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# Derivation of a new parametric impulse response matrix utilized for nodal wind load identification by response measurement

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A B S T R A C T

This paper provides new formulations to derive the impulse response matrix, which is then used in the problem of load identification with application to wind induced vibration. The applied loads are inversely identified based on the measured structural responses by solving the associated discrete ill-posed problem. To this end — based on an existing parametric structural model — the impulse response functions of acceleration, velocity and displacement have been computed. Time discretization of convolution integral has been implemented according to an existing and a newly proposed procedure, which differ in the numerical integration methods. The former was evaluated based on a constant rectangular approximation of the sampled data and impulse response function in a number of steps corresponding to the sampling rate, while the latter interpolates the sampled data in an arbitrary number of sub-steps and then integrates over the sub-steps and steps. The identification procedure was implemented for a simulation example as well as an experimental laboratory case. The ill-conditioning of the impulse response matrix made it necessary to use Tikhonov regularization to recover the applied force from noise polluted measured response. The optimal regularization parameter has been obtained by L-curve and GCV method. The results of simulation represent good agreement between identified and measured force. In the experiments the identification results based on the measured displacement as well as acceleration are provided. Further it is shown that the accuracy of experimentally identified load depends on the sensitivity of measurement instruments over the different frequency ranges.



## 1. Introduction

The load identification in engineering problems becomes more important if the excitations are caused by the actions which cannot be measured directly. A good knowledge on applied loads is necessary for extraction of their characteristics or their reproduction via simulation for other purposes. The idea of direct measurement of the applied loads generally becomes more infeasible if the structure as well as the load action become more complex. For example, wind loading is one of the dominant design parameters for structures having low natural frequencies such as tall buildings or long bridges.

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The presence of the fluctuating wind components due to turbulence makes the wind force measurement even tougher, because more sensitive force or pressure measurement devices in huge numbers are necessary, which might not be practically realistic.

On the other hand measurement of the response to the excitation is more common and better developed due to its extensive use in the other application areas such as system identification. Consequently an indirect procedure that gives the ability to identify the load from measured response — a so-called inverse problem — seems to be attractive. Load identification can be done in time or frequency domain, the best choice depends on the type of loading or the identification purposes. The authors' interest is to apply the solution of this inverse problem, i.e. the inverse wind load identification, in wind fatigue analysis of a full-scale guyed-mast. Therefore it is required to prepare and evaluate a load identification procedure in the time domain, which is consistent with the methodology in the subsequent application.

For the sake of load identification we initially need to set up a complete input–output relation for the direct problem (based on already known, e.g. previously identified parameters of the structure) for two reasons. Firstly having an updated finite element model for fatigue analysis is needed. Secondly utilization of an experimental input–output model such as quasi-impulse response matrix [1] due to its limitations is not appropriate.

Once the input–output model is generated the load identification can formally be treated in the discrete manner as a linear system of equations that is, $\mathbf{u}=\overline{\mathbf{H}}\mathbf{p}$. Unfortunately, it is an ill-posed problem since the impulse response matrix $\overline{\mathbf{H}}$ is usually ill-conditioned and the deconvolution by means of pseudo-inverse multiplication may lead to unbounded solutions in the presence of noise in measured data $\mathbf{u}$. Consequently we need to call upon alternative methods which are designed to solve discrete ill-posed problems. From a general aspect these methods are classified into direct or iterative procedures. However, neither regularization by means of projection of the problem nor the iterative regularization plus projection (c.f. [2]) falls within the scope of this paper. Thus the solution of a discrete ill-posed problem just based on a direct scheme is dealt with. In this scheme, there are several different ways such as Tikhonov regularization [3] and family of truncated singular value decomposition (TSVD) methods [4,5]. These methods aim at filtering out the contribution of noise in the response or improving the conditioning of $\overline{\mathbf{H}}$.

It must be noted that the regularization methods need a regularization parameter as a stop criterion to tune the amplitude of smoothening of the response. The parameter selection methods are categorized into two general classes. The first class includes the methods working based on a priori knowledge about the measurement noise and the second class, which is applicable independently. The methods of generalized cross validation (GCV) [6] and L-curve [7,8] are two examples of the second class. Also it has been recommended to evaluate which parameter selection method is more efficient according to the nature of the certain problem.

In this paper the regularization method of Tikhonov for the regularization together with two procedures of GCV and L-curve for finding the regularization parameter were selected. We provide the results of load identification via simulation and laboratory experiments for a rigidly clamped cantilever beam. The applied loads are realized by white noise limited to 25 Hz and wind excitation, which are identified separately from measured displacement and acceleration response by means of the derived ordinary and augmented impulse response matrices.

## 2. Dynamic response analysis of discrete-time systems

In this section an input–output relation in a discretized time domain is constructed. In other words we are going to build the impulse response matrix, which when multiplied by the input signal (i.e. force record) renders the output as time history of displacement. In this paper this aim was reached by means of modal analysis since it is closely consistent with modal testing methods of system identification in practical cases. It is mentioned here that the input–output relation might also be alternatively derived via testing, mathematical system identification [9] or simulation of application of impulsive loads on degrees of freedom when the finite element model of the structure exists.

### 2.1. Impulse response matrix

The linear equations of motion for an MDOF system with classical damping are given in the following system of differential equations:

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

while $\mathbf{u}$, $\mathbf{m}$, $\mathbf{c}$, $\mathbf{k}$ denote, the displacement, mass, damping and stiffness of the system respectively, as well as the dynamic force $\mathbf{p}$, which applies on the system's degrees of freedom.

Projecting Eq. (1) onto modal coordinates by means of substitution $\mathbf{u}(t)=\mathbf{\Phi}\mathbf{q}(t)$ together with premultiplying each term in the equation by $\mathbf{\Phi}^T$ renders the set of uncoupled modal equations of motion [10]:

$$\ddot{\mathbf{q}}+2\mathrm{diag}[\zeta_i\omega_i]\dot{\mathbf{q}}+\mathrm{diag}[\omega_i]\mathbf{q}=\mathbf{P}(t) \tag{2}$$