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Identification of fluctuating wind load distribution along the structure's height inversely by means of structural response

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ABSTRACT

This paper aims at identification of time-varying components of wind loads applied on a guyed mast. The corresponding inverse problem of load identification, when structural response is known, is solved by means of Tikhonov regularization method while L-curve assists in finding the regularization parameter. The proposed strategy of this research is to identify the wind load distribution of the Test-Analysis Model (TAM), corresponding to the guyed mast. There are two fundamental reasons underlying this proposal: Firstly the number of measurement points is usually much less than the number of degrees of freedom and secondly wind load has a continuous distribution acting on all elements of structure, as such identification of it's real distribution is not feasible in a large scale. The validity of the identified load is evaluated based on the comparison between the measured structural response and the displacements from the identified loads. Numerical simulations show that for low noise level in measurements the identified wind loads are in a good agreement with the actual loads and also the responses of unmeasured locations can be recovered with a good accuracy.

1. INTRODUCTION

In many cases in structural dynamic problems, a good knowledge on applied load is necessary either in the structure design phase or vibration control and health monitoring etc. The dynamic loads are generally caused by ambient excitation such as earthquake, wind-induced vibrations, crowd movement or machinery excitations etc. Wind-induced vibration is an example that there is not a limited number of excitation points because the wind force has a continuous distribution. Although the load identification problem has been dealt with extensively in the literature either in time or frequency domain, there are not many research results regarding wind load identification. For wind load identification from structural response, it is important to mention that in addition to the efforts associated with solving an inverse problem, there is also measurement data incompleteness since the response is almost always measured in only few points of the structure. Therefore it is necessary to find a way to

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cope with the data incompleteness problem. As an example (Law 2005) suggested an iterative scheme to recover the wind loads in which firstly they relate the wind force of other unmeasured point to the identified force of the measured degree of freedom. Then by adding the fluctuating term of the wind load from digital simulation of wind, they try to converge in successive steps to a wind load distribution, which generates the minimal response difference at the measurement point. There exist two fundamental critiques to this method: the first, it is a method not applicable to different types of excitation other than wind vibrations and the second, there is an enormous uncertainty in the iteration scheme because before the digital simulation of wind speed at iterative steps, the influential parameters of a field on wind velocities must be identified. Such parameters appear in the auto-spectral density function of wind speed. As a result, it is not very easy to identify a relatively accurate auto-spectral density function of a specific region since a vast statistical data analyses in different seasons must exist.

This paper suggests a strategy, which works independent of the knowledge on the excitation source. In order to circumvent the data incompleteness, the system parameters (mass and stiffness) associated with the detailed finite element (FE) model of the structure are reduced to the level of the structure's Test-Analysis model (TAM). Size of the TAM is equal to the number of measurement points. Finally the wind load is identified in time domain at the TAM level from the measured responses. This identified wind load must have two main features; it should have an acceptable accuracy with respect to the actual force transformed to the TAM level. Secondly the responses of unmeasured degrees of freedom, which are reproduced by the expansion of the responses of the TAM from identified load, should be very exact.

The results of numerical simulation show that the first feature is achievable in low noise level (say less than 5%) and consequently the responses of unmeasured degrees of freedom with a high accuracy can be obtained. For higher noise levels, the quality of the identified force is dominated by measurement noise, which is an inherent property of inverse problem solution obtained by regularization. Another reason for deviations from the actual transformed load is because; some features of the system parameters are lost within reduction to obtain the TAM system parameters.

2. THEORY

2.1. Forward problem setup

Consider the linear system of equations of motion for an n degrees of freedom system:

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = \mathbf{p}(t) \tag{1}$$

This system of equations is solved by means of an input-output relation in which the impulse response matrix multiplied by the input force renders the output signal i.e. structural response (displacements, velocity or acceleration). In this paper the augmented impulse response matrix, $\bar{\mathrm{H}}_{Aug}$, is used that automatically produces the structural response to the linearly interpolated force in m sub-steps (Kazemi Amiri 2014). The impulse response matrix (c.f. Eq. (2)) includes sub-matrices, which compute the response of a multi degree of freedom system to an impulse by means of modal analysis of a couple of modes. It is assumed that the structure FE model is already known and is validated by modal testing at least for some of its fundamental vibration modes. The response calculated by this impulse response matrix has a very good accuracy in comparison with the response of direct Newmark method when the force is interpolated.

$$\begin{bmatrix} \begin{Bmatrix} u_1 \\ \vdots \\ u_n \end{Bmatrix}_0 \\ \vdots \\ \begin{Bmatrix} u_1 \\ \vdots \\ u_n \end{Bmatrix}_k \end{bmatrix} = \frac{dt}{2m^2} \underbrace{\begin{bmatrix} 0 & & \cdots & & 0 \\ \bar{\mathrm{H}}_{1,1} & \bar{\mathrm{H}}_{1,2} & & & \\ \bar{\mathrm{H}}_{2,1} & \bar{\mathrm{H}}_{2,2} & \bar{\mathrm{H}}_{1,2} & & \\ & & & & \\ \bar{\mathrm{H}}_{k-1,1} & \bar{\mathrm{H}}_{k-1,2} & \cdots & \bar{\mathrm{H}}_{2,2} & \bar{\mathrm{H}}_{1,2} \end{bmatrix}}_{\bar{\mathrm{H}}_{Aug}} \begin{bmatrix} \begin{Bmatrix} p_1 \\ \vdots \\ p_n \end{Bmatrix}_0 \\ \vdots \\ \begin{Bmatrix} p_1 \\ \vdots \\ p_n \end{Bmatrix}_k \end{bmatrix} \tag{2}$$

2.2. Model order reduction and TAM setup

Two order-reduced models are consecutively created from the main FE model of the structure. The first one is an intermediate model, which determines the number of nodes for assigning the concentrated wind forces and is used for saving the time in the simulation procedure. It includes horizontal translational degree of freedom corresponding to one node at each panel of the mast.

The TAM for load identification is afterwards generated from the reduced model, which includes the measured degrees of freedom. The model order-reduction was performed by means of Improved Response System (IRS) (O'Callahan 1989) transformation matrix.

$$\mathrm{T}_{IRS} = \begin{bmatrix} \mathrm{I} \\ \mathrm{R}_{IRS} \end{bmatrix} \tag{3}$$

It should be noted that the identity sub-matrix in IRS transformation matrix retains the measured responses from the FE model to the TAM level. Moreover it also keeps the wind load pattern at the intermediate reduced-order model unchanged, since no loads exist on other degrees of freedom except the degrees of freedom of the intermediate reduced-order model.

The FE model assumed to have the Rayleigh damping and this damping was also transformed for intermediate model and its associated TAM.

2.3. Wind load and noisy measured response

The wind loads are generated from the product of the mean wind speed and the simulated fluctuating wind speed at different height of structure.

The mean wind speeds were computed by power law (Holmes 2007) with respect to the wind speed at a reference point on the structure.

In order to simulate the fluctuating wind speeds at different heights of the mast, the wind speeds were digitally simulated. The time steps for fast Fourier transform was 0.2 second.

The corresponding simulated wind loads are then applied on the intermediate model and the actual displacements are computed using the direct Newmark method while the loads are linearly interpolated to have a smaller time step for improved convergence.

2.3.1. Fluctuating Wind speed simulation

The simulated wind speed is generated based on the Kaimal's (Kaimal 1972) auto-spectrum. The wind speeds at different heights are considered as the multi-variate one-dimensional stationary processes. The wind field is assumed to be a random field (Bucher 2009) whose covariance matrix is equivalent to the wind speed PSD matrix in frequency domain. Therefore the wind field can be decomposed by spectral decomposition in frequency domain. Finally the superimposed wind speeds are transformed to time domain by means of fast Fourier transform. This way of wind speed simulation is comparable to digital simulation of wind speed proposed by (Di Paola 1998).

2.3.2. Noisy measured response generation

In order to generate the polluted measured data of displacement, u_{poll}, white noise is added to the actual displacement responses. The magnitude of this additive noise is chosen to be proportional to the standard deviation of the response's time history of a single degree of freedom.

2.4. Solving the Inverse problem

Since the impulse response matrix is usually ill-conditioned and due to the presence of noise in the measurements, a regularization method is required to identify the loads. In this study Tikhonov (Tikhonov 1997) regularized solution for the corresponding inverse problem was adopted:

$$\min\left\{\left\|u_{poll} - \overline{\mathrm{H}}_{Aug}\mathbf{p}\right\|_2^2 + \lambda\left\|\mathbf{p}\right\|_2^2\right\} \tag{4}$$

However the regularization parameter, λ, that controls the size of identified load is unknown, hence the regularization parameter is found by means of L-curve method (Hansen, 1993).

3. NUMERICAL RESULTS

3.1. The guyed mast specifications

The case study of this paper is an instrumented guyed mast with the height of 30 Ft (≈10 m) having 17 panels, which is serving as a weather station. The FE model of mast was made in slangTNG (Bucher 2007-2013) and its picture is given in Fig. 1.

The FE model has totally 420 degrees of freedom. Its main vertical elements as well as the cross support elements were modeled as beam elements while the guys were considered as the truss elements. Modal analysis of the structure shows that the first and second modes are coupled bending-torsional modes (due to the unsymmetrical stiffening elements) and the third one is a purely torsional mode. This mode configuration repeats for other higher modes, respectively.

3.2. The intermediate model and TAM specifications

The wind load pattern is made up of the concentrated forces acting on one node (master node) of each panel with 30 degrees deviation from central axis of the mast to excite the torsional modes too. Other unloaded degrees of freedom are eliminated and therefore the intermediate reduced model has 36 degrees of freedom.

Three measurement locations on the structures at the heights of 2.3, 4.6 and 9.3 m have been chosen. At each measurement location two horizontal displacements in perpendicular directions are measured. As a result the TAM will have 6 degrees of freedom. In Table 1 the natural frequencies of the FE and intermediate model as well as the TAM is provided.

Table 1. The first six natural frequencies (Hz) of the models

FE Model	Intermediate model	TAM
5.4	5.4	5.4
5.6	5.6	5.6
13	13	14.6
19.7	19.7	19.9
19.9	19.9	39.9
30.2	30.2	42

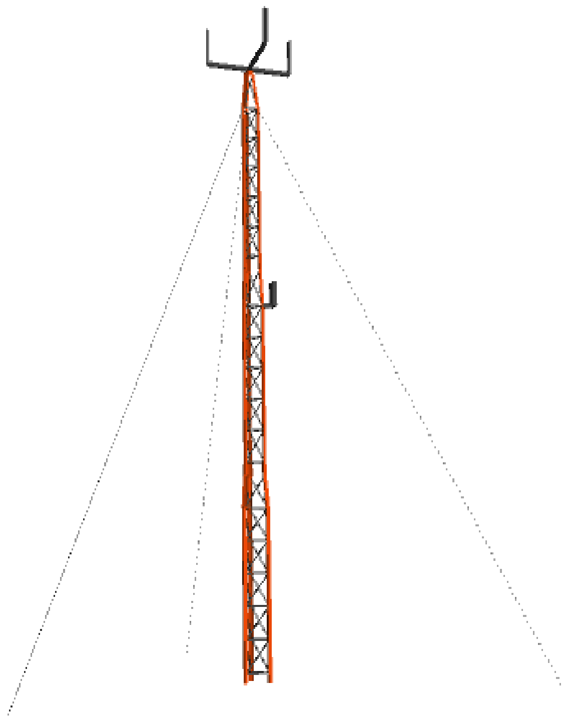

Fig. 1. Picture of FE model of the mast

3.3. Identified loads and the associated displacements

In order to compare the accuracy of identified wind loads, the actual forces are transformed to the TAM level, that is, $\mathbf{F}_{tr/act} = \mathbf{T}_{IRS}^{T}\mathbf{F}_{act}$. The best and the worst identified TAM wind loads at 1% and 5% noise level together with their corresponding actual transformed forces i.e. $\mathbf{F}_{tr/act}$ are plotted in Fig. 2.

The back calculated displacements of TAM from the identified wind loads are expanded to the intermediate model level. Table 2 provides the second norm vector error of the expanded retrieved displacements. It is also possible to obtain all degrees of freedom responses for FE model with a good quality from the displacement response of intermediate model, since this transformation acts very exactly up to the first eight natural vibration modes.

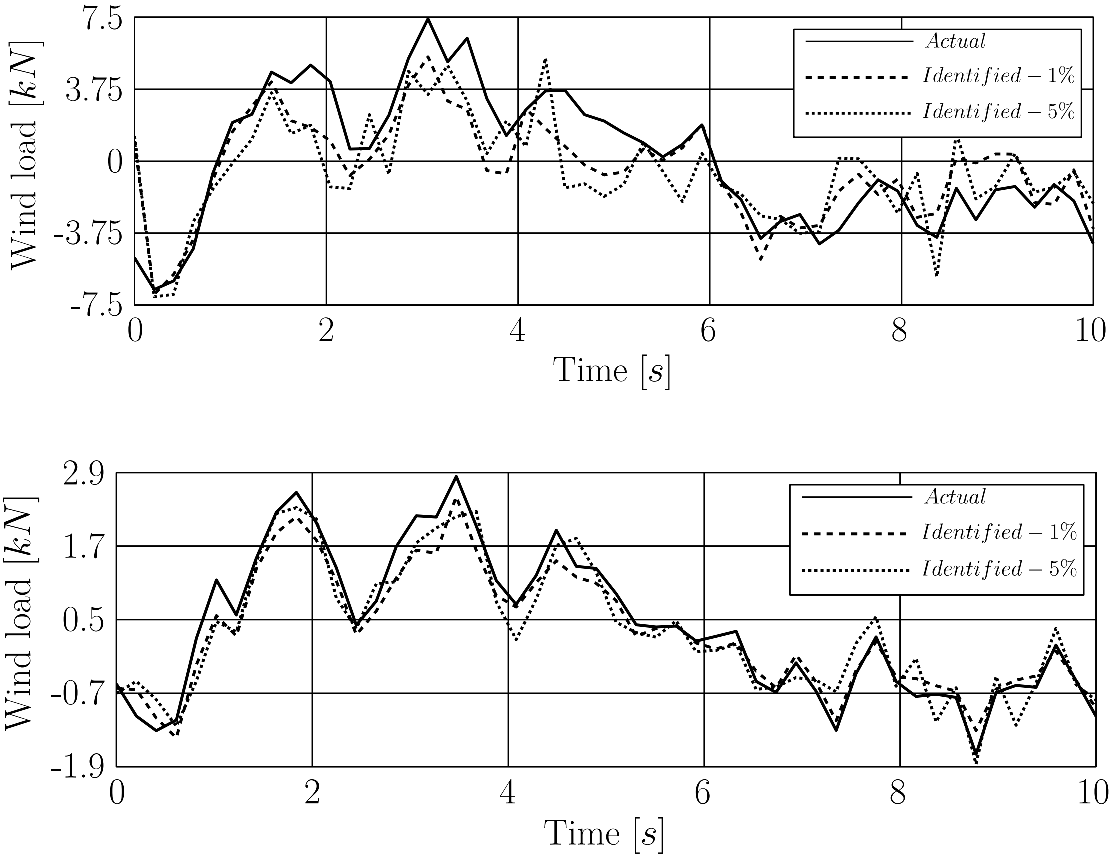

Figure 2. Comparison of identified wind loads at 4th (up) and 5th (down) degree of freedom of the TAM

Table 2. Error of displacements from identified wind loads for 36 degrees of freedom of the intermediate model

Noise level	1%	5%
Error (%)	4.4	1.9

4. CONCLUSION

This study proposes a strategy to identify the distribution of the wind loads inversely from the measured responses of few locations along an instrumented guyed mast. The identified wind load is an equivalent load pattern at the TAM level, corresponding to the measurement locations on the main structure. The load is identified from the Tikhonov regularization solution while the regularization parameter was found by means of L-curve method. This strategy uses the common methods of field measurement and works independent of the loading nature.

The idea of identifying the equivalent load is applied to circumvent the incompleteness of displacements data since just a limited number of degrees of freedom can be measured. On the other hand the order reduction method can influence the quality of the identified wind load. As given in Table. 1, the natural frequencies of 5th and sixth modes of the TAM are not well retained. Therefore these differences in natural frequencies and mode shapes could cause deviations in the identified loads.

However it is possible to apply more powerful methods to generate better TAM parameters. In this regard caution should be made so that the transformation matrix does not substantially change the rank features of the TAM parameters. Otherwise the regularization will be dramatically affected later.

Another source of error in identified load is the noise level in the measurement data. It can be observed from Fig. 2 that up to 5% noise level the identified wind loads still have acceptable accuracy. For higher than these noise levels a preprocessing of measurements data might be useful.

Finally it should be pointed out that identification of wind load acting on a structure under service could be very useful. Firstly due to the serious restrictions in direct wind load measurement in large scales and secondly the dynamics of wind loading can be used for different purposes in structural dynamics.

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