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New methodology for modal parameters identification of smart civil structures using ambient vibrations and synchrosqueezed wavelet transform

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ABSTRACT

Many applications related to modeling, control and condition assessment of smart structures require an accurate identification of natural frequencies and damping ratios. This identification is generally carried out through artificial and natural vibration sources. The latter is often preferred in many situations; yet their analysis represents a challenge since the measured data are non-stationary with a high noise level. In this paper, a new methodology is proposed based on the synchrosqueezed wavelet transform (SWT). First, the random decrement technique (RDT) is applied to estimate the free vibration response from measured ambient vibration signals. Then, the SWT algorithm is used to decompose the vibration response into individual mode components. Finally, the Hilbert transform (HT) and the Kalman filter (KF) are used to estimate the natural frequencies and damping ratios of each mode and to filter and smoothen the results. The effectiveness of the proposed approach is first validated through numerical simulation of damped free vibration response of a 3-degree of freedom (DOF) system with two closely-spaced frequencies. Then, numerical and experimental data of a benchmark 4-story 2×2 bay 3D steel frame structure subjected to ambient vibrations is analyzed. Finally, the natural frequencies and damping ratios of a real-life bridge located in Queretaro, Mexico are obtained. For comparison purposes, two recent and advanced signal processing techniques, the complete ensemble empirical mode decomposition (CEEMD) technique and the short-time multiple signal classification (ST-MUSIC) are also tested. Numerical and experimental results show accurate identification of the natural frequencies and damping ratios even when the signal is embedded in high-level noise demonstrating that the proposed methodology provides a powerful approach to estimate the modal parameters of a civil structure using ambient vibration excitations.

1. Introduction

Modal parameters identification (MPI) from acquired dynamic signals is a process to determine dynamic characteristics of a structure, which can be used to build or update a proper model of the structure (García-Palencia and Santini-Bell, 2013; Lozano-Galant et al., 2013; Yuen and Mu, 2015; Zhang et al., 2015; Oh et al., 2015; Boscato et al., 2015) for vibration control (Kang et al., 2012), condition assessment, health monitoring of the structure (Jiang and Adeli, 2007; Osornio-Rios et al., 2012). Hence, accurate identification of modal parameters such as natural frequencies and damping ratios through artificial and natural vibrations sources is a fundamental task of paramount interest. Artificial excitations require mechanical systems such as shakers and drop weights, among others (Peeters et al., 2001; Huang et al., 2005; Amezquita-Sanchez et al., 2013). This type of excitation, however, requires an easy access to the structure and its temporary closing during the monitoring of the structure. Further, artificial excitations for large civil structures are problematic. For example, if the excitation is small, the structure will not be excited correctly and the measured dynamic signals will only contain noise. In contrast, if the excitation is too large, the structure can suffer undesirable damage (He et al., 2011). For these reasons, in recent years a significant part of

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MPI research has focused on natural excitations or ambient vibrations due to wind, traffic loadings, and small to moderate earthquakes. Ambient vibrations have the advantages of being low-cost and not interrupting the structure's normal operation because no excitation equipment or traffic interruption are required. Further, it allows implementing real-time condition assessment (Yang et al., 2004; He et al., 2011; Shi et al., 2012). Accurate modal parameter identification using ambient vibrations, however, is challenging because measured data is non-stationary and embedded in high-level noise.

Different signal processing techniques have been employed to estimate the modal parameters of a structure using ambient vibrations such as peak-picking method, frequency domain decomposition (FDD) method (Soyoz and Feng, 2009; Torbol, 2014), stochastic subspace identification (SSI) (He et al., 2008), frequency response function (FRF) (Ibrahim and Reynolds, 2008), natural excitation technique (NExT) (Siringoringo and Fujino, 2008), eigensystem realization algorithm (ERA) (Urgessa, 2011), auto-regressive moving average (ARMA) (Lardies, 2010), natural excitation technique combined with the eigensystem realization algorithm (NExT-ERA) (Caicedo, 2011), and the McKelvey frequency domain subspace algorithm (Urgessa, 2011). The capabilities of the aforementioned techniques, however, are degraded in noisy environments, Further, they encounter difficulties in identifying closely-spaced frequencies commonly present in many civil structures because of symmetric geometry or similar physical properties in different directions (Bao et al., 2009; Wang and Chen, 2014; Amezquita-Sanchez and Adeli, 2015c).

In order to alleviate the shortcomings of the aforementioned techniques, new signal processing techniques have been used to estimate the modal parameters of civil structures such as the wavelet transform (WT) (Huang et al., 2005; Huang and Su, 2007; Yan and Miyamoto, 2006; Chen et al. 2009; Su et al., 2014a, 2014b) and approaches based on empirical mode decomposition (EMD) (Yan and Miyamoto, 2006; Bao et al., 2009). The WT is a more recent time-frequency technique intended for analyzing nonlinear and non-stationary signals (Adeli and Karim, 2005; Adeli and Kim, 2009; Tao et al., 2012). Unfortunately, the WT capabilities are also degraded for large real-life structures where the noise is unavoidable. Furthermore, WT requires various decomposition levels for proper estimation of the modal parameters independent of information contained in the signal (Chen et al., 2009; Amezquita-Sanchez et al., 2013). On the other hand, EMD is an adaptive technique capable of analyzing non-stationary and nonlinear signals according to information contained in the time series signal (Huang et al., 1998). However, an undesirable disadvantage of EMD is the mode mixing effect. This means that oscillations or frequencies with the same time scale are assigned to different estimated modes or frequency bands (Wu and Huang, 2009) which may compromise the closely-spaced frequencies identification (Yan and Miyamoto, 2006). In order to lessen this problem, Wu and Huang (2009) introduced the ensemble EMD (EEMD) as an adaptive noise-assisted method capable of providing a partial solution to the mode mixing problem. However, this method may produce spurious frequencies due to the added white noise (Torres et al., 2011). It also has difficulties estimating closely-spaced frequencies. In this regard, it is highly desirable to develop a signal processing technique immune to high-level noise which is also capable of estimating the modal parameters of a civil structure with great accuracy even thee closely-spaced ones. A review of recent articles on signal processing techniques for vibration-based SHM is presented in a recent article by Amezquita-Sanchez and Adeli (2015a).

Recently, Amezquita-Sanchez and Adeli (2015b) introduced a new vibration signal-based methodology for locating, detecting, and quantifying damage in highrise building structures using the synchrosqueezed wavelet transform (SWT). They note that SWT provides a reliable tool for denoising the acquired dynamic signals thus allowing the extraction of individual modal components according to their contained frequency information. The new methodology produces a high-resolution spectral estimation even when the data is noisy and has an increased detectability of the frequencies compared with previously-published methods. That research lead the authors to conclude that the SWT algorithm can be an effective tool for estimating the modal parameters of civil structures.

A review of the literature on system identification in structural engineering is presented in Sirca and Adeli (2012). In this paper a new SWT-based methodology is presented for identification of the natural frequencies and damping ratios of large civil structures using ambient vibration signals. The usefulness of the proposed methodology is assessed through three examples. In the first example, the simulated damped free vibration response of a 3-degree of freedom (DOF) system with two closely-spaced frequencies is used to evaluate the accuracy and noise immunity of the proposed methodology for estimating the natural frequencies and damping ratios. Further, in order to demonstrate the superiority of the proposed methodology the results are compared with those obtained from two other recently-developed methodologies: a) the complete ensemble EMD (CEEMD) technique (Torres et al., 2011), the latest EMD approach to improve its shortcomings and achieve a better spectral separation of the modes and frequencies, and b) the short-time multiple signal classification (ST-MUSIC) algorithm which exhibits good results for identification of frequencies, particularly the closely-spaced frequencies even when the signal is noisy (Amezquita-Sanchez et al., 2013).

In the second example, the new approach is applied to estimate responses of a benchmark 4-story 2×2 bay 3D steel frame structure subjected to ambient vibrations (Dyke et al. 2001). The results are compared with those obtained by a finite element analysis (FEA)-based model (Johnson et al., 2004). The third example identifies the natural frequencies and damping ratios of a real-life bridge located in Queretaro, Mexico, using its measured ambient vibration responses.

2. Methodology

Fig. 1 presents a schematic diagram of the new methodology for identifying the modal parameters of civil structures subjected to ambient vibrations. The methodology consists of three steps described in the following sections. In step 1, the random decrement technique (RDT) is applied to estimate the free acceleration response from the measured ambient vibration signal. In step 2, the estimated free vibration acceleration response is decomposed by the SWT algorithm into individual mode components, each one with a single frequency corresponding to one modal response of the free vibration. In step 3, the Hilbert transform (HT) is used to estimate both natural frequencies and damping ratios of calculated individual modal responses. Further, the Kalman filter (KF) is used to smoothen the natural frequencies and amplitudes values obtained by the HT method in order to obtain more reliable damping ratio values.

2.1. Step 1: Free response estimation using RDT

Random Decrement Technique (RDT) was proposed by Cole (1968) to extract the free-decay response of random signals produced by dynamic excitations such as ambient vibrations. RDT presents the following advantages: independent of the excitation data for obtaining the free-damped response and the raw data filtering as the technique averages selected segments of the raw