Journal of Sound and Vibration 433 (2018) 77–98

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Non-probabilistic wavelet method to consider uncertainties in structural damage detection

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ARTICLE INFO

Article history:
Received 14 December 2017
Received in revised form 11 April 2018
Accepted 4 July 2018

Handling Editor: I. Trendafilova

Keywords:
Uncertainties
Wavelet transform
Damage detection
Non-probabilistic
Interval analysis

ABSTRACT

In vibration-based damage detection studies, researchers have shown that wavelet transform (WT) is an effective tool for detecting damage. However, structural damage detection is hindered by uncertainties in structural models and measurement data. Various attempts have been made to address this problem by incorporating a probabilistic WT method. The success enjoyed by the probabilistic method is limited by lack of adequate information to obtain an unbiased probabilistic distribution of uncertainties. In addition, the probabilistic method involves complex and expensive computations. In this study, a non-probabilistic wavelet transform method is proposed that resolves the problem of uncertainties in vibration-based damage detection. The mode shapes of the damaged and undamaged structure are decomposed to obtain the wavelet transform coefficient values (m). With the interval analysis method, the uncertainties in the obtained mode shapes are taken to be coupled rather than statistically distributed. In this way, the interval bounds (upper and lower bounds) of the changes in the wavelet transform coefficient values are calculated. A coefficient increment factor (CIF) based on the wavelet transform coefficient value is established, and the elemental possibility of damage existence (PoDE) is defined. Numerical and experimental models of a four-side-fixed square steel plate are applied to demonstrate the efficiency of the proposed method. Furthermore, the effect of different damage severities and the impact of different noise levels on damage identification are presented. The proposed method effectively identified damage.

1. Introduction

Exposure of structures to harsh conditions leads to deterioration and damage. This may compromise the serviceability and safety of a structure. Detecting damage at an early stage reduces maintenance costs and prevents loss of lives. This has prompted the development of several vibration-based approaches to effectively address early damage detection in structures [1]. The dynamic data (acceleration and displacement) and modal properties (natural frequencies, mode shapes, and modal damping) are functions of the structure's physical properties (mass, stiffness, and damping). The existence of damage therefore leads to changes in the structure's dynamic and modal properties [2,3]. Based on this phenomenon, methods of

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https://doi.org/10.1016/j.jsv.2018.07.011

damage detection include changes in frequencies [4,5], mode shapes [6,7], mode shape curvatures [8–10] and frequency response functions (FRFs) [11,12]. Other advanced computational tools applied to damage detection are artificial neural networks [13,14], genetic algorithms [15,16], and fuzzy logic [17,18].

In addition, wavelet transform (WT) has proven to be a reliable tool for signal processing to detect damage in structures [19,20]. WT provides more details of the analysed signal based on its ability to localize signals in both the time and frequency domains [21], with an abrupt spike in the decomposed signal indicating the position of damage [22,23].

As civil structures become larger and more complex, the inherent problems of uncertainty become more significant. Uncertainties are inevitable and can cause changes in the dynamic properties of the structure. These changes can be equal to or greater than changes caused by damage [24], thereby leading to inaccurate damage diagnoses. The main sources of uncertainty in WT-based methods are modelling errors and measurement noise. In most practical application of WT for damage detection, damage is calculated by comparing measured data to baseline data. Since it is difficult to obtain undamaged data, finite element (FE) model is normally used as the baseline (undamaged). The existence of modelling error in FE is inevitable due to inaccuracy of physical parameters, non-ideal boundary condition, finite element discretization, and nonlinear structural properties. These errors may result in the vibration data generated from FE model not representing the exact dynamic behaviour of the undamaged structure, which may lead to error in damage detection. On the other hand, noise in measurement data is normally applied in the testing phase and may lead to inaccurate damage identification.

Inaccurate damage detection outputs due to uncertainties have led researchers to search for methods and indicators that are highly sensitive to damage, so that the effects of uncertainties are reduced, and uncertainties do not obscure damage [25]. For example, Law et al. [26] proposed a WT method to check uncertainties by analysing the measured acceleration response of a structure. Despite being able to identify local damage using few measurement points, the method was sensitive to measurement noise and modelling error. In applying modal data, Meruane and Heylen [16,27] considered uncertainties caused by environmental variations using natural frequencies and mode shapes. The proposed technique was verified using a bridge numerical model and data from the I-40 Bridge. The authors assumed that the materials' elastic moduli are temperature dependent. Despite success in locating damage, the technique only considered temperature variation along the bridge. However, most significant sources of modal variability from thermal gradients are through the height and width of a bridge cross-section. Dackermann et al. [28] combined FRF data and artificial neural network (ANN) techniques to detect damage in a two-storey frame structure. The tolerable uncertainty limit was 10% noise. This was improved upon when Fallahian et al. [29] applied a deep neural network (DNN) to scrutinize the effects of uncertainties caused by temperature on healthy structures. They applied principal component analysis (PCA) to reduce the frequency response function (FRF) to a defined pattern, with temperature serving as the input to the designed DNN. The severity of the damage influenced the accuracy of damage identification.

Several researchers used a statistical method to consider uncertainties in damage detection, based on either WT or other damage detection methods. For example, Yan et al. [30] considered the effects of uncertainties on modal parameters using a WT technique, with a bootstrap distribution applied for statistical estimation of uncertainties. Recently, Sarrafi and Mao [31] quantified uncertainties by applying a probabilistic WT method that involved using WT coefficients, with outlier analysis to determine the optimal detection threshold. In other damage detection methods, Xia et al. [32,33] considered the effects of random noise on natural frequencies and mode shapes, with statistical parameters calculated using the perturbation method. Flugate et al. [34] applied statistical process control method to detect damage in which an autoregressive (AR) model was fitted to the measured acceleration-time histories of an undamaged structure. The residual error was generated as the difference between the actual time history and the prediction from the AR model. Li and Law [35] proposed a statistical method for damage detection based on acceleration response with a reference model. Uncertainties were assumed to have a mean of zero and be normally distributed, as illustrated with a five-bay steel frame structure. Chandrashekha and Ganguli [36] demonstrated a fuzzy logic system to consider uncertainties using natural frequencies. Monte Carlo simulations were used for estimation of variations in frequencies and their statistical extracts. Mao and Todd [37] quantified the uncertainty of a transmissibility estimator magnitude through the output auto-power spectra. The Chi-square bivariate approach was applied to estimate the exact probability density function. The authors further established statistical models to quantify uncertainties of FRF estimated with randomly-excited experimental data [38]. The authors derived the probability density functions (PDF) of the magnitude and phase of the FRF through Gaussian bivariate statistical model. Recently, Hong et al. [39] presented a probabilistic model to measure uncertainties of relative acoustic nonlinearity parameter (RANP) by using a carbon fibre/epoxy laminate plate. A detailed explanation of the probabilistic method can be seen in Bendat and Piersol [40].

Regardless of the successes achieved by applying probabilistic methods to treatment of noisy data, the problem of assuming that the statistical distribution of uncertainties is known remains [41]. In fact, the probability density function is difficult to acquire due to the complexity of uncertainty sources [14,42]. In addition, experimental studies often do not provide adequate data, narrowing the chances of obtaining an unbiased probability density function. Furthermore, the probabilistic method requires long computation times due to the multiple data sets obtained through finite element (FE) modelling. In view of this, Qiu and Wang [43] emphasised the need for introduction of non-probabilistic interval analysis method. Unlike the conventional probabilistic approach, the non-probabilistic interval approach requires no assumptions regarding uncertainty distributions for estimating the possibility of damage existence (PoDE). Only the upper and lower bounds of the uncertain parameters are needed, thereby simplifying damage detection with noisy data, as well as reducing complex computation compared to the probabilistic approach.

With the non-probabilistic approach, Gabriele et al. [44] demonstrated the effectiveness of interval analysis in modal updating for damage detection problems affected by uncertainties. The intervals of the stiffness values were obtained by