Damage detection & localization on composite patch repair under different environmental effects

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Abstract
This paper presents a structural health monitoring (SHM) methodology for detecting damage in a composite bonded repair. The application of guided wave based techniques in a step-sanded bonded repair under operational and environmental load is thoroughly investigated. A two step damage detection and localization algorithm is presented, were in the first level the path damage indices (PDIs) for each transducer pair is calculated. The PDIs are then compared to a set threshold (based on the environmental and operational conditions) to increase the reliability of damage detection while reducing false alarm. In addition, a self-diagnosis approach based on electro-mechanical impedance (EMI) measure is proposed to identify the faulty sensors prior to the diagnosis. Once the transducer pairs with possible damage in their path has been selected, the second level of the proposed methodology is damage localization. To address the challenge of edge reflection, complex geometrical shape and layup of the repair patch which introduced anisotropy to the wave propagation, a novel damage detection based on probability imaging technique is proposed. The methodology is developed based on assigning probabilities of damage to the Minimal Intersection Score (MIS) to reduce the path saturation related to each path having the same probability of damage being located anywhere along it. The proposed method, uses a smart sub-division technique based on Voronoi Tessellation which is adaptable to any shape (circular, rectangular, elliptical). The reliability of the proposed method is then demonstrated with experimental results on a composite step-sanded repair subjected to impact damage under vibration and temperature variations, and the choice of input parameters such as wave form and excitation frequency on the probability of detecting damage is demonstrated.

1. Introduction

Scarf and step-sanded composite patch repairs are able to restore a significant amount of the structure’s strength without altering its aero-dynamics due to its minimal flushness. However, achieving its full recovery potential depends directly on the quality of the bondline which is difficult to keep consistence, because it has to be carried out in a controlled environment and depends on the skills of the technician [1]. Hence, the repair quality can vary significantly and currently there is no consistent way of evaluating the strength of a bondline without destructive testing [2, 3]. Therefore, the need for developing techniques which could monitor and assess the bondline during manufacture and in service is an important area of research. Composite repairs are even more in need currently due to the increase usage of composite materials in the new generation of aircraft. Novel manufacturing technologies allow the production of large composite structures [4]. However, since the repair of the composite primary structures currently is not broadly certified (case by case basis), this means that any extensive damage to the structure requires large sections to be replaced which is not an optimal economical nor an environmental solution, resulting in high volume of scraps. This highlights the need for developing non-destructive techniques (NDT) capable of monitoring bonded patch composite repairs through the application of structural health monitoring (SHM) techniques [5].
While guided-wave based SHM techniques have shown to be effective in detecting delamination/dishbond on composite panels [6–10], scarf and step-sanded repairs are more complex structures and the application of SHM systems to them is less investigated. Their efficiency comes from their good load transfer that creates a physical interface between the parent and the repair, leading to additional reflections and mode conversions in the context of guided waves. One of the first works evidencing the ‘smart patch’ solution is the work by Baker [11, 12] proposing an on-line monitoring system indicating damage by monitoring the strain transfer ratio between the primary structure and the patch, for metallic military aircraft. The challenge of the proposed system was identified as its reliability assurance under operational conditions of the flight. In a follow up study, a composite patch was applied to a cracked aluminium structure and tested under fatigue loading [13] to evaluate the effectiveness of the strain-based SHM approach to detect crack growth during flight. It was concluded that although the reliability and probability of detection (PoD) of the SHM system has to be demonstrated to meet the airworthiness requirements. For this reason, a single sensor systems or ones where the response of the sensors are averaged are not reliable enough in case of sensor failure. Therefore a sufficiently large number of sensors allowing for sensor failures and malfunctions will improve the system.

There are many different damage detection and localization algorithms that have been developed for detecting and localizing damage in composite structures under operational and environmental conditions, see [14, 15] just to name a few. The detection methodology depends on several factors, such as on-line or off-line capability of the system which results in passive systems [16, 17] which are required to operate during flight, and active systems which can be interrogated upon demand [10]. Some investigation have been carried out in characterizing damage as well [9]. However, it is extremely challenging to identify type and severity of damage just from point sensor data obtained from a sparse network of sensors. Some of the existing SHM systems have been specifically designed and/or modified to be applied to bonded composite patch structures [18–22] each with different advantages and challenges. The main challenge for the application of smart repair patch is the reliability of detection and the PoD of the full system, including the on-board equipment as well as the on-ground diagnostic software. The goal of the SHM system is to minimize false alarm while maximize defect detection. This requires the system to be adaptable to various sizes and complex geometries of scarf repair solution.

Therefore this paper proposes a novel damage detection & localization algorithm based on guided waves called Minimal Intersection Score (MIS) that takes into account the complexity of repaired structures. The methodology in particular is designed to operate with a network of piezoelectric (PZT) sensors to have high reliability and to monitor the bondline quality during operation. The robustness of the MIS algorithm is assessed under typical operational and environmental variations of in-flight. In order to validate its potential, MIS is compared to other common guided wave based algorithms such as RAPID [23–25] and Delay-And-Sum [26, 27] on a step-sanded composite patch repair. Multiple variation of actuation signals are tested in order to find the optimal excitation frequency with high sensitivity to damage.

2. Minimal intersection score

The proposed algorithm is based on guided wave propagation in composite structures, where the propagational properties of different wave modes can be used to detect any changes in the structures or in the bondline. The Minimal Intersection Score (MIS) algorithm for the damage detection & localization is based on the first wave packet difference between pristine and damage signals of different transmitter-receiver (T-R) pairs in a sparse array (figure 1).

The guided wave responses are recorded at two different states: Pristine and Damage. Assuming a panel is equipped with \( n \) transducers, there is \( n(n - 1) \) different \((i, j)\) possible paths. The signals related to these two states are denoted by \( S_{ij}^{\text{Pristine}} \) and \( S_{ij}^{\text{Damage}} \) respectively. After being bandpass filtered to remove the noise, a time window \([\text{ToA}(i, j), \text{ToA}(i, j) + \Delta t]\) based on the pristine signals Time of Arrival (ToA) is applied in order to limit the signals only to the direct paths and remove any reflections. It has been demonstrated that the damage reduces the amplitude of the wave when it is located on the direct path and this amplitude change can be used as a clear indication of damage. While far from the direct path, the damage reflected waves have to be utilized to detect and locate damage. In most guided wave based damage detection algorithms, the desire is to isolate the effect of damage on the recorded signals, while the unwanted effects such as influence of temperature, vibration, humidity, loading and boundary conditions are minimized [15, 28, 29], to increase the reliability of the diagnosis.

One of the factors which reduces the reliability of the diagnosis is edge reflections, because they interfere with the propagating wave and superimpose on various modes and challenge the damage detection. Therefore, the aim is to use information from the direct path with a time-window corresponding to the wave propagating from actuator to sensors, to avoid reflections and result in higher reliability in damage detection.
To identify the change between the two states (i.e. pristine and current) Path Damage Indices (PDIs) are computed for each path $i \rightarrow j$, which quantifies the difference between the two signals. Therefore, the direct path approaches, provide a single PDI for each transducer pair. This means that the probability of damage on the entire path is the same. To localize damage with higher precision the PDIs are input to imaging algorithms with fusion methods such as RAPID [25] where the PDIs are summed or averaged. Simply averaging the PDIs means that the locations in the structure which have many paths intersecting have higher probability of damage being located there and hence can result in false alarm. There are proposed modifications to address this, for example the RAPID-G method proposed in [30] which was shown to improve the accuracy at room temperature and

\begin{align*}
\text{MIS}(i,j) &= \min_{\forall (i,j) \in P(i,j)} \text{PDI}(i,j) \\
\text{MIS}(i,j) &= \text{D}(i,j)
\end{align*}
laboratory controlled environment. Step-sanded repairs are more challenging due to their complex geometry and layup (discontinuity of the lamina at the interface and different fibre orientation in each layer). Therefore, the extension of the existing methodologies to step-sanded repairs is not immediate.

It is also known that guided wave methods based on sparse sensor network have good detectability for the area inside of the sensor network. Sensor optimization algorithms have also been proposed to maximize the area inside of a sensor network, while reducing the edge reflection [31]. Therefore, in this work a new probability based imaging algorithm is proposed where the geometrical data such as transducers location and the path intersections inside the zone of interest (a repair in this case) contribute to the probability of damage being detected. If there are $n$ transducers in the structure, there are $n \times (n - 1)$ direct paths each having a different intersecting score $(0, 5$ or $6)$, see the Path Intersection image in figure 1. However, these intersection points are not uniformly distributed within the structure and if the structure is divided into uniform sized pixels (as in the case of the delay and sum probability based imaging), the question remains which intersection score to assign to each pixel. To address this challenge, a novel imaging map generation based on Voronoi Tessellation is proposed here which is explained in more detail later in this chapter.

Each point $(x, y)$ in the structure, will have $n \times (n - 1)$ damage indices $PDI(i_n, j_n)$. The Minimal Intersection Score (MIS) is defined as:

$$MIS_{xy} = \min(PDI(i_1, j_1), PDI(i_2, j_2), \ldots, PDI(i_n, j_n))$$

(1)

where $MIS_{xy}$ is the minimum difference between the current and the pristine state from all the paths crossing that point directly or close to. Hence, if a damage is in its vicinity, its MIS should be higher. The fact that only the minimum is taken into account ensures a better robustness to noise as most of the outliers are going to be filtered out. On the other hand, the risk of false negative is increased as every paths of the intersection point has to be examined. However, these intersection points are not uniformly distributed within the structure and if the structure is divided into uniform sized pixels (as in the case of the delay and sum probability based imaging), the question remains which intersection score to assign to each pixel. To address this challenge, a novel imaging map generation based on Voronoi Tessellation is proposed here which is explained in more detail later in this chapter.

2.1. ToA estimation

The presented damage detection algorithm is based on the analysis of the guided waves in their direct path. Only the first wavepackets are considered during the path damage index calculation, hence the ToA has to be estimated. There are multiple ways to estimate the ToA of guided waves such as cross-correlation [32], dispersion compensation [33, 34] and matching pursuit [35] methods but the additional reflections and mode conversion created by the repair steps makes these techniques inadequate and not accurate. For the MIS algorithm, the Rayleigh Maximum Likelihood Estimate (RMLE) [36] has been chosen for its robustness. One should note that the ToAs could be also generated from group velocities recorded beforehand via other techniques such as laser Doppler vibrometry. The ToA estimation procedure of a signal $S$ can be described in three steps:

- The Hilbert envelope $E(S)$ of the signal $S$ after being bandpass filtered about the actuation frequency is computed:

$$E(S) = |S + iH(S)|$$

(2)

where $H(S)$ is the Hilbert transform.

- The Rayleigh Maximum Likelihood Estimate (RMLE) [36] is then calculated:

$$w(\eta) = -\eta \log \hat{\sigma}^{(1)}(\eta) - (N - \eta) \log \hat{\sigma}^{(2)}(\eta)$$

(3)

where

$$\hat{\sigma}^{(1)}(\eta) = \sqrt{\frac{1}{2\eta} \sum_{i=1}^{\eta} E_i^2(S)}$$

(4)
where \( N \) is the sample number of \( \mathbf{S} \)

• The first local maxima of \( w(\eta) \) is considered the sample when the ToA occurs

Figure 2 shows an example of Lamb wave signal where the ToA has been estimated using the RMLE. In a context of highly-anisotropic, path-dependant and overlapping modes guided waves, this method is a robust estimator of the time of arrival.

2.2. Path damage index

The Path Damage Indices (PDIs) are calculated with the Pearson’s linear correlation coefficient: The PDI of the actuator \( i \) to the sensor \( j \), \( PDI_{ij} \), with \( S_{ij} \) and \( S_{ij}^{Ref} \) the windowed guided wave recording of the path \( i \rightarrow j \) at the current and pristine state respectively. The time window applied to the waveforms reduces the time domain to \([\text{TOA}(i, j), \text{TOA}(i, j) + \Delta t]\) in order to consider only the direct path and remove any reflections. In particular, the ToA is always computed from the pristine state to avoid any influence of damage on the estimation. \( \Delta t \) is considered to be the actuation signal duration and is given by:

\[
\Delta t = n_{cycles} / f
\]

where \( n_{cycles} \) is the toneburst cycles number and \( f \) the actuation frequency.

\[
PDI_{ij} = 1 - \frac{\sum_{k=1}^{n} (S_{ij,k} - \bar{S}_{ij})(S_{ij,k}^{Ref} - \bar{S}_{ij}^{Ref})}{\sqrt{\sum_{k=1}^{n} (S_{ij,k} - \bar{S}_{ij})^2 \sum_{k=1}^{n} (S_{ij,k}^{Ref} - \bar{S}_{ij}^{Ref})^2}}
\]

where \( \bar{S}_{ij} \) and \( \bar{S}_{ij}^{Ref} \) are the means of \( S_{ij} \) and \( S_{ij}^{Ref} \) respectively.

2.3. Threshold

In order to detect damage, the PDIs have to be above a set threshold. This threshold has to be reliable in order to minimize false alarms due to operational and environmental effects on the signals as well as avoiding missed-detection (false negative). For this study, this threshold is calculated from the pristine signals which are recorded multiple times (i.e. \( n_r \) times) for each paths. The individual recording of the same path are then compared to each other to define the noise threshold: for each transmitter-receiver pairs \((i,j)\), the combinations of the \( n_r \) recordings are used as signal and reference. \( n_r \) recordings per path creates \( n_r(n_r - 1) \) different pristine PDIs (\( PDI_{ij}^{P}(1, 2, \ldots, n_r, (n_r - 1)) \)). Because all paths are considered with the same weight in this descriptive statistical study, the pristine set of observations \( PDI_{ij}^{P} \) is given by:

\[
PDI_{ij}^{P} = \bigcup_{i \neq j} PDI_{ij}^{P}(1, 2, \ldots, n_r, (n_r - 1))
\]

where \( n \) and \( m \) are the number of transmitters and receivers respectively \( 1 \leq i \leq m \) and \( 1 \leq j \leq n \). The threshold \( T \) is then calculated as:
$T = \overline{\text{PDI}} + 5\sigma$  

(9)

where

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(\text{PDI}_i - \overline{\text{PDI}})^2}{N}}$$  

(10)

$\overline{\text{PDI}}$ is the mean, $\sigma$ the standard deviation and $N$ the total number of observations. If the $\text{PDI}_{ij}$ follow a normal distribution, any PDI greater than the threshold can be described as 'abnormal' with a five-sigma effect (99.99994% confidence). The structure is considered 'damaged' when the PDIs taken at the current state satisfy:

$$\exists (i, j) \in (1 \ldots n, 1 \ldots m): \text{PDI}_{ij}\text{Current} > T$$  

(11)

2.4. Voronoi tessellation

Once the PDIs are obtained for the sensor network, they will be input to an imaging algorithm to provide the most probable damage location based on their intensity. By dividing the structure into different pixels, based on the location of the pixel, the probability of damage being positioned there can be estimated from the PDIs that cross that point. This image is called a heatmap of damage. In this work, a novel subdivision of the structure is proposed for the repair patch, in order to comply with the complexity of any shape of repair and also to reduce the computational cost of having uniformly distributed cells when the path intersections is not distributed uniformly. The heatmap is generated using a Voronoi decomposition [37] with the intersection points as Voronoi nodes. The properties of the Voronoi regions are advantages for dividing the region of interest into cells surrounding the intersection points of direct paths. The computation of the Voronoi tessellation needs to be done only once, thus reducing even more the computational power required to display the heatmap. The Voronoi regions are calculated with the following steps as shown in figure 3:

- Delaunay triangulation is applied to the set of intersection points [38]
- The circumcenter of every Delaunay triangle is computed, it corresponds to the Voronoi vertices
Each Voronoi edges are equidistant (Euclidean distance) from 2 Voronoi nodes (intersection points), thus the Voronoi regions are equally distributed path-wise: no intersection point has an higher impact than its counterparts.

2.5. Performance evaluation
To assess the performance of the MIS algorithm, it is compared with two other known localization algorithms which have proven to be reliable for composite panels: Reconstruction algorithm for Probabilistic Inspection of Damage (RAPID) [23, 24] and Delay And Sum (DAS) [27]. In order to suppress the effect of other parameters in damage detection and only compare the efficiency of the algorithms in damage localization, the 3 algorithms use the same ToAs estimation technique described previously.

For detectability, RAPID and MIS are compared with the same PDIs (equal to the Signal Difference Coefficient (SDC)) but RAPID compares all of them to the threshold described previously while the MIS algorithm only compares the minimum Damage Index (DI) at the intersection points to the threshold. In particular, unlike RAPID, MIS algorithm takes into account the geometrical relation of the different paths with the intersection points DIs. For localization, a damage localization error is used as the Euclidean distance between the real position of the damage and the predicted one.

3. Experimental Set-up
3.1. Repair Manufacturing
To test the performance of the proposed algorithm a composite coupon was prepared with a step sanded bonded repair. The $280 \times 200$ mm panel is made of 16 $T300/914$ prepreg plies with a $[0/\pm 45/\pm 45/90]_2$, quasi-isotropic lay-up. The $120$ mm step-sanded repair is made of $4$ $T300/914$ plies with an overlap length of $12.5$ mm and a Cytec FM300 adhesive film. A $20$ $\mu$m thick Teflon layer of size $15 \times 20$ mm was inserted between the parent and the first ply of the repair to introduce an artificial defect from which the disbond is expected to form. The repair was then cured in autoclave and equipped with $10$ PZT transducers (PI255 manufactured by PI)
ceramics) surface mounted with adhesive film. The transducers were positioned around the repair as shown in figure 4. The initial integrity of the repair was assessed using thermography, figure 5 (right), where the artificial defect can be noticed.

3.2. Environmental effects
The repair remains on the structure which undergoes operational and environmental variations during flight as well as on the ground. The robustness of the MIS algorithm under environmental effects should be investigated as the SHM system is interrogated in the field and each state of the structure is recorded at different environmental condition, i.e. after each flight. Even if the engines of the aircraft is on or off will have a significant effect on the recorded signals due to the vibration. In order to test the effect of the vibration, the worst case scenario is considered and the vibration profile during flight has been chosen. In the case of temperature
variations, the aircraft is considered to operate in the European region. According to MIL-STD-810G [39], most of Europe has a ‘Basic’ climatic design type (Basic Cold C1, Basic Hot A2). The temperature variation for this study is chosen in the range $[-20^\circ, 45^\circ]$. The test campaign has been divided into two steps:

- Vibrations test: while the pristine panel is subjected to vibrations, Lamb waves are recorded. An artificial damage is used to simulate the presence of a Barely Visible Impact Damage (BVID).
- Temperature test: guided waves are recorded at different temperatures before (pristine state) and after impact (damage state).

### 3.2.1. Vibration:

The vibration set-up consisted of a TMS 2110E shaker driven with a 2050E09-FS power amplifier. The Crystal Instruments Spider 81-B controller used a 352C33 high sensitivity ceramic shear ICP accelerometer for the frequency measurements. Three fixtures clamps, 15 cm apart fixed the plate and the shaker connected at the centre (figure 7(a)). The frequency response function was recorded and was used in a closed feedback loop to achieve the required Acceleration Power Spectral Density (APSD) control profile (figure 6) for the RTCA/DO-160G specifications for a turbojet during flight [40]. Due to the amplitude of the vibration, the actuation...
Signals were amplified to 70 V, frequencies between 50 and 300 kHz with 5 or 10 cycles tonebursts were recorded, the actuation signal cases and their respective acquisition parameters are shown in table 1.

The measurements were done with or without vibrations with 2 different damage locations (figure 7(b)). The artificial damage used in this test was Blu-tack with a small mass (100g). 6 states of the composite patch repair have been recorded during the vibration test:

- \( P_v \) and \( P_{v-} \): Pristine state with and without vibration, respectively;
- \( D_{v1} \) and \( D_{v1-} \): ‘Damage’ state with an artificial damage on Location 1, with and without vibration respectively;
- \( D_{v2} \) and \( D_{v2-} \): ‘Damage’ state with an artificial damage on Location 2, with and without vibration respectively.

3.2.2. Temperature:
The pristine and damage (impacted) states were recorded inside the J2235 Thermal Vacuum Chamber (figure 8). The temperature of the chamber was varied between −20 °C and 45 °C in steps of 5 °C. The temperature of 0 °C was omitted to avoid the thermal instability during the phase change of steam, the humidity ratio was kept constant throughout the test (30%). The temperature control profile (figure 9) was set to 10 mins heating and 4h constant temperature, the measurements were recorded after 2 hours to ensure that the temperature of the panel was stabilised. The actuation signal cases recorded can be seen in table 2.

3.3. Impact
After the pristine measurement were taken during different operational and environmental load conditions, the specimen is impacted to cause BVID. An Instron CEAST 9350 drop tower was used to impact the top of the panel with a 10 mm-radius hemispherical impactor with a low-velocity impact at the side of the PTFE layer introduced during the manufacturing process (figure 4). The impact energy was set to 20 J. As the damage was not visible on either side of the panel (no dent), a DolphiCam CF16 Ultrasound Camera was used to check for damage. The C-scans before and after the impact (figures 10(a) and (b)) confirmed that the impact introduced a BVID by creating a delamination between the PTFE layer and the repair. It should be noted that the C-scans have been done from the backside of the panel, thus inverting the position of the PTFE layer.
4. Results

In this section, the results of the damage detection algorithm under vibration and temperature loads are presented. First step, however is to demonstrate the self-diagnosis capability of the SHM system to avoid any false alarms due to sensor failure. Following that, the effect of both load types on the sensor signals under different frequencies/cycles of the actuation signals is investigated in order to find the optimum excitation parameter for this particular step-sanded repair and post-processing algorithms to remove the environmental effects. Afterwards, for the damage localization, the MIS algorithm accuracy and robustness against environmental and operational variations are investigated and compared to DAS and RAPID algorithms.

4.1. Self-diagnosis of sensors

For a SHM system to be considered as a maintenance strategy for diagnosis of a real structure, it has to demonstrate 90% PoD with 95% reliability. As part of that, it should demonstrate self-diagnostic capabilities to detect faulty parts, i.e. sensors, connectors, attachment. An established method for detecting faulty sensors is through the electro-mechanical impedance (EMI) measurements of the sensor [41–43]. EMI measures the local stiffness of the structure (sensor and the host), by applying a harmonic voltage to the terminals of the PZT and measuring the current. The electro-mechanical admittance $Y$ is defined as the ratio between the current and the excitation voltage. Any local changes such as damage to sensor, debonding between the sensor and the host will alter the dynamics of the structure and affect the resonance frequency response. Therefore, by monitoring the impedance (inverse of the admittance) the presence of defect in the sensor as well as the quality of the bonding can be analysed [44]. Two type of change can be notices in the EMI spectrum where the stiffness of the structure changes: shift in the resonance frequency response (changing between free transducer and fully attached), and change in the slope (depend on the type of damage to the sensor and type of sensor). Therefore, the EMI measures before and after the impact on composite plate were taken to indicate the health of the sensor. The results of only a few of the sensors are presented here for compactness. Figure 11(a), represents the sensor locations and numbering. All of the sensors had almost identical admittance spectrum before and after impact except for PZT1. This is the closest sensor to the impact location and it can be seen from figure 12(a) than there is significant change in both real and imaginary part of the admittance. This indicates damage to the sensor and possible damage in the close vicinity of the sensor. Upon further investigation it was noticed that PZT1 indeed have been damaged due to the impact taking place very close to it. There is also damage to the bondline at the location of the impact. It is worth mentioning that PZT2 which is the closest one to the damage after PZT1, did not experience any noticeable change to its spectrum (see figure 12(b)) similar to PZT6 which is the farthest form the impact site (figure 12(c)). This demonstrates the capability of the EMI method in detecting very local changes and identifying faulty sensors. This transducer is now removed from the further diagnosis of the structure to increase the reliability of the decision making. Figure 11(b), presents the updated transducer paths and intersection map after the self-diagnosis.

![Figure 11. (a) Sensor configuration and numbering (left), (b) Path intersection after self diagnosis (right).](image-url)
4.2. Effect of Vibration on Guided Waves

Figures 13(a) and (b) show the effect of vibration load on signals recorded at two frequencies which represent two dominant propagation modes: 50 kHz for Anti-symmetric mode and 250 kHz for the symmetric mode.

Figure 12. Admittance plot pre and post-impact.
First step in the signal post-processing is to remove the effect of environmental and operational load. A zero-phase digital band-pass filter was used to remove the vibrations from the acquired signals. The results varies for the two different frequencies: The close proximity of the 50 kHz signals to the random vibrations and its low amplitude compared to higher frequencies (200 kHz – 300 kHz) explains why the filtered signal still has significant variations from the original signal even after post-processing (filtering and averaging) (figures 13(a) and (c)). On the other hand, higher frequency excitations after post processing were almost identical to the original signal which is more reliable for damage detection under the vibration (figures 13(b) and (d)). To further investigate whether the symmetric excitation mode performs with higher reliability under vibration load, the...

![Figure 13](image)

![Figure 14](image)
PDIs of each path is measured for two frequencies 50 and 200 kHz for the pristine state with and without vibration. Since both states relates to the pristine state, the PDIs should all fall below the damage threshold (which was set based on the methodology presented in 2.3.

Figures 14(a) and (b) display different results: at low frequency (50 kHz), a number of paths are already above the threshold resulting in false alarm. The 200 kHz frequency is more robust to the vibration load, with no PDIs being high enough to exceed the threshold. In addition, the initial results with artificial damage (added mass) at two locations, shows that with and without vibration damage could be detected, see figure 15 for the PDIs and the section 3.2.1 for the description of different test states. It should be noted that these results are for artificial damage, and it is recorded before the panel was impacted, hence PZT 1 is still functional.

4.3. Effect of temperature on guided waves

The temperature effect on Lamb waves is complex and difficult to interpret: the amplitude and phase changes are dependent on the frequency, the mode and the path. As seen on figure 16, a decrease of amplitude is observed when the temperature increases. On the other hand at low frequencies the $S_0$ mode is not affected by any phase change and the amplitude change is minimal. At high frequencies, the Lamb waves amplitude seems to be more affected by the temperature change. The effect of temperature on guided wave signals is significant and without a temperature compensation algorithm, any temperature change will result in false alarm. See figure 17 where all PDIs from two pristine states are above the set threshold. Therefore, a temperature compensation approach is applied first to remove the effect of temperature. Temperature compensation methods have drawbacks. Since the effect of temperature is similar to effect of damage on guided waves (i.e. phase shift and amplitude reduction), there is the danger of correcting or reducing the damage effect on the guided waves signals, thus resulting in missed-detection.

The temperature compensation algorithm used in this study is the instantaneous phase alignment (IPA) to compensate the effect of temperature. It has been proven to effectively reduce the effects of temperature in order to detect damage [45]. The current signal $S^P_T$ taken at the temperature $T$ is aligned in phase with the baseline signal $S^P_{T_{ref}}$ taken at the reference temperature $T_{ref}$. The time window used is the same described in the section 2.2. The signal compensated to $T_{ref}$, $S_{T_{ref}}^P$, is given by

$$S_{T_{ref}}^P = \Re(S_T^P e^{i(\phi_{T_{ref}} - \phi_P)})$$

(12)

where

$$\phi_D = \arg(S_T^P + iH(S_T^P))$$

(13)

$$\phi_{T_{ref}} = \arg(S_{T_{ref}}^P + iH(S_{T_{ref}}^P))$$

(14)

This phase correction technique is appropriate for any damage detection method using the proposed PDI because only the phase of the signals is corrected and the amplitude remains the same. As RAPID or MIS algorithm utilise the first wave packet (i.e. direct wave packet’s amplitude is affected by damage), any amplitude correction could affect the sensitivity of the damage detection. Figures 18(a) and (b) display the compensated pristine cases shown previously in figures 17(a) and (b). The IPA temperature compensation method has indeed reduced the effect of temperature and has prevented false alarms for the temperature difference of $\Delta T = \pm 5 ^\circ C$ for the higher frequencies such as 300 kHz. The 50 kHz frequency still has 2 paths that fall above the damage threshold in this temperature range ($\Delta T = \pm 5 ^\circ C$) and hence resulting in false alarm. In addition, some of the values are too close to the threshold and shows a small confidence in the diagnosis. Therefore, the symmetric mode (i.e. higher frequencies such as 200 to 300 kHz) is more appropriate for damage detection under both
vibration and temperature variation. However, with the proposed temperature compensation where only the phase is corrected, temperature different of more than 10 degrees between the two states cannot be used in the diagnosis with high reliability and PoD.

Figure 16. Path 1 → 6, effect of temperature on different actuation frequencies.
Next step is to use the post-processed PDI values with the proposed damage localization method MIS and compare its outcome with RAPID and Delay and Sum method. First, the efficiency of the MIS algorithm in detecting and localizing the damage under vibration load in two locations is assessed in this section. It should be noted that the vibration test was carried out before impacting the specimen to cause BVID, therefore the results shown below is with artificial damage. Three cases \( D_{PV1} \), \( D_{PV2} \) and \( PPV \) at 50 and 250 kHz are shown in tables 3 and 4 respectively. It should be noted that the maximum and minimum intensity values have different meanings depending on the algorithm. For the MIS algorithm, the intensity values are PDIs (the minimum on each tiles), for RAPID and Delay and Sum, they are the results of a pixel-based calculation. In addition, only selected results are presented here for compactness.

The localization results of both RAPID and MIS are very similar, the damage cases \( D_{PV1} \) and \( D_{PV2} \) have always higher intensity than the pristine case \( PPV \) showing that the threshold method will avoid false alarm due to vibration load. Although RAPID and MIS are sharing the same PDI values in this study, MIS imaging does not suffer from path saturation like RAPID that needs an additional step to increase the contrast. The frequency has an affect on the image quality and the 5 cycles 250 kHz toneburst exhibits the best image for both RAPID and MIS algorithms, see table 4. On the other hand, DAS results are mixed, the localization is approximate at best, while in some cases the intensity values are higher for the two pristine states than the damage states. This is probably due to the fact that DAS algorithm relies on wave reflections and group velocities. The complexity of the repaired composite structure makes this reflection-based damage detection algorithm not ideal for composite path repair under vibration. In conclusion the MIS algorithm was shown to detect artificial damage for step-sanded composite patch repair under vibrations (similar load to aircraft levels) with similar accuracy as RAPID but with slightly better robustness when compared across a range of frequencies and cycle numbers (5 and 10 cycles). The efficiency of the MIS algorithm in detecting and localizing the impact damage under different temperature variations is assessed in this section, for the specimen after impact to induce BVID. The temperature of reference for the pristine state is 20 °C while the temperature of the damage state (after impact) is varied between 10 °C and 30 °C leading to a \( \Delta T \) of \([-10, -5, 5, 10]\) °C. The damage detection under \( \Delta T = 0 \) is shown in table 5. While this case is the least challenging, it still shows the performance of the different algorithms in detecting a disbonds in a composite patch repair. The RAPID and MIS algorithm have similar results and locate successfully the impact damage with both 50 and 250 kHz (table 5), although the MIS does not need any post-processing on the intensity map to get rid of the path saturations. The Delay and Sum algorithm did not locate the damage at 150 and 250 kHz.
As it was demonstrated in section 4.3, the proposed methodology is robust for $\Delta T = \pm 5 ^\circ C$. Therefore the performance of MIS for these temperature variation range is compared to RAPID and DAS for the two representative frequencies: 50 and 250 kHz, in table 6 and table 7 respectively. Although the symmetric mode has resulted in higher reliability in detecting damage under vibration and temperature (PDIs further from the threshold), however, in terms of localization of the BVID under temperature variation, 50 kHz results shows a better localization accuracy. It is worth noting here that the results highlight the fact that artificial damage (such as added mass) is not a good representation of the complexity of a real impact damage and hence should not be used for validation of any SHM system.

The results of the detection shows better performance and higher reliability for MIS and RAPID algorithm. The advantage of the MIS algorithm is that no extra post-processing is required to reduce the path saturation intensity. In addition, the computational cost is lower, as it will only use one value per cell, rather than fusing them. This also increases the reliability under the operational and environmental conditions.

5. Summary and conclusion

In this paper, the application of SHM for monitoring a bonded composite step-sanded repair is thoroughly investigate under environmental and operational conditions of flight. Piezoelectric transducers were utilised as a sparse sensor network to excite the structure with ultrasonic guided waves and detect and locate damage by comparing the current state to a pristine state. The extension of SHM techniques developed for composite plates to bonded repair patch is not straightforward due to the complexity of geometry, size and layup of the repaired structure and have not been thoroughly investigated by many researchers. Therefore, in this work an new algorithm called Minimal Intersection Score is proposed where the complexities of the bonded repair as well as reliability under operational conditions have been considered. In the proposed methodology, for each transducer pair, first the path damage index (PDI) is calculated to indicated the probability of having damage on that path based on correlation coefficient of the signal recorded at pristine and at the damage state. The PDI is then compared to a set threshold to indicate the probability of damage being located on that path. Since the aim of this work has been to propose a method which is robust to environmental and operational conditions of the structure in service, a post-processing step has been introduced based on filtering, averaging and applying temperature compensation algorithm to remove these effects from the recorded signals before the PDI is

![Figure 18. PDIs of every paths for 6V 5-cycles toneburst at 50 and 300 kHz, pristine state at $T = 20 ^\circ C$ compared to pristine at $\Delta T = (-10, -5, 5, 10 ^\circ C)$ with IPA temperature compensation method.](image-url)
calculated. Once the paths with PDIs above the threshold have been indicated, they are then used in the next step to localize damage. A new imaging algorithm was proposed, where the aim has been to remove path saturation based on interaction scores of the direct paths translated into sub-regions or cells around these intersection points. For this aim, Voronoi Tessellation sub-division technique is proposed since it is capable of non-uniform distribution of sub-regions in the structure around the points of similar intersection scores. The algorithm was then tested with a composite coupon manufactured, repaired and sensorized. The coupon was subjected to

Table 3. MIS, RAPID and Delay and Sum heatmaps for 70 V 5cycles 50 kHz toneburst actuation.

| Case          | MIS        | Algorithm | DelayAndSum |
|---------------|------------|-----------|-------------|
| $D^1_1/P_{HI}$ | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| $D^1_2/P_{HI}$ | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| $P_{HI}/P_{HI}$ | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |

Table 4. MIS, RAPID and Delay and Sum heatmaps for 70 V 5cycles 250 kHz toneburst actuation

| Case          | MIS        | Algorithm | DelayAndSum |
|---------------|------------|-----------|-------------|
| $D^1_1/P_{HI}$ | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| $D^1_2/P_{HI}$ | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |
| $P_{HI}/P_{HI}$ | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) |
vibration and temperature variation similar to levels which a regional aircraft is exposed to. The robustness, reliability and capability of the algorithm in detecting and localizing damage has been demonstrated by comparing the results to well-established RAPID and DAS methods. The performance of MIS was evaluated for a range of frequencies and various input cycle forms (i.e. number of cycles) to establish the optimal excitation frequency for the particular structure under investigation.

The MIS algorithm was able to detect and locate different types of damage under vibration and temperature loads. Its robustness and efficiency was ensured by demonstrating that no false-alarm was raised under the operational and environmental loads for diagnosis of a complex composite structure such as a step-sanded repair. It should be noted that in the case of the repair, the damage detection is much more important than damage localization since the presence of any damage indicates that the repair is obsolete and has to be replaced. The MIS showed a good detectability for the repaired structure under temperature ($\Delta T = \pm 5^\circ C$) and vibration load and without any false alarm if the actuation signal is selected carefully. This work also demonstrated the importance of a parametric study and a thorough investigation into damage detection for each type of structure since the choice of optimum frequency, number of sensors, location of sensors, damage

Table 5. MIS, RAPID and DAS heatmaps for BVID detection, 6V 5cycles 50, 150 and 250 kHz toneburst actuation for $\Delta T = 0$.

| Frequency (kHz) | MIS | Algorithm RAPID | DelayAndSum |
|----------------|-----|----------------|-------------|
| 50             | ![MIS Heatmap](image1) | ![Algorithm RAPID Heatmap](image2) | ![DelayAndSum Heatmap](image3) |
| 150            | ![MIS Heatmap](image4) | ![Algorithm RAPID Heatmap](image5) | ![DelayAndSum Heatmap](image6) |
| 250            | ![MIS Heatmap](image7) | ![Algorithm RAPID Heatmap](image8) | ![DelayAndSum Heatmap](image9) |

Table 6. MIS, RAPID and Delay and Sum heatmaps for 6V 5cycles 50 kHz toneburst actuation, compensated.

| $\Delta T$ | States | MIS | Algorithm RAPID | DelayAndSum |
|------------|--------|-----|----------------|-------------|
| -5 $\frac{\Delta T}{F_{N,f}}$ | ![MIS Heatmap](image10) | ![Algorithm RAPID Heatmap](image11) | ![DelayAndSum Heatmap](image12) |
| 5 $\frac{\Delta T}{F_{N,f}}$ | ![MIS Heatmap](image13) | ![Algorithm RAPID Heatmap](image14) | ![DelayAndSum Heatmap](image15) |
detection algorithm, filters and post-processing techniques is not trivial and cannot be generalized for each structure. It was noticed that different frequencies (i.e. wavemodes) have different sensitivity to the type of damage. When added mass (surface mounted) was used with vibration load, the higher frequency ($S_0$ mode) had better localization accuracy compared to the lower frequency where $A_0$ is the dominant mode. However, for the case of impacted specimen with BVID, the $A_0$ mode had better localization accuracy. In both scenarios, the $S_0$ mode had higher reliability for damage detection (not localization) because of the higher amplitude and better signal to noise ratio. The importance of having a fail-safe SHM system was demonstrated, where one sensor was damaged after impact and it was detected through EMI measure of the sensor. This avoided false alarm due to sensor failure. In summary, this research has demonstrated the potential for SHM techniques to be applied to hot spots such as bonded repair patch. However, its application is not straightforward and a parametric study is required to demonstrate the reliability of the proposed SHM under operational and environmental loads and for all possible damage scenarios.

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