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Continuous debonding monitoring of a patch repaired helicopter stabilizer: Damage assessment and analysis

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ABSTRACT

The present work focuses on the structural health monitoring of an aluminium vertical helicopter stabiliser with a pre-introduced crack which was repaired with an adhesively bonded composite patch. The structure was monitored under bending fatigue and its performance was evaluated with Lamb waves, lock-in thermography and ultrasonic testing. Outlier analysis of Lamb waves captured the onset and progress of the damage in the form of patch debonding, enabling the identification of five damage-severity regions. Principal component analysis showed distinctive clusters that corresponded to different damage levels while the application of principal curves on the selected features proved to be an additional damage detection index. Amplitude and phase lock-in images accurately captured the onset and evolution of the damage in the form of patch debonding and honeycomb/skin debonding in agreement with the damage indices obtained from Lamb waves. C-scan further validated the damage mechanisms that were captured by the other methods.

1. Background

This work focuses on adhesively bonded composite patches as a repair technique. This technology was first introduced to Australian military aircraft industry in the early 1970s and later in the USA in the early 1980s [1] in an attempt to prolong the life of ageing aircraft and to address the repair challenges in the new composite ones in a cost effective and reliable way. The considerable performance of the technique extended its application to civil aviation [2].

External patch repair is a type of repair that aims to provide a temporary restoration of the mechanical strength at regions that are not so critical in terms of structural performance [3]. There are certain design parameters which need to be considered before the application of an external patch such as the patch thickness, the overlap length, the adhesive thickness and the design scenario. A complete review was made by Hart-Smith, based on the results of a theoretical model [4,5] and further developed by Hu and Soutis [6]. An evaluation on the benefits of the use of one-sided and two-sided external patches can be found in previous work [7]. Studies have shown that adhesively bonded repairs can restore up to 80% of the original structural strength [8].

In recent years, researchers have become increasingly interested in the problems related to repair patches that can emerge either from design issues or from extensive loading, such as the risk of debonding between the patch and the substrate when the ultimate shear strength of the adhesive is exceeded [9]. A number of studies have investigated these phenomena [10–12]. Clearly, a reliable in service monitoring of the performance is a very critical step towards the certification of the technique by the Civil Aviation Authorities, especially of primary load carrying structures [2,13].

A number of non destructive techniques have been used in order to assess performance of external bonded repairs in an off-line and on-line mode. Among the most notable work that can be found in the literature are; infrared thermography (IrT) has been effectively used for the off-line monitoring of artificially introduced delamination of CFRP patches from their aluminium substrate and for the on-line monitoring under fatigue loading [14]. Digital Image Correlation (DIC) has been used for the reliable on-line assessment of external and scarf repairs under tensile loading [15]. Despite the accuracy and reliability of the aforementioned techniques, they usually require a priori knowledge of the presence of damage and its location, and they require the use of expensive

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and bulky equipment with any problem arising due to accessibility restriction or they require the removal of parts. These can lead to an increased inspection cost that might require downtime of the aircraft. Therefore the next step in damage detection moves towards structural health monitoring techniques [16].

Structural health monitoring employs built-in structural diagnosis methods which utilise a number of on-line monitoring methods where a number of sensors (sensor arrays or optic fibres) can be inserted in the critical plies of the patch. These can continuously monitor the structural integrity. The aforementioned concept is a relatively new concept which needs to be extensively investigated with the aim of industrial approval. Among the most notable work that can be found; an optical fibre sensor array was used for the monitoring of the crack and delamination growth under a bonded repair [17]; a SMART layer employing Lamb waves was used in order to evaluate the cure and bond level of a composite repaired panel along with damage under fatigue loading [18].

The current work focuses on the monitoring of a repaired helicopter stabilizer subject to bending fatigue, with Lamb waves, lock-in thermography and ultrasonic inspection (C-scan). In Section 2, a brief background is presented related to the use of Lamb waves for damage detection focusing on the signal post processing through outlier analysis and linear and nonlinear principal component analysis. In the same section a brief background of the lock-in thermography is presented. In Section 3 the experimental set up is illustrated and in Section 4 the results for the three monitoring techniques are presented and discussed in detail. Finally, in Section 5, the most important conclusions of the work are discussed.

2. Structural health monitoring techniques

2.1. Lamb waves

Lamb waves are elastic perturbations that propagate in plate-like structures. They are a type of ultrasonic waves that are guided between parallel free surfaces, such as the upper and lower surfaces of a plate. Lamb waves exist in two possible modes, the symmetric modes and the anti-symmetric modes, which represent the motion of the particles in a longitudinal and in a parallel to the propagation direction respectively. For more information the reader is referred to the literature reviews [19,20]. A considerable number of researchers have used several approaches for the effective use of Lamb waves for damage detection purposes, such as modelling and numerical analysis [12], physics-based [21] and signal processing-based [22] techniques. Among the most notable works performed on composite repaired structures; the first anti-symmetric Lamb wave mode was generated at low frequencies in sandwiches and composite single and double-lap repairs in order to detect impact damage [23]. Moreover two SMART layers with an embedded network of piezoelectric actuators/sensors were inserted into a boron/epoxy laminated patch at different ply-locations to successfully monitor crack growth via Lamb wave excitation [24]. However very limited work has been performed on large scale, industry representative structures in order to demonstrate the efficiency of the monitoring techniques under in-service operating conditions.

2.1.1. Outlier analysis

Outlier analysis (OA) is referred to as the process of statistical determination of the class of a set of data, dealing with two general classes: normal or damaged. The aim is the detection of outliers within a set of given data. These outliers reflect the value that makes the monitored system deviate from the normal condition, corresponding to a damaged condition. The deviation is estimated on the basis that the normal condition data follow a Gaussian distribution.

The discordancy value in the case of multivariate data is called the *Mahalanobis squared-distance* and it can be estimated by the following equation:

$$D_\zeta = (\underline{x}_\zeta - \bar{\underline{x}})^T S^{-1} (\underline{x}_\zeta - \bar{\underline{x}}) \tag{1}$$

where, $\underline{x}_\zeta$ is the potential outlier feature vector and $\bar{\underline{x}}$ and S are the mean vector of the normal condition features and the corresponding sample covariance matrix, respectively. T indicates transpose. The estimation of an assigned threshold, is performed through the employment of a Monte Carlo approach and by taking into consideration the dimensions of the extracted features for the monitored system. Any observation that lies above the threshold is classified as an outlier; further details on the analysis and relevant applications can be found in earlier works [22,25–27].

2.1.2. Linear and nonlinear principal component analysis

Linear principal component analysis (PCA) has been used for the representation of multivariate sets of data in a reduced-dimensional space to enable an easier data interpretation. This is achieved through the projection of the data into a lower-dimensional space (e.g. a new set of axes) through orthogonal linear transformations. Each of these new variables is a linear combination of the original variables. In the current work PCA was performed through the application of the singular value decomposition (SVD). Notable work that employed PCA for damage detection purposes can be found in the literature [27–29].

Principal component analysis projects the data on principal components by extracting linear relationships (e.g. by projecting data into lines). In the current work a more generalised concept was established which allows the projection of the data into curves or surfaces instead of lines or planes, namely the nonlinear principal component analysis (NLPCA). This is achieved through the extraction of both linear and nonlinear relationships such as higher-order statistics, through the minimisation of orthogonal projection lengths from the data points to the curve. This is graphically shown in Fig. 1. NLPCA can be a valuable tool for the interpretation of high-dimensional data sets in structural health monitoring problems. However, until now, it has not been systematically exploited for structural health monitoring applications and only a few case studies can be found in the literature [30,31]. A FORTRAN programme was used for the implementation of the current work which starts with a prior line, the first principal component [27,31,32] and after a number of iterations bends to fit the distribution of the processed data. The hypothesis is that the arc length of the principal curve could serve as a valuable damage index which could describe the deviation of the system from the baseline reference with a single line.

2.2. Lock-in thermography

Lock-in thermography (LT) is an active thermographic technique usually employed to identify internal imperfections in materials or follow any degradation process during service. The advantage of LT over other methods is the synchronisation of the thermal sensor with the thermal stimulation source. Ultrasonics, electrical current, optical (lamps) or mechanical loading [14] are the most common thermal excitation techniques. In the case of mechanically loaded structures, LT is applied on-line in order to follow the structural deterioration process. Mechanical loading generates inherent mechanical stresses which through thermomechanical coupling are detectable by the thermal camera. Recorded mechanical stresses stem from the presence of stress raisers i.e.