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Robust multi-damage localisation using common eigenvector analysis and covariance matrix changes

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Damage-induced local singularities in structural characteristic deflection shapes (CDS's) are widely used in non-model-based damage localisation. Despite substantial advances in this kind of methods, several issues must be addressed to boost their efficiency and practical applications. This study deals with two essential problems of CDS-based damage localisation: the noise robustness of CDS estimation and the criterion to properly weight damage information of several CDS's. On the first problem, it is well known that CDS estimation is vulnerably compromised by various uncertainties such as measurement noise and computational errors, which will decrease the accuracy and increase the difficulties in damage localisation. A modified common eigenvector analysis (CEA) is proposed based on a bank of digital filters and a joint approximate diagonalisation technique, which statistically estimates the CDS's as the common eigenvectors of a set of covariance matrices. On the second problem, a new robust damage index (DI) is proposed, which is comprised of damage-caused local shape distortions of several CDS's weighted by their participation factors in the covariance matrix at zero-time delay. The advantage of doing this is to include fair contributions from changes of all CDS's concerned and the proposed DI provides a measure of damage-induced changes in the covariance matrix. Then a numerical study is presented to demonstrate the noise robustness of the modified CEA method over proper orthogonal decomposition and second-order blind identification in CDS estimation. Moreover, a comparison of the proposed DI over some traditional damage localisation methods is conducted based on an experimental study. The results of numerical and experimental studies demonstrate that the proposed CDS estimation method is more robust to noise and the proposed DI is highly accurate for multi-damage localisation.

1. Introduction

Structural damage detection and assessment are essentially important in maintaining the safety and reliability of engineering structures such as aircraft, bridges and buildings, which help maintain healthy states and prevent catastrophic incidents due to structural failures [1,2]. This is an inverse problem and damage is likely to be detected, localised and quantified through monitoring certain structural dynamic parameters. The basic principle behind this is that damage-induced changes in certain structural properties will alter structural dynamic responses, which can be reflected in modal parameters or other dynamic features such as frequency response function and transmissibility [3–5].

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Vibration-based damage identification methods are numerous and can be categorised according to different criteria such as levels of damage identification, linear or nonlinear vibration responses and whether using physics-based models or not [6–8]. Here, damage identification is classified according to the practical availability of baseline information. Basically, structural damage identification can be considered a pattern recognition problem, which compares the extracted features of current states of the structures with the benchmark features to determine the damage state [9–11]. But, establishing the damage feature bank for pattern recognition is challenging due to various possible damage scenarios. An alternative solution is to build the physics-based model of structures such as finite element model. In this case, the damage identification is accomplished via model updating techniques [12–15]. However, a well correlated structural model and the accurate initial state of the structure are primarily required. Moreover, the large number of updating parameters and the non-uniqueness of updated models increase the difficulties of model updating based damage identification methods [16,17].

In the absence of a damage feature bank and physics-based model of structures, damage can be detected by comparing the damage features of damaged structures with baseline data of heathy structures [18–20]. Even when the baseline data of healthy structures is not available, structural damage identification in the form of detection, localisation and relative severity quantification can still be achieved by measuring the deviations from some properties of healthy structures such as normal distribution of probability density function under random excitation and smoothness of mode shapes for geometrically uniform and material-isotropic structures [21–24].

The purpose of this paper is to propose a robust multi-damage localisation method using structural characteristic deflection- shapes (CDS's) without baseline data of healthy structures, which is desirable and promising in practical damage identification of engineering structures. Here, CDS's are referred to as structural spatial deflection vectors such as mode shapes, proper orthogonal modes (POMs) and operational deflection shapes, which are evaluated based on output-only vibration data.

Structural characteristic deflection shapes have been studied for damage detection and localisation in the last decades, but the crucial issue is the noise robustness of CDS estimation, which often involves substantial inaccuracies [25,26]. There are mainly four sources of uncertainties in CDS estimation: operational, environmental, measurement and computational [27]. Among various output-only CDS estimation approaches, proper orthogonal decomposition (POD), also known as the Karhunen–Loève decomposition (KLD), is a multivariate statistical approach aiming at using a linear combination of orthogonal functions/vectors to represent the stochastic data. When applied to finite dimensional cases and truncated after a few terms, the POD method is equivalent to principal component analysis (PCA) [28]. The proper orthogonal modes of POD are estimated as the eigenvectors of the covariance matrix from vibration output responses, which are commonly calculated by Eigen-decomposition or singular value decomposition (SVD).

Galvanetto et al. [29] investigated POMs in beam structures under sinusoidal excitation of several frequencies. The POM differences between healthy and damaged structures were used to identify the damage. Shane and Jha [30] employed POMs to filter out the environmental influences on the data and with the help of POMs of undamaged structures to calculate the residual errors in the time series to detect the damage. Thiene et al. [31] combined POM and a gapped smoothing method together to localise damage using only the vibration data of damaged structures.

However, just using a single covariance matrix of random vibration responses to estimate all the POMs is not robust and reliable due to various uncertainties. From a statistical point of view, it is desirable and promising, for the accuracy and robustness, to estimate CDS's based on a group of datasets or covariance matrices. For this purpose, a modified common eigenvector analysis (CEA) is proposed and investigated based on common principal components [32,33], which statistically provides a kind of 'average Eigen-structure' shared by a set of covariance matrices from a group of datasets or from one dataset. In this paper, joint approximate diagonalisation (JAD) algorithm is used to get the solutions for CEA in time domain to avoid estimation of complex eigenvectors. Traditionally, JAD approach is extensively applied in blind source separation due to its better performance in addressing noisy data [34]. Moreover, second-order blind identification (SOBI) based on JAD approach has been studied for operational modal analysis by many authors [35–37]. But in SOBI, a pre-whitening procedure is required before JAD procedure, which introduces a bias or error to the final solution. To overcome this issue, the pre-whitening procedure of SOBI is to be replaced by digital filters in this study. By doing this, the simultaneous estimation of all CDS's in SOBI method is converted to evaluating each CDS individually to enhance its accuracy and noise robustness. For digital filters, infinite impulse response (IIR) filter is chosen, since it has much better frequency response when compared with finite impulse response filter of the same order.

The CDS estimation by the proposed modified CEA has three steps: (1) identify the resonant frequencies; (2) design a set of IIR filters with different orders and bandwidths around each resonant frequency and compute the covariance matrices of the filtered data; (3) apply JAD approach to the covariance matrices in step 2 to estimate the CDS's. When there is only one mode in the filtered data, the estimated CDS will coincide with the mode shape regardless of the mass distribution [28].

With the CDS's of damaged structures, damage localisation can be accomplished by comparing with baseline CDS's of intact structures. Nevertheless, the main drawback of this approach is that the CDS's of damaged structures and healthy structures are difficult to be matched under various operational conditions. Fortunately, the principle that CDS's of healthy structures without stiffness and mass discontinuities are smooth can be used for damage identification in beam- or plate-type structures [38]. Based on this, a new damage index (DI) is proposed without baseline data of healthy structures, which uses the squared Euclidean distance of local shape distortions of several CDS's. Moreover, the damage information in different CDS's is weighted by their participation coefficients in the covariance matrix at zero-time delay. By doing this, the proposed DI indicates the damage-induced changes in covariance.

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