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Improved independent component analysis based modal identification of higher damping structures

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ABSTRACT

Structural modal parameter identification under ambient excitation has strong engineering value and theoretical significance. As the most popular tool for solving Blind Source Separation (BSS) problems, Independent Component Analysis (ICA) is able to directly extract the time-domain modal parameters, including frequencies, damping ratios and modal shapes. ICA, however, has a fatal flaw of failing to identify structures with higher damping. To overcome the flaw above, the paper proposes a new method named "ICA + IDT". Firstly, free vibration response of a structure is obtained from structural outputs under ambient excitation. Inverse damping transfer (IDT) is employed to turn a highly damped signal into a low damping response signal without changing of frequencies and mode shapes. Then, structural modal parameters are extracted from the low damping response signal by ICA. Finally, the identified damping ratios are adjusted to eliminate the impact of IDT. To verify the effectiveness and applicability of IDT + ICA proposed herein, two numerical simulations—mass-spring model and simply supported concrete beam—and an experiment model of three-story steel frame are built, and the analysis results reveal that presented method can identify structures with higher damping effectively.

1. Introduction

To assess structural health status and develop effective maintenance strategies, researchers in the field of structural health monitoring are in full swing [27]. With the deepening of theoretical research, many structures have been equipped with SHM systems, such as Tsing Ma Bridge in Hong Kang of China, Runyang Bridge and CB32A Offshore Platform in mainland of China, Okashi Kaiko Bridge in Japan, I40 Bridge in New Mexico of United States, Confederation Bridge in Canada, Oresund Bridge in Denmark and Geumdang Bridge in Korea [18].

As one of necessary prerequisites to structural health monitoring, modal identification directly determines the effectiveness of a SHM system health monitoring system and further maintenance strategies [28]. Structural modal identification comprises the identification of frequency, damping ratio and mode shape.

Traditional structural modal parameter identification complies with the wisdom of system identification, which is based on the relationship between input and output signals. This corresponds to an ideal test situation in which excitation to the system can be controlled or measured. In the real-world, due to the large size of structures, such as long-span bridges, high rise buildings and large scale dams, it is extremely difficult and expensive to excite the

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structure, which limits the application of traditional structural modal identification in actual structures. Ambient excitation is usually a combination of the natural excitations such as micro-tremors, wind, traffic and other environmental effects. Related studies show that the ambient excitation basically has the characteristics of a stationary broadband excitation, which can be approximated by white noise, which makes it possible to identify structural modal parameter under ambient excitation. In the past decades, structural modal identification due to ambient excitation has attracted more and more attention for its advantages, such as no need of an input excitation. After decades of development, considerable progress has been made in output only ambient excitation methods, in which more sophisticated methods involving frequency domain methods, time domain methods and combined time–frequency domain methods have been adopted. Frequency domain methods include peak picking method, frequency domain decomposition method and least squares complex frequency domain method; time domain methods include time series analysis, random decrement method, ITD methods and natural excitation method, stochastic subspace methods, the minimum squares complex exponential method and the features of the system realization method; time–frequency domain methods include Wigner and short-time Fourier transform, wavelet transform and Hilbert–Huang transform methods [5,19]. Most of these methods are sensitive to the measurement noise and non-stationary excitation which structures commonly confront in their service environment, which undermine the effectiveness of the existing methods.

In recent years, Blind Source Separation (BSS), due to its advantages of directly extracting sources from observed signals without known information about sources or mixing processing, have been used in many fields, such as acoustics [2], communication [16], image processing [3] and neural science [10,14]. BSS shows prominent capacity as a new unsupervised signal processing tool [9] and has been introduced into structural dynamics [1]. Since it can recover the hidden sources and their underlying factors using only observed mixtures; it may thus be suitable to perform output-only modal identification [24].

Independent component analysis (ICA), as a popular tool to solve BSS problem, was proposed with the development of BSS at the end of 1990s [12,26]. Based on the assumption of statistical independent sources, ICA tries to extract the sources from the observed mixture sources without knowing the information about sources and mixture matrix. According the principle of modal shape superposition of linear dynamical system, modal shapes and modal coordinate response can be separated from system outputs by ICA. Modal parameter identification technique is employed to obtain frequencies and damping rations then. Though ICA has obtained so much attention for its advantages, however, its fatal flaw of restricting to low level of damping in structures (the damping ratio less than 1%) [15], limits the actual structural application of ICA in civil structures for their higher damping. For example, the damping ratio of steel structures is always bigger than 1%. So, we give the definition of "higher damping structure" here as the structure with damping ratio more than 1%.

For using this powerful technical in structural modal identification without the limitation of low level damping, a new method of structural modal identification called "IDT + ICA" is proposed in the paper. The main contributions in the paper may be summarized as follows: (1) Analyzing the reasons why ICA is unable to identify higher damping structural outputs; (2) Introducing Inversed Damping Transfer (IDT) to turn the outputs of higher damping structure into low-damping signal. (3) Performing ICA to the low-damping signal obtained in step (2) and obtaining structural modal parameters including frequencies, damping ratios and model shapes. (4) Further treatment is performed to eliminate the impacts of IDT and obtain the actual structural modal parameters.

The layout of this paper is as follows: Section 2 provides the basic theory of BSS and ICA. Section 3 elucidates the process of structural modal identification by ICA. Inversed Damped Technique (IDT) technique is addressed in Section 4 and new method called "IDT + ICA" identifying higher damping structural modal is proposed in Section 5. Numerical simulation of 3-dof mass-spring and a simply supported concrete beam are introduced to verify the effectiveness of the presented methodology in Section 6, and Section 7 presents experimental results of a three-story steel frame to demonstrate the application of the method, followed by the discussion and concluding remarks in Section 8.

2. Blind source separation and independent component analysis

2.1. Blind source separation, BSS

The fundamental goal of Blind Source Separation (BSS) is to estimate unknown original sources from a set of observed mixtures without prior information about either the sources or the mixing process [1]. To limit the generality, specific restrictions are placed on the mixing model and the source signals. Although convolutive and nonlinear mixtures can be considered [22,21], the paper focuses on linear and static mixtures for which BSS is well established.

The observed mixtures are defined by linear instantaneous model as weighted sum of unknown source signals to be identified. Such transformation is then described as

$$X = A \cdot S \tag{1}$$

where X is the observed mixture vector with the size of $m \times N$, m and N are the numbers of mixtures obtained by measurement of sensors and available samples respectively. Matrix S contains the samples of original unknown sources with the size of $d \times N$, d is the number of unknown sources. A single row of X or S will be further denoted as x_i or s_i, a single column of $X(n)$ or $S(n)$ is described as $x_i(n)$ or $s_i(n)$ respectively. The unknown $m \times d$ matrix A is the mixing matrix to be estimated, representing parameters of the mixing model. It is assumed that $m = d$, i.e. A is square; otherwise the over-determined or underdetermined BSS