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System identification method by using inverse solution of equations of motion in time domain and noisy condition

Peiman Davari Dolatabadi [a], Karen Khanlari [b,*], Mohsen Ghafory Ashtiany [c], Mahmood Hosseini [c]

[a] Department of Structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Department of Structural Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[c] International Institute of Earthquake Engineering and Seismology, Tehran, Iran

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ABSTRACT

In direct system identification (DSI) method, inverse solution of the equations of motion is applied to obtain physical parameters of a linear system (structural mass, damping, and stiffness matrices). With the small error in measurement, caused by sensor drift or signal noise, these physical parameters are identified with a significant drift. In this paper, a new simple post-processing method is proposed, for error reduction in DSI in the time domain in a manner that structural properties are identified without applying the optimization process. In noisy condition, baseline correction is applied through a nonic curve-fitting approach. The modified signals are partitioned into a number of sub-signals, and their mean is applied for system identification. The number of sub-signals is optimized so that the root mean square (RMS) of off-diagonal components of the mass matrix becomes near zero. Seeking more precision, the residual force in every time step at all degrees of freedom (DOFs) is minimized. The validity of the proposed method is tested on a multistory structure, subjected to a random force at the foundation level. In terms of incomplete measurement and 5% noise, identified parameters including mass, stiffness and damping matrices, have satisfying mean errors of 0.094%, 0.545%, and 4.42% with the coefficient of variations of 0.35%, 1.38% and 6.98%, respectively. The sensitivity of the proposed method to the noise level is also investigated. It is observed that the baseline slop of velocity and displacement signals are sharply increased when the noise level goes beyond 3%.

1. Introduction

System identification methods are divided into three categories: identification of static system [1,2], system identification in the frequency domain [3–8] and system identification in the time domain [9,10]. Accurate data of static sites of real structures are usually not easily measured, so system identification methods in the time domain and frequency domain have more applications in practical cases. In the time domain methods, the sensors data is directly used for system identification. In the frequency domain methods sensors data are converted to data in the frequency domain using Fourier transform. Since the response of the structure is usually within a certain frequency range, in order to identify the system in the frequency domain, the higher noise level data can be separated from more useful data. This means that

* Corresponding author.
E-mail address: khanlari.kaaren@gmail.com (K. Khanlari).

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frequency-domain methods are less sensitive to the noise signals. For this reason, in system identification processes, frequency domain methods have been developed over time domain methods. However, the time domain methods are more efficient in detecting the damping characteristics of the structure and are less sensitive to the modeling errors [10]. The direct use of sensors data in estimating the system parameters is an advantage of the time domain methods. However, increasing the degrees of freedom improves its efficiency, so that in large frames, large errors are seen even at low level of measurement noise for instance the mean error of the identified stiffness matrix in an eight-story structure with 1% of noise in responses and input forces using random loading has increased up to about 12% [11]. Another challenge is the need to stimulate all degrees of freedom. If not all degrees of freedom are stimulated, the corresponding row without stimulation will be obtained by zero. In this case, the application of the matrix symmetry conditions is necessary that increases the error of estimation, for instance, by applying random load on the third floor of a three-story building and considering the matrix symmetry conditions, the mean error of determined stiffness matrix reaches 14% when the noise ratio is just 1% [11]. Among the above challenges, noise is the more important one. If the structural responses are without noise, the parameters of *Ndof* (*N* degrees of freedom) system are determined accurately through measuring responses in $3N$ time steps, however, in the case that the structural responses are polluted with noise, signal processing and optimization algorithm are required. In some studies, an error vector is defined based on the error between the input force and measured responses. This approach tries to minimize the error vector. The results showed that the scaling of data could have a great impact on the accuracy of the method. In many time-domain methods, least-square-estimation (LSE) is a fundamental math work for the inverse solution of equations of motion. In noisy condition that accurate data is not available, LSE cannot deliver the proper results. The precision of the detected physical parameters depends on the amount of noise to signal ratio [12]. In frequency domain, noise is easier to be encountered and there are many methods like data filtering [13–15], autoregressive moving average noise [14,16,17], recursive methods [18], equivalent models [19] and optimization approaches [20–22], to improve the accuracy of the identified parameters. Some of the prementioned methods are applicable in the time domain, but the results are not as effective as the frequency domain, for instance, the optimization approach indirect system identification (DSI) has not acceptable result in time domain while its performance in the frequency domain is acceptable [11]. This indicates that despite the existing methods, noise is still a major challenge in the time domain system identification methods. Structural system identification needs complete pure measurements; it means that signals of displacement, velocity and acceleration should be measured in a noise free condition. As such, a huge data acquisition is not possible, and acceleration is the only economic and available signal to be measured, system identification is adopted by applying incomplete measurements. Obtaining velocities and displacements from noisy acceleration records is accompanied by successive integrations that cause large drift and singularity. In this context, baseline correction methods (BCMs) are typical approaches for correcting signals. The adjustment may take the form of the polynomial [23,24] or multiple linear segments [25], hybrid method of polynomials and low frequencies filtration [26,27] or the target-base correction algorithm [28]. The modified signals obtained from the above methods do not have the required accuracy for the reverse methods and computational methods [29–46] and system identification in time domain.

In this paper, a simple signal processing method is proposed in which measured acceleration signals in noisy condition are processed and employed effectively indirect system identification of large structures in time domain through very limited base stimulation. The effectiveness of the proposed method is studied, and its superiority is demonstrated. Since the residual force is the cause of subsequent errors, structural responses are modified in a manner that residual forces are minimized. As velocity and displacement are obtained by the integration method, due to the noise effects, achieved signals have gross errors. For error reduction, nonic-curve fitting baseline correction approach is adopted. To make these corrected signals suitable for reverse methods, signals are divided into specific numbers of sub-signals. Average of these sub-signals makes some new corrected signals that are suitable for applying in system identification. The optimum number of time steps in any subdivision is obtained by minimizing the off-diagonal mass matrix components. The validity and efficiency of the proposed method are tested on a multistory-non-proportional-damping-structure subjected to a random white noise forces at the foundation level. It is shown that the proposed method can estimate the system parameters with a high level of accuracy. The advantages of this proposed method are its simplicity, the direct use of sensors data, limited DOFs need to be stimulated and effectively applied for system identification when the noisy and incomplete measurements are available.

2. Proposed approach

Assume mass, M, damping, C, and stiffness, K, matrices as the system properties. By defining response and property matrices as $R_{m\times 3n} = \begin{bmatrix}\ddot{X}^T_{m\times n} & \dot{X}^T_{m\times n} & X^T_{m\times n}\end{bmatrix}$ and $P_{3n\times n} = \begin{bmatrix}M_{n\times n} & C_{n\times n} & K_{n\times n}\end{bmatrix}^T$ respectively, the equations of motion for a viscously damped linear system with, n, number of degrees-of-freedom and, m, time steps are:

$$R_{m\times 3n}P_{3n\times n} = F^T_{m\times n} \tag{1}$$

$F^T_{m\times n}$ is the transpose of input matrix in m time steps and n degrees of freedom. The residual force is the error caused by the presence of the noise that is obtained by $\varepsilon_{m\times \boldsymbol{n}}$ Eq. (2) [22].

$$\varepsilon_{m\times \boldsymbol{n}} = R_{m\times 3n}P_{3n\times n} - F^T_{m\times n} \tag{2}$$