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A study of two unsupervised data driven statistical methodologies for detecting and classifying damages in structural health monitoring

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ABSTRACT

This article is concerned with the practical use of Multiway Principal Component Analysis (MPCA), Discrete Wavelet Transform (DWT), Squared Prediction Error (SPE) measures and Self-Organizing Maps (SOM) to detect and classify damages in mechanical structures. The formalism is based on a distributed piezoelectric active sensor network for the excitation and detection of structural dynamic responses. Statistical models are built using PCA when the structure is known to be healthy either directly from the dynamic responses or from wavelet coefficients at different scales representing Time–frequency information. Different damages on the tested structures are simulated by adding masses at different positions. The data from the structure in different states (damaged or not) are then projected into the different principal component models by each actuator in order to obtain the input feature vectors for a SOM from the scores and the SPE measures. An aircraft fuselage from an Airbus A320 and a multi-layered carbon fiber reinforced plastic (CFRP) plate are used as examples to test the approaches. Results are presented, compared and discussed in order to determine their potential in structural health monitoring. These results showed that all the simulated damages were detectable and the selected features proved capable of separating all damage conditions from the undamaged state for both approaches.

1. Introduction

Ways for reliable and suitable inspection of structures providing valuable information about the origin and importance of a discontinuity in a structure have been an extensive field of research for long time in the Structural Health Monitoring (SHM) community. The last years have witnessed a huge increase in efforts for the design of smart structures with the integration of materials, transducers and algorithms able to monitor the structural condition in real time and to detect at an early stage any defects that can compromise the structural integrity [1]. To date, several useful techniques are available but their applicability depends on factors such as maximum admissible damage size detection, maximum range of inspection, etc. For example, vibration-based techniques have being developed for global monitoring [2]. However, in view of the fact

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that incipient damage is typically a local phenomenon and the local response is mostly captured by higher frequency modes, these techniques present some practical difficulties since it is more complicated to excite the higher frequency response as more energy is required to produce measurable responses at these higher frequencies [3]. On a more local level, conventional non-destructive inspection (NDI) methods based on ultrasonic tests have been successfully applied by well-trained technicians. Nevertheless, due to possible inaccessibility, short range inspection capabilities as well as due to high costs, a vast quantity of critical structures is still monitored with NDI technology only within long intervals. As a result, alternative procedures such as guided ultrasonic wave-based techniques rapidly emerged due to their very well-known properties and were adapted to the concept of SHM [4]. These techniques enable the recording of baseline measurements in order to relate changes in the signals to structural damage and allow the monitoring of complex structures [5].

Generally speaking, the damage identification problem can be addressed using model-based approaches where a high-fidelity physical model of the structure is required [6] or by data-driven approaches requiring a statistical model representation of the system [7]. Farrar and Worden define that the SHM problem of damage detection can be essentially tackled as one of the statistical pattern recognition [8]. Within this context, data pre-processing forms an important aspect of pattern recognition procedures for reliable health monitoring [9]. Until the present time, there exist many dimension reduction and feature extraction techniques, each using different criteria in order to decide which information should be discarded. For instance, Principal Component Analysis (PCA) has been extensively applied to measured structural dynamic response signals with the purpose of dimensionality reduction studies [10,11], to distinguish between changes due to environmental and structural damage [12,13], for sensor validation [14], among others. Wavelet applications have also been extensively studied for damage detection by several researchers and a considerable amount of literature has been published on this topic [15–18]. Englehardt et al. used Wavelet Packets and Principal Component Analysis for improving myoelectric signal classification [19]. Xu et al. developed an enhanced sensor fault detection, diagnosis and estimation strategy for centrifugal chillers combining Wavelet analysis and Principal Component Analysis [20]. Torres et al. used the Discrete Wavelet Transform (DWT) in combination with Hierarchical Non-linear Component Analysis in order to create the feature vectors from structural dynamic responses for the training of a Gaussian process for the purpose of impact identification and for Acoustic Emission denoising [21,22].

Reduction of dimensionality also allows for visualising the results which is very important for damage detection. However, it is not always possible to reduce the dimension to two or three for visualising the data while keeping a good classification performance in a lower dimensional space [23]. Hence, working in a high dimensional space becomes necessary. In order to overcome this problem, pattern recognition has been proposed as a suitable multivariable technique for the classification of structural dynamic responses. For example, clustering algorithms, based on Self-Organizing Maps (SOM), attempting to organise feature vectors into clusters have been used for example for the classification of Acoustic Emissions [24,25] and for active sensing damage classification [26]. A detailed review of data clustering can be found in [27].

In the above references, concerning PCA and Wavelet-PCA analysis, just the first principal components or the projections to these principal components were studied. Nevertheless, there exist a number of additional PCA-related statistical measures that provide valuable information about the modeled and non-modeled dynamics within the statistical model, such as the squared prediction error (*SPE*) statistic, the T^2-statistic or combined statistics [28,29]. These measures can be used in conjunction with the projections to the principal components in order to provide a robust set of features for the improvement of future inferences. The objective of this paper is to compare and evaluate two parallel methodologies for damage detection and classification in mechanical structures combining some common techniques such as MPCA, Wavelet analysis, Damage detection indexes and SOMs. The formalism is based on a distributed piezoelectric sensor network for the detection of structural dynamic responses where each sensor acts in turn as an actuator during each phase. In each phase, one PZT is used as an actuator, where a known electrical signal is applied, and the others are used as sensors collecting the wave propagated through the structure at different points. In the first methodology, PCA models are built directly from the collected structural dynamic time-domain histories. In the second methodology, PCA models are built instead from DWT coefficients calculated from these dynamic responses allowing to extract time–frequency information of the regarded signals. The idea behind introducing the second methodology is to explore the use and advantage of incorporating the DWT analysis as pre-processing feature extraction step for building the PCA models. Thus, a method for SHM using ultrasonic guided waves in complex isotropic and anisotropic structures in terms of a pattern recognition problem is assumed here. To validate the approaches an aircraft fuselage structure from an Airbus A320 and a multilayered carbon fiber reinforced plastic (CFRP) plate are used.

The paper is organised as follows: For completeness, the article first presents the basic background on the concepts of PCA, Damage Detection Indexes, Discrete Wavelet Transform and Self-Organizing Maps in Section 2. In Section 3, the methodology for sensor data fusion and a systematic implementation of the damage diagnosis approach is described. The experimental set-up and data handling procedures are presented in Section 4. The analysis together with the discussion of the results is presented in Section 5. Finally, the concluding remarks are given in Section 6.

2. Theoretical background

2.1. Principal component analysis and damage detection index

Principal Component Analysis (PCA) is a technique of multivariable and megavariate analysis which may provide arguments for reducing a complex data set to a lower dimension and reveal some hidden and simplified structure/patterns