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Underdetermined blind modal identification of structures by earthquake and ambient vibration measurements via sparse component analysis

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ABSTRACT

Sparse component analysis (SCA) approach was adopted to handle underdetermined blind modal identification of structures, where the number of sensors is less than the number of active modes. To exploit the sparsity of structural responses in time–frequency domain, Short Time Fourier Transform (STFT) was used in this study. The proposed SCA-based approach has two main stages: modal matrix estimation and modal displacement estimation. In the first stage, hierarchical clustering algorithm was used to estimate the modal matrix. The clustering algorithm was preceded by a preprocessing step to select the points in time–frequency domain that only one mode makes contribution in the responses. These points were fed to the clustering algorithm as an input. Performing this analysis enhanced the modal matrix estimation accuracy and reduced the computational cost while conducting clustering analysis. Having estimated mixing matrix, the complex-valued modal responses in the transformed domain were recovered via Smoothed zero-norm (SL-0) algorithm. In a broad sense, using the SL-0 algorithm permits researchers to use any kind of transform in seeking sparsity, regardless of obtaining real-valued or complex-valued signals in transformed domain. Natural frequencies and damping ratios were extracted from the recovered modal responses. Performance of the proposed method was investigated using a synthetic example and a benchmark structure with earthquake and ambient excitation, respectively.

1. Introduction

Modal identification of structural systems when only system responses are available is a challenging issue [1,2]. Blind source separation (BSS) technique [3] is a statistical signal processing tool that has been widely used to deal with this problem [4–7]. Introducing modal displacements as virtual sources paved the way for application of BSS in modal identification problems [8,9]. Independent component analysis (ICA) [10] and second order blind identification (SOBI) [11] are the mostly used techniques in BSS, which are based on fourth order and second order statistics, respectively. Independence of the sources is the basic assumption of the ICA-based methods; however SOBI-based ones only require that the source signals should be uncorrelated.

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Sparse component analysis (SCA) is another approach which is well suited to underdetermined problems. This approach comprises two major stages: mixing (modal) matrix estimation and source (modal displacements) recovery. SCA-based methods require no condition on independence or uncorrelatedness of the sources and sparsity is the only requirement that can be satisfied in transformed domain [12]. The choice of underlying transform plays a pivotal role in determining the type of excitation that any identification algorithm can undertake. Trying to exploit sparsity of structural responses in transformed domain, different transforms have been used in the literature. To cite a few, Discrete Cosine Transform (DCT) [13], linear time–frequency analysis [14,15] and quadratic time–frequency analysis [16,17] were used successfully in blind modal identification field.

In first stage, clustering algorithms [18] can be used to estimate modal matrix of structural systems. However, considering the fact that in practical situations the sources may have overlap in transformed domain, a criterion should be set to discard these points. Different researchers have investigated this issue exclusively and have reported a number of criteria [19–22]. Of those, comparing the direction between real and imaginary part of the mixture signals was used in this study to distinguish Single Source Points (SSPs) from Multiple Source Points (MSPs), where only one and multiple sources make contribution in the responses, respectively [21]. Although this criterion was originally developed for speech signals, it showed promising results for vibration problems as well. Using this preprocessing step not only enhanced the estimation accuracy significantly, but it also reduced the computational cost while conducting clustering analysis.

Once the incomplete mixing matrix has been obtained, an underdetermined system of linear equations is formed. Solving this equation, especially when the source signals are complex-valued, is a challenging task [15]. In attempt to avoid complex elements, the authors in Ref. [13] chose DCT as underlying transform and used l_1-magic algorithm [23] in recovery stage. But regarding the fact that DCT transform is in frequency domain, their proposed method was incapable of handling non-stationary excitations, like earthquake. Using Smoothed zero norm (SL-0) algorithm [24–26] in this paper enabled us to use any kind of transform, regardless of obtaining real-valued or complex-valued signals in transformed domain.

In this study, Short Time Fourier Transform (STFT) was chosen to fulfill sparsity requirement and to provide a general framework for tackling wide variety of excitations like earthquake and ambient vibration. In addition, constituent elements of the first and second stages were designed in such a way to render the proposed algorithm robust against noise, computationally efficient and less dependent on type of sparsifying transform that might yield real or complex coefficients.

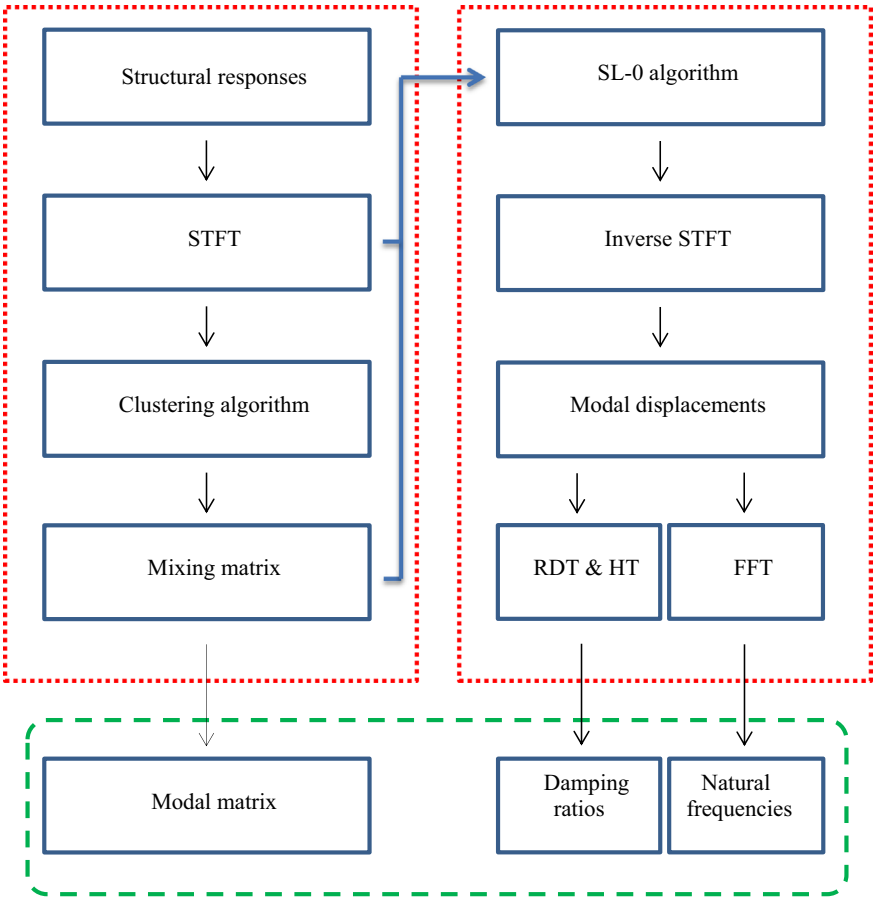

Fig. 1. Flowchart of the proposed SCA-based method.