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Vibration-based structural damage identification using wavelet transform

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Abstract

This paper presents a new damage identification technique based on the statistical moments of the energy density function of the vibration responses in the time–scale (or time–frequency) domain. The continuous wavelet transform is first conducted to decompose the vibration responses into discrete energy distributions as a joint function of time and scale. The principal structural response features are then extracted from the energy density functions using moments. Consequently, the zeroth-order moment (ZOM) known as the total energy of the joint density function is computed at each measurement grid point for the pre-damage and post-damage states and is then implemented for detection and localization of damage in a concrete plate model and in a steel plate girder of a bridge structure. The significant contribution is that the wavelet coefficients are transformed into a new damage identification parameter in the space domain which is considered to be a novel application of the wavelet analysis coefficients. The major advantage is that the time–frequency analysis conducted using the wavelet transform provides a powerful tool to characterize deterministic as well as random (stationary and non-stationary) responses and can be used to detect slight changes in the response characteristics and local variations. Finally, comparison of the results obtained from the proposed method and those obtained from existing non-model-based damage identification techniques shows that the proposed method is more sensitive to damage than these other methods.

Keywords: Damage localization; Wavelet transform; Statistical moments; Plate; Bridge

1. Introduction

Structural damage causes changes in structural physical properties, mainly stiffness and damping, at damaged locations. These changes in structural properties in turn alter the dynamic response behavior of the structure from its initial pre-damage condition. Therefore, it is common practice in structural condition assessment to monitor the structural physical dynamic characteristics of the structure under test so as to identify damage at the earliest stage of development. Thus, assessment of structural condition is not only beneficial for on-time decision making regarding maintenance, rehabilitation, and possibly replacement but

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also increases the overall efficiency of operation and life-span of important infrastructure and can avert the probability of loss of human lives due to undetected structural failures.

In the last few decades, changes in the vibration responses have been widely used for damage identification and health monitoring in the areas of aerospace, automotive, civil, and mechanical engineering. Detailed literature reviews concerning these techniques and response parameters used for damage identification can be found elsewhere [1].

Generally, there exist three main classes of response parameters widely used for damage identification studies, namely modal properties and their derivatives [2–8], frequency response function (FRF) and its curvatures [9–11], and power spectral density (PSD) and its mean square value (MSV) [12,13]. However, most of the aforementioned methods are applied in the context of a deterministic input–output measurement framework. For cases where random vibration responses are used for damage identification, practical difficulties are often encountered. The simplifying assumption usually made is that the excitation is a stationary white noise process. On the other hand, random vibrations often encountered in practical problems tend to be non-stationary. There always exist nonlinear response components caused by large excitation amplitudes or uncontrolled excitations and pounding of structural components during vibration measurements. The Fourier transform-based global spectral analysis method is often used to characterize the overall frequency content of the signal and thus lacks the flexibility to deal with the local changes, discontinuities, and time-varying signal with transitory properties. Hence, for these types of signals the Fourier-based analysis methods are not suitable and the corresponding response parameters thus obtained from these analyses are not effective to characterize the aforementioned signals' characteristics.

Moreover, to counter the shortcomings of the Fourier transform in dealing with signals with local discontinuity and non-stationary properties, the short time Fourier transform (STFT) has been implemented as a compromise for the time and frequency domain analyses. However, the STFT approach suffers from the lack of the necessary resolutions in both time and frequency. Therefore, it is important to look for new damage indicators that can be applied for all structural conditions and that utilize various types of responses with non-stationary, nonlinear, transient, or fast changing response behavior. In this paper, the wavelet transform is applied as an alternative to detect and localize damage in concrete plate model and in a steel plate girder of a bridge structure. The significance of the wavelet analysis-based damage identification is that it has wider practical application than existing and widely used linear damage identification methods, since most damage mechanisms exhibit nonlinear features such as breathing cracks and delamination in composites.

In the past, wavelet analysis has been widely implemented for various unique purposes, such as de-noising of signals, compression of signals and images, information retrieval from noise polluted signals, classification, and pattern recognition applications [14]; characterization of non-stationary dynamic responses [15,16]; and identification of nonlinear structural dynamic systems [17]. The applications of wavelet analysis in the areas of damage identification and health monitoring have also been widely reported. Kim and Melhem [18] applied wavelet analysis to structural damage identification in a concrete beam subjected to fatigue damage. Yam et al. [19] presented a damage identification technique in composite structures using the wavelet transform and artificial neural networks. Hou et al. [20] presented a damage identification and health monitoring technique using wavelets analysis based on simulated data from a simple structural model with breakage springs subjected to harmonic excitation, and recorded earthquake response data from a reinforced concrete moment-resisting frame structure. Yoon et al. [21] conducted detailed experimental work to investigate damage mechanisms in a plain concrete beam, notched beam, a reinforced concrete beam, and a reinforced concrete beam with corrosion effects using acoustic emission parameter analysis, wavelet analysis, and the Fourier transform. Liew and Wang [22] proposed wavelet analysis technique for detection of localized non-propagating crack damage in a simply supported beam. Moyo and Brownjohn [23] applied wavelet analysis for characterization of the response behavior of a bridge during and after construction by using long-term strain measurement data.

However, the focus of the majority of the aforementioned studies was centered on the interrogation of the continuously monitored signal histories measured at limited degrees of freedom. The potential applications of these investigative parameters were not systematically exploited for detection and localization of damage in the space domain. To the knowledge of the authors, there appears to be no reported studies with respect to the use of the energy content of the wavelet coefficients determined from moments for damage identification in the