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Damage Detection of Structures Using Blind Source Separation and Multifractal Detrend Fluctuation Analysis

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ABSTRACT: In this paper, a damage detection technique is proposed based on multifractal detrended fluctuation analysis and blind source separation. In the first stage, the accuracy of three methods of blind source separation is compared and the most efficient method in decomposing structural vibration signals is selected. These methods include blind modal identification, combined method, and sparse coding. Three structural models are employed to investigate the of the procedures which consists of a range of numerical SDOF models with a limited degree of freedom to real structures. In the second stage, a damage index is proposed based on the width of the multifractal spectrum. Results show that the aforementioned method can identify various damage patterns and can detect slight damages.

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1. Introduction

By progress in sensor technology and computational effort, structural health monitoring techniques that can detect damage in early stages have become very important. By doing so, repair costs can be reduced and indirect costs such as repair time can be minimized. For this reason, such techniques must be able to detect slight damages. However, a large number of algorithms that have proposed so far are unable to identify early-stage damages. One of the approaches that can be employed is Multifractal approach. Fractal method in time series was first introduced by Hurst [1] and after than these methods were widely utilized in medicine, meteorology, ethnology, physics and engineering [2]. In recent years, several methods such as Detrend Fluctuation Analysis (DFA) [3] and MultiFractal Detrend Fluctuation Analysis (MFDFA) [4] have been proposed which can eliminate trend from time series. However limited studies have been carried out in this area. The aim of this study is to propose a hybrid method based on MFDFA and BSS to detect slight damage in the structures.

2. Structures Used

2.1 Mass-Spring model

As the simplest structure, a 5DOF mass-spring system is used. Mass and stiffness matrices are show below

$$\mathbf{M}=\begin{bmatrix}1&0&0&0&0\\0&2&0&0&0\\0&0&2&0&0\\0&0&0&2&0\\0&2&0&0&3\end{bmatrix}$$
$$\mathbf{K}=\begin{bmatrix}800&-800&0&0&0\\-800&2400&-1600&0&0\\0&-1600&4000&-2400&0\\0&0&-2400&5600&-4000\\0&0&0&-4000&7200\end{bmatrix} \quad (1)$$

2.2 ASCE/IASC benchmark structure

This structure is a 1/4 scale of a 4-story braced frame tested at the University of British Colombia. 6 damage patterns are defined for this structure including 1) no stiffness in braces of the first story 2) no stiffness in braces of the first and third story 3) no stiffness in one brace of the first story 4) no stiffness in one brace of the first and third story 5) similar to pattern 4 plus loosening of bolts in one connection of the first story 6)2/3 stiffness in one brace of the first story [5].

2.3 Burbank Building

Burbank building is a steel moment frame located in California. 13 sensors are mounted on the structure which has

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recorded accelerations of 5 ground motions. Data from the Northridge earthquake is employed in this study [6].

3. Modal Identification

First, the vibration mode of the structures is extracted by Fourier transform (FT). Next, BSS is applied to the response data and then FT is applied. It is clear that by applying BSS, modes of vibration are separated since only one peak exists in each Fourier spectra. Table 1 shows the vibration modes and damping calculated by the aforementioned BSS procedures. It is observed that method 2 yields more exact results.

4. Multifractal Analysis

In this section, signals are investigated from a multifractal point of view. ASCE/IASC structure is used since both healthy and damaged data of the structure exist. Mapped data shows that vibration signals in random walk representation totally differ from biological signals as no large peaks are observed in these signals and the signals show a noise-like behavior. Also, cubic curves perform better than other curves to detrend vibration signals.

From another point of view, Hurst's exponent for different q reveals that modal response shows multifractal characteristics. A decrease in h(q) for larger q means that blocks with less fluctuation show more random walk behavior while blocks with larger fluctuations are similar to noise.

5. Damage Detection Method

First, by using BSS, the structural response is decomposed and SDOF vibrations are obtained. Next, MFDFA is employed to the obtain width of multifractal spectra, as the damage criteria. The spectrum is calculated for each signal and the results are averaged. The relative difference index of damaged and healthy states is considered as a damage index.

$$DI = \frac{I_h - I_d}{I_h} \times 100 \qquad (2)$$

Where I_h and I_d are the damage criteria of healthy and damaged cases, respectively.

To consider environmental effects, a base case (with 5% noise level and 150 story force) is selected and other cases with 5-10% noise and 150-250 story force are defined. Fig. 2 plots the damage indices for the aforementioned damage patterns of 20 samples. aAll the indices are below 0.27 for the healthy state which considerably differs from damaged cases (over 1.3).

6. Conclusions

In this paper, a damage detection method based on BSS and MFDFA was proposed which can detect slight damages. First, BSS was employed to extract signals and then Hurst's exponent of the extracted signals was calculated as a damage

Table 1. Frequency and damping of the structures

Strcuture	analytical		method 1		method 2		method 3	
	Freq.	damping	Freq.	damping	Freq.	damping	Freq.	damping
5DOF	1.53	0.0278	1.53	0.0280	1.53	0.0171	1.53	0.0280
ASCE/IASC [7]	9.41	-	9.38	0.0027	9.42	0.0314	9.38	0.0027
Burbank [8]	0.71	-	0.66	0.0006	0.70	0.0972	-	-

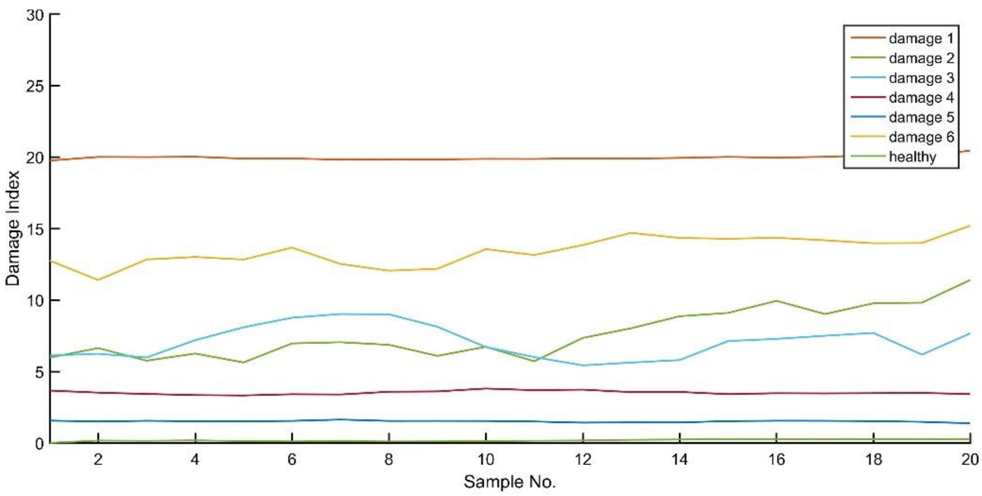

Fig. 1. Damage indices for different damage patterns

index. From the results, the following conclusions can be drawn

1- Among the three BSS methods, BMID outperforms the others since it has acceptable accuracy and computational time

2- The width of the multifractal spectrum is an effective criterion for damage detection of structures.

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