Engineering Structures 100 (2015) 189–200

Contents lists available at ScienceDirect

Engineering Structures

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

Nonlinear structural model updating based on instantaneous frequencies and amplitudes of the decomposed dynamic responses

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ARTICLE INFO

Article history:
Received 23 November 2014
Revised 31 May 2015
Accepted 1 June 2015
Available online 20 June 2015

Keywords:
Analytical mode decomposition
Hilbert transform
Instantaneous frequency
Instantaneous amplitude
Nonlinear structure
Nonlinear model updating

ABSTRACT

This paper proposes a new nonlinear structural model updating method based on the instantaneous frequencies and amplitudes of the decomposed dynamic responses under forced vibration. The instantaneous frequencies and amplitudes of the decomposed mono-component are first extracted by analytical mode decomposition (AMD) and Hilbert transform. Then, an objective function based on the residuals of instantaneous frequencies and amplitudes between experimental structure and nonlinear model is created for calibration of the nonlinear model. In this paper, the structural nonlinear properties are simulated by using hysteresis material parameters of Bouc–Wen model, and the optimal values of the hysteresis parameters are obtained by minimizing the objective function using the simulated annealing global optimization method. To validate the effectiveness of the proposed method, a three-story nonlinear shear type structure under earthquake and harmonic excitations is simulated as a numerical example. Then, the proposed method is verified by the shake table test of a real high voltage switch structure under forced vibration. The updated nonlinear structural model is further evaluated by the shake table test of the switch structure subjected to a new severe excitation. Both numerical and experimental results have shown that the proposed method can effectively update the nonlinear model and the updated model can be further used to predict the nonlinear responses due to new severe excitations.

1. Introduction

Structural models such as finite element model have been extensively used for analyzing and researching purposes in civil, aerospace and mechanical engineering fields. An accurate alternative structural model can greatly reduce cost in engineering application. However, these structural models are normally constructed based on idealized engineering designs, and they may not accurately represent all the aspects of actual structures. As a result, the structural model predictions usually differ from the results of the real structures. The residuals between the structural model and the corresponding real structure can be optimized by updating or calibrating parameters of the model.

To obtain a better predicted result, the finite element model updating procedure has been developed for modifying the model parameters based on experimental data [1]. For instance, the non-iterative method [2–4] is directly used to update the elements of mass and stiffness matrices by using the one step procedure. However, this method does not generally maintain structural connectivity and the updated matrices are not always physically meaningful. The other method for finite element model updating is the iterative parameters updating method [5–9]. For this kind of method, an objective function based on the residuals between experimental data and model predictions is designed, and the model parameters are then updated by minimizing the objective function. More recently, Guo and Zhang [10] found that, response surface method can obtain the same accurate results by comparing with the sensitivity-based finite element model updating method. Ren et al. [11,12] further validated the response surface method and concluded that the response surface method is faster and feasible when a real structure is complex and the number of model parameters is large.

However, complex nonlinear behavior of structures has been observed not only when they are subjected to extreme loads (such as, earthquake and typhoon), but also during the operational conditions. Characterization of the nonlinearity may provide critical diagnostic and prognostic information. At present, the structures can be analyzed by use of tools with assumptions of linear and stationary structural behavior. Determination of the dynamic characteristics for a structure exhibiting nonlinear behavior by assuming linearity and stationarity may lead to misleading results. Thus, it is critical to know if a structure is behaving nonlinearly and to detect and estimate the impact of the nonlinearity both qualitatively and

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http://dx.doi.org/10.1016/j.engstruct.2015.06.002
0141-0296/

quantitatively. Only then can it become possible to assess the need for nonlinear analysis depending on the type of analysis and application.

In order to calibrate the nonlinear model, some researchers suggested to identifying the parameters of nonlinear structures, whose nonlinearity is simulated by defining hysteresis models. Therefore, the problem of identifying a time-varying nonlinear system is considered as the identification of constant parameters of a nonlinear hysteretic model. In the previous studies, the parameters of hysteretic models have been identified based on dynamic response data by using different time-domain methods, mainly including least square estimation [13–15] and Kalman filter methods [16–22].

The other methods to calibrate nonlinear system are to update the nonlinear model based on the nonlinear properties of the responses. For instance, Hemez and Doebling et al. [23] presented the correlation of non-linear models with test data based on the test responses. Their purpose is to provide experimental data for validating the strategies implemented for test-analysis correlation and inverse problem solving of nonlinear structures. However, the proposed test-analysis correlation and inversed problem solving for nonlinear structures must address the following issues: (1) How to characterize the variability of an experiment? (2) How to generate additional or surrogate data sets that can increase the knowledge about the experiment? (3) How to select features that best characterize a nonlinear data set? Song et al. [24] further introduced a nonlinear FE model updating method for RC structure under low amplitude ambient vibration. Silva et al. [25] compared the nonlinear finite element model updating methods in frequency domain, such as, harmonic balance method, restoring force surface method, and proper orthogonal decomposition method. Richard et al. [26] combined the structural reliability theory and Bayesian networks for robust updating of nonlinear structural models.

More recently, with the development of time–frequency analysis method, the nonlinear model updating based on time–frequency features is starting to attract attention. For many nonlinear structures, the nonlinearity can be simulated by defining hysteresis model such as Bouc–Wen model [27,28]. Asgarieh et al. [29] proposed nonlinear model updating for structures with hysteresis model based on time-varying modal parameters. The time-varying parameters are extracted using deterministic-stochastic subspace identification method [30]. Their method mainly relied on the identified instantaneous frequency and modes. However, the identified modes for nonlinear structures are still ambiguous.

In this paper, a new nonlinear model updating method based on instantaneous characteristics of the nonlinear structures with hysteresis model is proposed. Since the nonlinear characteristics of a nonlinear structure are implied in both amplitude and frequency of the responses during the oscillation, the structural instantaneous characteristics including instantaneous frequencies and instantaneous amplitudes are used as objective functions for nonlinear model updating in the paper. The instantaneous frequencies and amplitudes are first extracted by using AMD and Hilbert transform [31,32]. The extracted instantaneous amplitude and frequency of the decomposed mono-component can keep the complete information of the nonlinear features and can be used to update the nonlinear model. Thus, an objective function is defined using the residuals of the instantaneous frequency and amplitude of the decomposed mono-component between experimental structure and nonlinear model. The optimal values of the nonlinear parameters are obtained by minimizing the objective function using the annealing global optimization method [33,34]. To validate effectiveness of the proposed method, a three-story nonlinear shear type structure under earthquake and harmonic excitations is simulated as a numerical example. The proposed method is also verified by the shake table test of a real high voltage switch structure subjected to various excitations.

2. Theoretical background

2.1. Instantaneous frequency and amplitude extraction

The frequencies of the responses of a nonlinear structure often change with time. For the signal with time-varying frequencies, Wang and Chen [32] extended the AMD to the time-varying vibration signal. Instead of selecting constant cutoff frequencies [31,35], the time-varying cutoff frequencies are selected, and each frequency modulated individual components between any two time-varying cutoff frequencies can then be analytically extracted. The theorem with time-varying cutoff frequency is described as follows.

Let $x(t)$ denotes a real time series of n significant individual components with frequencies: $\omega_1(t), \omega_2(t), \ldots, \omega_n(t)$, all positive, in $L^2(-\infty, +\infty)$ of the real time variable t. It can be decomposed into n signals $x_p^{(d)}(t)$ $(p = 1, 2, \ldots, n)$ whose frequency ranges satisfy: $|\omega_1(t)| < \omega_{c1}(t)$, $\omega_{c1}(t) < |\omega_2(t)| < \omega_{c2}(t), \ldots, \omega_{c(n-2)}(t) < |\omega_{n-1}(t)| < \omega_{c(n-1)}(t)$, and $\omega_{c(n-1)}(t) < |\omega_n(t)|$. That is,

$$x(t) = \sum_{p=1}^{n} x_p^{(d)}(t) \tag{1}$$

in which $\omega_p(t)$ represents a frequency variable for decomposed signal $x_p^{(d)}(t)$, and $\omega_{cp}(t) \in (\omega_p(t), \omega_{p+1}(t))(p = 1, 2, \ldots, n-1)$ are $n-1$ time-varying cutoff frequencies. Each individual signal can be determined by

$$\begin{aligned} x_1^{(d)} &= s_1(t), \ldots, x_p^{(d)}(t) = s_p(t) - s_{p-1}(t), \ldots, x_n^{(d)}(t) \\ &= x(t) - s_{n-1}(t) \end{aligned} \tag{2}$$

$$\begin{aligned} s_p(t) = {} & \sin\left[\int_{-\infty}^{t} \omega_{cp}(\tau)\mathrm{d}\tau\right] H\left\{x(t)\cos\left[\int_{-\infty}^{t} \omega_{cp}(\tau)\mathrm{d}\tau\right]\right\} \\ & - \cos\left[\int_{-\infty}^{t} \omega_{cp}(\tau)\mathrm{d}\tau\right] H\left\{x(t)\sin\left[\int_{-\infty}^{t} \omega_{cp}(\tau)\mathrm{d}\tau\right]\right\} \\ & (p = 1, 2, \ldots, n-1) \end{aligned} \tag{3}$$

Eq. (3) operates like a low-pass filter that passes any low frequency signal $s(t)$ but reduces the fast signal $\bar{s}(t)$ in time domain. The block diagram of such a low-pass filter with time-varying cutoff frequency is shown in Fig. 1.

For an n DOF nonlinear system, the equation of motion can be written as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{F_c}[\dot{\mathbf{x}}(t)] + \mathbf{F_s}[\mathbf{x}(t)] = \mathbf{f}(t) \tag{4}$$

in which $\mathbf{M}$ is mass matrix, $\mathbf{F_c}[\dot{\mathbf{x}}(t)]$ is damping force vector, $\mathbf{F_s}[\mathbf{x}(t)]$ is stiffness force vector, and $\mathbf{f}(t)$ is excitation vector.

For a nonlinear structure, the nonlinear restoring force as function of time can be transformed into a multiplication form $\mathbf{K}(t)\mathbf{x}(t)$ with a new time-varying stiffness matrix $\mathbf{K}(t)$ and a system solution $\mathbf{x}(t)$ with an overlapping spectrum [36,37]. Similarly, the nonlinear damping force can also be transformed into a function of time as a multiplication $\mathbf{C}(t)\dot{\mathbf{x}}(t)$ between the time-varying

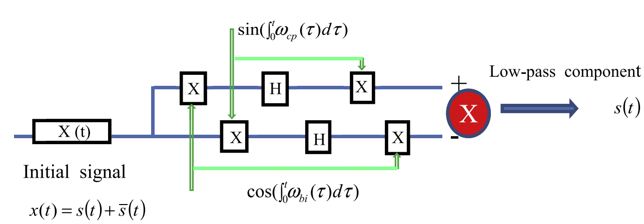

Fig. 1. Block diagram of the low-pass filter with time-varying cutoff frequency.