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Extended FDD-WT method based on correcting the errors due to non-synchronous sensing of sensors

Reza Tarinejad ^{*}, Majid Damadipour

Faculty of Civil Engineering, University of Tabriz, Tabriz, East Azerbaijan Province, Iran

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ABSTRACT

In this research, a combinational non-parametric method called frequency domain decomposition-wavelet transform (FDD-WT) that was recently presented by the authors, is extended for correction of the errors resulting from asynchronous sensing of sensors, in order to extend the application of the algorithm for different kinds of structures, especially for huge structures. Therefore, the analysis process is based on time-frequency domain decomposition and is performed with emphasis on correcting time delays between sensors.

Time delay estimation (TDE) methods are investigated for their efficiency and accuracy for noisy environmental records and the Phase Transform – β (PHAT- β) technique was selected as an appropriate method to modify the operation of traditional FDD-WT in order to achieve the exact results. In this paper, a theoretical example (3DOF system) has been provided in order to indicate the non-synchronous sensing effects of the sensors on the modal parameters; moreover, the Pacoima dam subjected to 13 Jan 2001 earthquake excitation was selected as a case study. The modal parameters of the dam obtained from the extended FDD-WT method were compared with the output of the classical signal processing method, which is referred to as 4-Spectral method, as well as other literatures relating to the dynamic characteristics of Pacoima dam. The results comparison indicates that values are correct and reliable.

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1. Introduction

Performance evaluation of an arch dam during a large earthquake is a significant engineering challenge. System identification provides the modal characteristics, which are important in the seismic analysis of dams. The accuracy of the results obtained from structural dynamic analysis depends on having a precise mathematical model that is known as the modal model of the system. In fact, the purpose of system identification is to extract information about the mathematical model that characterizes a phenomenon that is observed in the laboratory or the field.

Many civil and mechanical structures are difficult to excite artificially due to their physical size, shape or location. In addition, ambient forces, for example, waves, wind or traffic, load civil engineering structures while operating machinery exhibits self-generated vibrations. These natural input forces, which cannot easily be controlled or correctly measured, are used as unmeasured input for Operational Modal Analysis (OMA). OMA is based on measuring only the output of a structure

^{*} Corresponding author. Tel.: +98 4133392386; fax: +98 4133344287.

E-mail address: r_tarinejad@tabrizu.ac.ir (R. Tarinejad).

and using the ambient and operating forces as unmeasured input. It is used instead of classical modal analysis in order to identify the modal parameters under actual operating conditions and situations where it is difficult or impossible to control an artificial excitation of the structure.

In OMA, Dynamic characteristics of a structure can be extracted using techniques such as Peak-picking (PP) and frequency domain decomposition (FDD) in the frequency domain [1–3], Stochastic Subspace Identification (SSI) in the time domain [4] and continuous wavelet transform (CWT) in the time – frequency domain [5–10].

In the previous study, the authors presented a novel approach based on the FDD-WT (frequency domain decomposition-wavelet transform) for modal identification of structures [11,12]. In this research, this method is extended for modal identification of large structures considering the correction of errors due to non-synchronicity of records. In large and complex structures, time delays between the recorded responses of seismometers are unavoidable therefore, it is essential to solve the delay problem in order to estimate the modal parameters accurately. Therefore, several TDE (time delay estimation) techniques are introduced and their efficiency and accuracy for noisy environment records are investigated. The appropriate method (PHAT- β method) was selected and applied to modify the cross power spectral density used in the traditional FDD-WT method. In order to show the efficiency and accuracy of the extended method, a theoretical example (3DOF system) was provided to indicate the non-synchronous sensing effects of the sensors on the modal parameters. Besides, a real complicated problem, the Pacoima dam, has been selected as a case study.

2. Methodology

2.1. FDD-WT method

The frequency domain decomposition (FDD) technique is a non-parametric operational modal analysis technique introduced by Brincker et al. [3,13]. It is very similar to the Peak-peaking (PP) method and uses the power spectral density (PSD) of the signals instead of just the Fourier transform of the impulse response function (FRF).

If the power spectral density matrix of system frequency can be decomposed into its singular values and vectors in the desired frequency, peaks of the first singular value will be equal to the natural frequency of the system and singular vectors corresponding to the peaks of the first singular values approximate mode shape vectors. In this method, the half-power bandwidth or logarithmic decrement technique can be used to obtain the damping coefficient. Both techniques use the singular values spectrum for extracting damping ratios, but the values would have significant errors because of leakage errors in these spectra. Therefore, using the CACF (cyclic averaging of correlation functions) technique and also, time-frequency domain methods (e.g., wavelet transform) is necessary [11,12]. The continuous wavelet transform is a linear transform, which is defined as the convolution of the free decay signal and the dilated one. In this research, the modified complex Morlet wavelet function is selected as the mother wavelet function.

Use of the CACF technique avoids the preprocessing of ambient responses with the random decrement technique (RDT) [14–16]. The length of time segments that are extracted from the response time histories is important for the RD technique. In the frequency domain modal identification methods, it is important that the RD functions are evaluated with sufficient time length to have a complete decay within that length, so that the effects of leakage and noise are reduced [17]. For short signals, it is difficult or impossible to achieve this aim and the use of RDT is not proper. The use of averaged correlation functions is a powerful technique for reducing the leakage and random errors. The averaging technique reduces the leakage bias error by digitally filtering the data to eliminate the frequency information that cannot be described by the FFT [18]. On the other hand, the number of analytical signals (correlation functions) is decreased from n^2 to n signals, and therefore, the computational time is also decreased.

In the work reported here, the accuracy and efficiency of the TDE methods are investigated and the proper one was utilized in order to eliminate the undesirable effects of the time delays between sensors installed in the structure. For this purpose, based on the works of [19], the CPSD matrix used in the FDD-WT algorithm was extended and modified to determine the modal parameters of huge and complex structures (e.g., hydraulic and marine structures), accurately.

2.1.1. Extended FDD-WT algorithm

The FDD method can extract natural frequencies and non-scaled mode shapes. The parameters can be estimated by improving the CPSD matrix. In this work, the PHAT- β technique based on a filter or weighting function was used to modify the CPSD. On the other hand, the WT method has the ability to decouple the measured multicomponent signal to mono-component signals via the modified Morlet wavelets, and is thus able to estimate the damping ratios [11,12]. The modal identification process of the extended FDD-WT method is presented in Fig. 1.

2.2. 4-Spectral method

The classical signal processing method, referred to as 4-spectral, was used to re-compute the modal parameters of the dam in order to verify the results obtained using the extended FDD-WT method. The 4-spectral method is an easy and straightforward tool to process ambient records and extraction of modal parameters that is described below [20–22]:

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