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Blind identification of damage in time-varying systems using independent component analysis with wavelet transform

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ABSTRACT

This paper proposes a novel output-only damage identification method based on the unsupervised blind source separation (BSS) technique termed independent component analysis (ICA). It is discovered that ICA biases to extract sparse component, which typically indicates damage, from the observed mixture signals. The measured structural responses are first preprocessed by wavelet transform (WT). The wavelet-domain signals are then fed as mixtures into the BSS model, which is solved by ICA. The obtained "interesting" source with sharp spike and its associated spatial signature in the recovered mixing matrix reveal damage instant and location respectively. Following which, identification of the time-varying modes is carried out by ICA using the structural responses before and after the identified damage instant. For illustration, numerical simulations are conducted, where damage is modeled by abrupt stiffness variation in the time-varying system. Experimental and real-world seismic-excited structure examples with time-varying stiffness are also presented to illustrate the capability of the developed WT–ICA method. Results show that the WT–ICA algorithm realizes accurate and robust blind identification of damage instant and location in single or multiple damage events.

1. Introduction

Identifying damage in an early stage is a critical issue to ensure structural integrity and safety. It allows prompt maintenance and thus reduces the repair cost. More importantly, in extreme events such as earthquake and impact, timely damage information makes possible for immediate actions before catastrophic destruction occurs.

The recently developed structural health monitoring (SHM) techniques may realize structural damage monitoring. An SHM system is embedded with sensors continuously recording structural response data, which are readily accessible to damage identification algorithms, such that the structural health state can be evaluated.

To date modal-based damage identification methods have been extensively studied (a summary review [1]). Other parameter-dependent methods are also developed, e.g., the observer-based methods [2–4], flexibility-based method [5], method using input error function [6]. These methods tend to assume that the structural behaviors follow a certain form of

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model, where abnormal behavior indicates damage. Their effectiveness is undermined; however, when the assumption of the model behaviors fails.

On the other hand, signal-based techniques have shown significant promise in extracting damage information from measured structural response data. They feature efficient computation and make no prior assumption with respect to the structural model, which makes them enjoy broader applicability in damage identification. Recent successful examples include time-frequency analysis based [7] (e.g., wavelet-based [8–11] and Hilbert–Huang transform-based [12,13]), neural network-based [14] methods. However, reliable damage identification remains a challenge when influenced by measurement noise, which is induced by the harsh operating environment of structures.

Independent component analysis (ICA) [15] has arisen as a popular multivariate data analysis tool in the recent years. As an unsupervised (blind) learning algorithm, ICA is able to reveal the characteristic factors hidden in the data using only the observed mixture signals; it has seen various successful applications reported in acoustic [16], communication [17], neural science [18], financial data [19], also in structural dynamics [20], system identification [21,22], and condition monitoring [23,24].

This paper presents the application of ICA for blind identification of structural damage due to abrupt variation of the time-varying stiffness. Structural vibration response data are first transformed into the wavelet domain and then fed as mixtures into the blind source separation (BSS) model, which is analyzed by ICA. It is found that ICA can clearly reveal damage information hidden in the data, such that accurate and robust identification of both damage instant and location is realized in single or multiple damage events. Subsequently, the structural responses are divided into segments before and after the identified damage instants and then analyzed by ICA, respectively, thereby identifying the time-varying modes.

The organization of the paper is as follows: Section 2 provides the theory of wavelet transform (WT). Section 3 explores the learning rule of ICA and accordingly establishes a WT–ICA model for damage identification. Section 4 summarizes the proposed WT–ICA damage identification algorithms while Section 5 introduces the ICA algorithm for identification of time-varying modes. Numerical simulations are carried out in Section 6. Experimental and real-world seismic-excited structure examples with time-varying stiffness are presented in Sections 7 and 8, respectively, followed by the concluding remarks in Section 9.

2. Wavelet transform (WT)

The discrete wavelet transform (DWT) achieves a multi-resolution analysis of a signal $f(t)$ by [25,26]

$$v_k^l = \frac{1}{2^{l/2}}\int_{-\infty}^{\infty} f(t)\phi^*\left(\frac{t}{2^l}-k\right)dt \tag{1}$$

$$w_k^l = \frac{1}{2^{l/2}}\int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t}{2^l}-k\right)dt \tag{2}$$

where l and k are the scale and translation parameters, respectively, and $*$ denotes the complex conjugate operator. v and w are the resultant approximation and detail (wavelet) coefficients from the scaling function $\phi(t)$ and wavelet basis $\psi(t)$, respectively.

Therefore, WT realizes a multi-resolution time-frequency analysis of $f(t)$ by decomposing it into low-frequency (approximation) and high-frequency (detail) band at each level. At the lth scale level, the approximated component $f_a^l(t)$ and detailed component $f_d^l(t)$ also retain the temporal information of $f(t)$ and are represented, respectively, by

$$f_a^l(t) = \sum_k v_k^l \phi\left(\frac{t}{2^l}-k\right) \tag{3}$$

$$f_d^l(t) = \sum_k w_k^l \psi\left(\frac{t}{2^l}-k\right) \tag{4}$$

If $f(t)$ is decomposed into L levels, then it can be reconstructed by

$$f(t) = f_a^L(t) + \sum_{l=1}^{L} f_d^l(t) \tag{5}$$

The interesting property (e.g., pulse-like feature) of $f(t)$ may be revealed on certain wavelet scales [25]. However, it is easily destroyed by noise. The following example intends to illustrate this point:

A signal $f(t)$ with a sampling frequency of 100 Hz

$$f(t) = \begin{cases} \sin(2\pi\cdot 1\cdot t)+\sin(2\pi\cdot 1.5\cdot t), t=0\sim 10\ s \\ \sin(2\pi\cdot 1\cdot t)+\sin(2\pi\cdot 1.499\cdot t), t=10\sim 20\ s \end{cases}$$

experiences a slight frequency transition from 1.500 Hz to 1.499 Hz at the 10th second. Although no sign of such transition can be observed from its time history, pulse-like feature is distinguished in the wavelet-domain decomposed signal using the db10 wavelet basis [26]; it is shown in Fig. 1(a) as an impulse-like feature at the 10th second in the detailed