing modes of a multi-degrees of freedom (MDOF) system [7,3]. The energy contribution θ of the first q vibration modes can be determined based on the POD method

$$\theta = \frac{\sum_{i=1}^{q}\lambda_i}{\sum_{i=1}^{n}\lambda_i} \quad (1 \leqslant q \leqslant n) \tag{5}$$

where λ_i is the ith eigenvalue of the covariance matrix of the acceleration response, which represent the energy contribution to structural responses. Generally, in order to obtain an accurate reduced-order representation of acceleration responses, the required energy contribution of the selected governing modes should exceed 99% of the total energy of the structural responses.

If the mode shapes are mass orthonormal, that is

$$M_i = \boldsymbol{\phi}_i^T\boldsymbol{M}\boldsymbol{\phi}_i = 1 \quad (i = 1, 2 \ldots, \mathrm{n}) \tag{6.1}$$

$$K_i = \boldsymbol{\phi}_i^T\boldsymbol{K}\boldsymbol{\phi}_i = \omega_i^2 \quad (i = 1, 2 \ldots, \mathrm{n}) \tag{6.2}$$

$$C_i = \boldsymbol{\phi}_i^T\boldsymbol{C}\boldsymbol{\phi}_i = 2\xi_i\omega_i \quad (i = 1, 2, \ldots n) \tag{6.3}$$

where $\boldsymbol{\phi}_i$ is the ith mode shape. M_i, C_i, and K_i are the modal mass, damping and stiffness of the ith mode, respectively. ω_i and ξ_i are the frequency and damping ratio of the ith mode, respectively.Then, Eq. (1) can be reduced to

$$\ddot{U}_i + 2\xi_i\omega_i\dot{U}_i + \omega_i^2 U_i = \boldsymbol{\phi}_i^T\boldsymbol{F} = f_i \tag{7}$$

where U_i and f_i are the modal displacement and modal wind load of the ith mode, respectively.

$$\text{Defining} \quad \boldsymbol{X}_i(\mathrm{t}) = [U_i \quad \dot{U}_i]^T \tag{8}$$