Disbond detection in adhesively bonded composite structures using vibration signatures

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Abstract

This paper presents a structural health monitoring technique based on analysis of the dynamic signature of the structure, which changes as damage occurs, due to alterations in structural properties such as stiffness and damping. Experiments performed on plate specimens and T-joint specimens which had various degrees of damage in the form of delaminations showed that it is possible to quantify the effect of damage on the acoustic response resulting from a tap in thick GFRP laminates. Subsequent experiments were conducted on adhesively bonded GFRP composite beam specimens with artificial delaminations of various sizes and locations embedded in the bonding line. The specimens were excited using piezoelectric actuators bonded to the surface at various locations and the structural and acoustic responses were analysed. The results of these tests and analyses are presented and it is concluded that the structural and acoustic responses of such specimens to a piezoelectric actuator can be used to identify the presence of a delamination and may potentially be used to determine its size and location.

Keywords: Structural health monitoring; GFRP; Composite; Vibration; Acoustic response

1. Introduction

Glass fibre reinforced polymer (GFRP) materials are being used extensively in aerospace and maritime applications. Although having many advantages over traditional materials such as high strength to weight ratio and excellent corrosion resistance, these materials are susceptible to delamination and disbonding which can occur from manufacturing defects or from operational loads such as shock or impact. This can significantly reduce the structural integrity of the structure and yet the damage may not be visible from the surface.

Many different non-destructive inspection (NDI) methods are available for damage diagnosis in composite structures. Traditional methods are labour intensive and require the structure to be taken out of service for the inspection to be carried out. Continuous structural health monitoring (SHM) allows assessment of the health of the structure without removing the structure from service. Critical areas of the structure can be targeted for inspection. SHM systems either work by detecting the presence of damage using onboard sensors, or by recording the occurrence of high-risk events, such as impact.

One NDI method that has been used extensively is the coin tap technique. A tap is applied manually to the structure of interest and by listening to sound produced the operator can interpret if there is damage present. The focus of this paper is on the application of the technique to a range of bonded GFRP specimens each with different levels of delamination to assess its effectiveness as an SHM diagnostic tool.

2. Vibration-based in-situ health monitoring technique

The coin tap method is one of a number of vibration non-destructive testing techniques currently applied in
various fields [1]. Although the coin tap technique does rely on the global response of the structure, in the sense that the entire structure has a part to play in the generation of the acoustic response, in practice coin tap is a local technique because a tap needs to be applied directly above a defect in order for any problem with the structure to be identified. This is in contrast to the ‘wheel tap’ technique. The wheel tap technique has been applied in the rail industry, where the health of a large steel wheel can be assessed by tapping anywhere on the wheel, and listening to its ‘ring’. In this sense, the wheel tap technique is a global method. In contrast, the coin tap method relies on a change in the impulse applied to the structure (caused by the defect), rather than modification of the vibration modes induced in the structure.

This is a subtle theoretical point which has a large influence on the implementation of the coin tap technique. It means that taps need to be applied over the entire structure in order to determine whether the structure is defect-free. However it may be possible that a combination of the two techniques will lead to a more effective NDI system. Further details regarding the theoretical basis of the coin tap technique can be found in Cawley [2].

The current technique uses a frequency analysis of the structural or acoustic response to identify the presence of damage within the structure. The response of undamaged samples is compared with that of samples with varying degrees of delamination. Damaged samples are identified by shifts in the frequencies at which some of the vibration modes occur and broadening of peaks which identifies increased damping. Preliminary work by the authors [3,4] indicated that quantification of the audio response from a tap test had the potential to be used in structural health monitoring.

Initial testing of the technique was performed using an instrumented force hammer to apply the excitation to the structure. For application to an in-situ health monitoring system the excitation was provided by lead zirconate titanate (PZT) piezoelectric elements which have the dual capability of being sensors and actuators. There are a number of advantages in using PZT actuators and sensors: they are durable, they can be distributed throughout the structure and the have a very good frequency response for frequencies above about 500 Hz [5].

The aim of the work is to extend the manual coin tap technique for application to an in-situ test health monitoring system for large composite structures which uses piezoelectric elements as miniaturised tappers and miniature microphones or PZT elements as sensors.

3. Preliminary investigation

Initial tests were performed on GFRP plates with varying degrees of delamination to determine the viability of the proposed in-situ health monitoring technique [6]. It was found that the technique was effective in the detection of both through-width and encapsulated delaminations. The enclosed delaminations were more difficult to identify and required scrutiny of the higher region (>800 Hz) of the frequency response of the structure.

Subsequently, tests were conducted on T-joint sections which represent a more realistic damage scenario. The T-joint sections were manufactured to represent T-joints in a GFRP ship structure connecting a bulkhead and to the ship hull. Details of the manufacturing process may be found in reference [7]. The multiple interfaces in the T-joint are all possible locations for the development of disbonds, which can initiate when the structure is loaded, particularly by shock or impact. Fig. 1 shows the possible locations for the development of delaminations.

A number of T-joint specimens were fabricated for testing. One of the specimens was undamaged (healthy) and was used to obtain a baseline response for comparing the acoustic signatures from the respective specimens. Two of the specimens had Teflon inserts located at different locations within the structure to simulate disbonds. The locations of the Teflon inserts corresponded to typical sites for the development of damage and are indicated in Fig. 2.

It should be noted that each specimen had an artificial disbond in only one of the locations indicated in Fig. 2. For convenience, the disbonds in the two locations considered are shown in the same diagram.

To represent a more severe damage case, two specimens which had failed during mechanical pull-out tests [7] were also examined. These two failed specimens had extensive disbonding throughout the hull section but no disbonds in the bulkhead section.

The excitation input was derived from PZT elements (type 5A4E) mounted on the surface of the T-joints. A high-sensitivity microphone (Bruel & Kjær 1/2" type 4189) was mounted adjacent to the PZT actuator to obtain the acoustic response.

A total of five T-Joint sections were tested. For each specimen the excitation input was applied in each of two

![Fig. 1. T-Joint specimen showing typical disbond locations.](image-url)
positions as shown in Fig. 3. These are directly over the locations for the respective artificial disbonds in two of the specimens, and are referred to as bulkhead inputs and hull inputs, respectively. In each case, the microphone was located close to the input point.

Fig. 4 shows the frequency spectrum of the transfer function of the acoustic response to a piezoelectric actuator input at the hull location for the healthy sample, a failed sample and samples with the artificial disbonds.

The acoustic response for the T-joint section with the disbonds between the bulkhead and overlamine (i.e. remote from the piezoelectric actuator input location) was also distinguishable from that of the healthy T-joint section. In this case the differences are most striking in the 7000–8000 Hz range with a strong peak at 9800 Hz, which was barely evident in the response to the hammer-tap. These changes are presumably caused by local vibrations in the disbonds region at a short distance from the excitation and the microphone.

The signatures of the failed T-joint section are clearly distinguishable from that for the healthy T-joint section. The signature of the healthy T-joint section is characterised by a series of well defined narrow peaks. In the signatures of the failed T-joint sections, there are significant frequency shifts in the various peaks and significant broadening of these peaks, indicating increased damping in the failed T-joint sections.

Evidently, the acoustic response signature to a piezoelectric actuator excitation was confidently able to detect the presence of the damage in all of the cases examined, even when the excitation was not applied immediately above the damage.

4. GFRP beam tests

In a practical in-situ SHM application, it is not always possible to have sensors located directly above the site of the delamination due to the unpredictable nature of damage initiation. Results from the T-joint tests showed that it is possible to detect the presence of damage when the actuator is not located directly over the delamination. Experiments on the beam specimens were designed to examine this further.
4.1. Samples and test apparatus

A large glass/vinyl ester plate was manufactured using 23 plies of woven 800 g/m² E-glass fabric and a vinyl ester resin (Derakane® 411-350). The plate was manufactured using vacuum assisted resin transfer moulding (VARTM) with a final thickness of 15 mm. The cured plate was cut into two halves and adhesively bonded using the same resin. Delaminations were introduced into the plate, before the two plates were bonded together, using thin brass shims sandwiched between two sheets of Teflon® impregnated glass films. The size of the Teflon® impregnated glass film and brass shims characterised the length of the delamination. The thin brass shim and the two layers of the Teflon® impregnated glass films had a total thickness of 0.3 mm. One undamaged and three damaged beams with delamination lengths of 50, 100 and 150 mm were produced with dimensions of 600 mm (length) × 34 mm (width) × 31 mm (thickness), as shown in Fig. 5. When the beams were cut the thin brass shims were removed to produce open delaminations.

PZT ceramic piezoelectric plates (type 5A4E) were used as actuators for the vibration assessment of the composite beams. The thickness of the PZT plates used was 0.267 mm. The PZT plates were cut into elements with a size of 20 mm × 20 mm. Copper shims with a size of 20 mm × 30 mm and a thickness of 50 μm were prepared. A silver powder and Araldite® mixture was used to establish electrical contact between the copper shims and the underside of the PZT elements. Eight PZT elements were surface bonded to each beam using Araldite® epoxy adhesive. Table 1 shows the numbering and locations of the PZT elements used during the experiments. These locations were chosen so the PZT elements would not be located at nodal points.

To provide a simply pinned support, steel rods with a diameter of 12.7 mm were fastened to the ends of each beam. The beams were secured between L-shaped steel supports on a heavy concrete-backed steel block. Spherical bearings were used to attach the rod on each end of the beam to the supports. The use of spherical bearings, compared to the ball bearing support used in a previous study [6], significantly improved the simply supported boundary conditions and eliminated twisting of the beam in vibration. A photograph of the experimental set-up is shown in Fig. 6.

To simulate tap inputs, electrical impulses of 0.16 ms were applied to the chosen PZT actuator element at 1 s intervals for 10 s. The duration (width) of the impulse was chosen to produce a frequency bandwidth of 10 kHz to excite the first 10 modes of vibration, with a 2 dB drop in signal amplitude over the range. A PZT amplifier was used to drive the actuator with a final peak voltage of 72.4 V. All eight PZT elements were used as the actuator in turn. To record the structural response all eight PZT elements were used as the actuator in turn, with the remaining seven as sensors. The frequency response of each actuator–sensor pair was obtained, yielding a total of 56 transfer functions. To record the acoustic response a high-sensitivity microphone was placed directly over the actuator element. The frequency response of each actuator–sensor pair was obtained, yielding a total of eight transfer functions for each beam.

The test matrix for the beam experiments is presented in Table 2.

4.2. Results and discussion

4.2.1. Maxwell’s reciprocal theorem

The matrix-type data acquisition allowed the frequency response of all possible PZT actuator–sensor pairs to be obtained. An interesting observation was made after the examination of each PZT actuator–sensor pair and its reciprocal (i.e. actuator and sensor changed over), that Maxwell’s Reciprocal Theorem, which was developed for static systems, can be applied equally well to a dynamic system, provided that it is linear elastic.

Maxwell’s Reciprocal Theorem stipulates that the displacement caused at point 1 by a force at point 2 is equal to the displacement caused at point 2 by the same force at point 1. Since the added dimension of time in a dynamic system does not change its load-displacement linearity, the
Theorem can be expected to remain valid. This will also be reflected in the frequency domain, in terms of the frequency response functions, as shown by the experimental results in Fig. 7. Although only the frequency responses of the undamaged beam are shown in Fig. 7, a parallel behaviour was observed for the beams containing damage of various sizes, indicating that only small non-linearities were introduced by the damage.

### 4.2.2. Frequency response

Due to the automated input force with negligible variability, the responses of the PZT sensors were highly repeatable. The frequency response functions of the sensing elements showed excellent agreement in terms of the natural frequencies, although the relative magnitudes of the resonance peaks were different due to the different sensor locations. Fig. 8 shows the frequency responses of PZT 2 through PZT 8 of the undamaged beam with PZT 1 as the actuator. The frequency response of the same beam with PZT 3 used as the actuator is shown in Fig. 9. It can be seen that the location of the force input had a noticeable effect on the power spectral distribution. It is also evident that the response of the PZT below 1000 Hz was relatively poor and noisy. This is attributable to the poor performance of the PZT sensors and actuators at low frequencies. The very large peaks at 50 Hz were attributed to electrical interference from the mains electricity supply, from which the test equipment were powered. The fundamental frequency of the beam, which was around 150 Hz, could not be consistently identified. However, it is not expected that the lower modes of vibration would be noticeably affected by the presence of moderate delaminations.

The acoustic frequency response functions showed excellent agreement with the structural responses measured using the non-actuating PZT elements in terms of the natural frequencies. Fig. 10 shows the frequency response of the microphone against those of the PZT sensors on the undamaged beam with PZT 1 as the actuator. The frequency response of the same beam with PZT 3 used as the actuator is shown in Fig. 11.

### 4.2.3. Damage identification

The presence of delamination caused noticeable changes in the frequency responses, even when the input force was remote from the damage. The frequency response functions of an actuator–sensor pair remote from the damage and the acoustic frequency response recorded at above the location of the actuator is shown in Figs. 12–14. The responses are separated for clarity; each plot contains the response for one beam with a defect compared to that of the undamaged beam. Changes in the measured natural frequencies were the same for all sensors for a given defect size.

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**Table 2**

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Damage</th>
<th>Supports</th>
<th>Input/output</th>
<th>Actuator/sensor location</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a Beam 600 × 34 × 31</td>
<td>Undamaged</td>
<td>Pinned</td>
<td>Piezo/PiezO</td>
<td>Piezo response recorded at each sensor</td>
<td>13</td>
</tr>
<tr>
<td>4b</td>
<td>50 mm long</td>
<td>Pinned</td>
<td>Piezo/PiezO</td>
<td>Piezo response for each actuator location</td>
<td>13</td>
</tr>
<tr>
<td>4c</td>
<td>100 mm long</td>
<td>Pinned</td>
<td>Piezo/PiezO</td>
<td>Piezo response for each actuator location</td>
<td>13</td>
</tr>
<tr>
<td>4d</td>
<td>150 mm long</td>
<td>Pinned</td>
<td>Piezo/PiezO</td>
<td>Piezo response for each actuator location</td>
<td>13</td>
</tr>
<tr>
<td>4a Beam 600 × 34 × 31</td>
<td>Undamaged</td>
<td>Pinned</td>
<td>Piezo/Mic</td>
<td>Acoustic response recorded</td>
<td>13</td>
</tr>
<tr>
<td>4b</td>
<td>50 mm long</td>
<td>Pinned</td>
<td>Piezo/Mic</td>
<td>Acoustic response recorded</td>
<td>13</td>
</tr>
<tr>
<td>4c</td>
<td>100 mm long</td>
<td>Pinned</td>
<td>Piezo/Mic</td>
<td>Acoustic response recorded</td>
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<tr>
<td>4d</td>
<td>150 mm long</td>
<td>Pinned</td>
<td>Piezo/Mic</td>
<td>Acoustic response recorded</td>
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</tr>
</tbody>
</table>
For the 50 mm defect case, the change in the frequency response was small for both the PZT actuator–sensor pair and the PZT, microphone actuator–sensor pair. There was a very slight reduction in the natural frequency of the 4th mode (just over 2000 Hz) and almost no reduction in frequency for the two succeeding higher modes. However, a notable reduction in the frequency of the 8th mode (just over 6000 Hz) can be observed for the PZT actuator–
sensor pair. The acoustic response of the undamaged specimen produced no resonant mode at this frequency, however the frequency spike shown in the acoustic response for the damaged sample is comparable with that seen in the PZT response. It would appear that this level of damage represents the lower limit of detection based on vibration assessment.

For the 100 and 150 mm defect case the structural and acoustic responses were very similar. Changes to the frequency response were markedly greater for the beam with

Fig. 9. Frequency responses of undamaged beam with PZT 3 as actuator.

Fig. 10. Frequency responses of undamaged beam with PZT 1 as actuator.

Fig. 11. Frequency responses of undamaged beam with PZT 3 as actuator.
a 100 mm delamination. In this case, there were significant reductions in the natural frequencies from the 3rd mode upwards, the extent of which were large enough even for the human ear to discern. A similar trend can be observed for the beam with a 150 mm delamination, with even greater reductions in the natural frequencies.

The acoustic response in general exhibits the same trends as the structural response, however the additional vibration modes present in the acoustic response reveal additional shifts in the dominant frequencies between the damaged and undamaged beams.

The response of the beam in the higher frequency range is of low amplitude. Further investigations are required to determine whether the differences in the respective signatures in the 7–10 kHz range are significant.

There is little doubt that, as far as damage detection is concerned, sensors and actuators in a vibration based health monitoring system do not need to be close to the damage in order to reveal its presence. This is because delamination reduces the out-of-plane stiffness of the damaged area which in turn affects the global vibration modes of the structure. The ensuing reductions in the natural frequencies can be measured anywhere on the continuous structure, making possible global damage identification.

However, revealing the presence of the damage alone satisfies the requirement of only the most basic health monitoring system. An effective SHM system must also be capable of determining the location and size of the damage once a positive identification is made.

It is well established that the relative extents of natural frequency reductions are dependent on both the size and location of the damage [1]. Hence, damage characterisation based on global sensing can be achieved provided that data is available on the response of the structure with a large variety of damage configurations, to which an unknown measurement can be compared. Whilst it is possible to

![Graph](image-url)
construct such a database based on experimental testing, this approach would be prohibitively resource intensive. A more feasible method relies on the creation of a high-fidelity model of the structure, from which responses can be calculated numerically.

Global sensing is an attractive option since only a small number of strategically positioned sensors and actuators are required to cover the entire structure. However, such techniques are almost always model-dependent as it is practically infeasible to generate damage databases by experimental testing. Hence, the creation of accurate dynamic structural models is vital for the successful implementation of global damage identification systems.

Unfortunately, it is not always straightforward to create high-fidelity dynamic structural models, especially for structures with complex geometric features and boundary conditions. The modelling of delamination is also a difficult subject matter which is receiving great research attention. An alternative technique for damage characterisation relies on the detection of unique features of the structure which are only present in the vicinity of the damage. This local detection method does not require that a large database be available for comparison. Instead, sensor measurements are compared with each other to identify features associated with damage [8]. The location and size of the damage can be readily determined by knowledge of the sensor locations.

The experimental results showed that, in some cases, large additional peaks appeared in the frequency response functions of the PZT actuator–sensor pair, as shown in Figs. 15 and 16, and the PZT microphone actuator–sensor pair shown in Figs. 17 and 18. This only occurred when both the actuator and sensor were located over or very close to the delamination for the structural vibration case. When using the microphone, additional peaks in the acoustic response manifested when the actuator was positioned...
close or over the disbonds. It is believed that these additional peaks corresponded to the secondary vibrations within the delaminated sections. Indeed, it is these secondary vibrations that are believed to be the critical factors differentiating damaged areas of a structure from healthy areas in traditional manual tap testing.

For the beam with a 100 mm delamination, additional peaks in the frequency responses were observed for the PZT 2 and PZT 3 pair and for the PZT microphone pair for the same actuator positions. The delamination in this case was between PZT 3 and a location 40 mm short of PZT 1. The PZT and acoustic response at location 1 did not appear to be affected by the delamination, presumably due to its relatively large distance from the damage. For the PZT 2 and PZT 3 pair and the acoustic response at locations 2 and 3, one additional peak occurred at 3219 Hz, as shown in Figs. 15 and 17. A second additional peak occurred at 8250 Hz (see Figs. 15 and 17), which was assumed to be a harmonic of the former vibration mode.

The beam with a 150 mm delamination yielded additional resonance peaks in the frequency responses for PZT actuator–sensor combinations involving PZT 1, PZT 2 and PZT 3, and for the acoustic response at the same actuator–sensor locations, as shown in Figs. 16 and 18. The delamination in this case almost covered all three PZT elements.

Fig. 16 shows the PZT responses of the sensor with PZT 2 used as the actuator. The results using PZT 1 and PZT 3 as the actuator were similar. Fig. 18 shows the acoustic responses for all actuator locations for the beam, the additional peaks present at actuator locations 1, 2 and 3 are highlighted. For both the PZT and microphone sensor configurations the additional peaks present due to the damage occurred at the same frequencies although the magnitude

![Graph](https://example.com/graph1.png)

![Graph](https://example.com/graph2.png)

Fig. 14. Frequency responses of beams with various levels of delamination compared to the undamaged specimen: (a) using PZT 8 as actuator and PZT 7 as sensor, (b) using acoustic response measured above PZT 8.
of the additional peaks compared to the other modes was
different between the PZT and acoustic responses. The first
additional peak occurred at 1650 Hz, which was slightly
lower in frequency than the 4th global mode of vibration
(1769 Hz). A second additional peak, although much less
prominent, can also be seen in the frequency response
curves at 7963 Hz. Evidently, the longer length of the
delaminated section compared to beam C (100 mm delam-
ination) produced local vibrations with lower natural
frequencies.

No additional peaks in the frequency responses were
observed for the beam with a 50 mm delamination, due
to the damage being relatively far from any actuator–
sensor pair, even though one tip of the delamination was
close to PZT 2. However, it is believed that if an actuator
was available close to the damage, secondary vibrations
would be readily detected. Indeed, the same phenomenon
was identified in a previous study using an instrumented
hammer as the actuator and an acoustic microphone as
the sensor [4].

Fig. 15. Large additional peaks appearing in the frequency responses of PZT 2 and PZT 3 pairs for the beam with 100 mm delamination: (a) PZT 2 used as actuator, (b) PZT 3 used as actuator. (One tip of the delamination was located between PZT 2 and PZT 3.)

Fig. 16. Frequency responses of beam with 150 mm delamination and PZT 2 as actuator, showing large additional peaks appearing at sensor locations PZT 1 and PZT 3. (The delamination covered an area approximately from PZT 1 to PZT 3.)
The experimental results showed that where global sensing is impractical due to the lack of a damage database either through accurate structural modelling or experimental testing, a localised technique can be used for the characterisation of damage. However, as with all localised techniques, this requires that actuators/sensors be available over the damaged area, necessitating a priori knowledge of likely structural ‘hot spots’. Consequently, an extensive optimised actuator/sensor network is required for the health monitoring of a large structure. The design of the actuator/sensor geometry requires consideration of the damage criticality characteristics of the structure.

For such a model-independent health monitoring system, a 2-stage approach may be employed for the characterisation of damage. Firstly, the monitoring system needs to establish whether damage is present; it would be a futile exercise attempting to characterise damage when none is present. This can be achieved by simple comparison of the most prominent higher-order natural frequencies with those of the healthy structure using any actuator–sensor pair. As shown by the experimental results, even actuator–sensor pairs remote from the damage are sensitive to the damage-induced changes to the global vibration modes. If the resonant frequencies of the condition-unknown structure fall outside of the boundaries of acceptable variations compared to the healthy reference, damage is deemed present. It is then a matter of examining the frequency response of each actuator–sensor pair for the presence of secondary resonances indicative of damage. This can be automated by the use of a simple computer program.

If a dense enough actuator/sensor network is available, characterisation of damage can be expected to be achievable with a high degree of accuracy. Evidently, the resolution and precision are limited by the actuator/sensor spacing, and the most efficient network design is one which achieves the required accuracy with the least number of elements. A system such as this can replace the traditional manual tap test to significantly reduce the labour and resource requirements of structural health assessment and greatly increase the speed of inspection. The model-independent nature of the technique allows its installation in a large variety of structures, whether during host manufacture or through retro-fitting.

5. Conclusion

The coin tap method currently used to manually inspect thick GFRP structures which is based on the audio and tactile perception of an experienced operator. The work
presented in this paper indicates that automation of this system is possible to detect and characterise (size and location) delaminations in thick GFRP structures.

Automated tap tests were applied to GFRP beams with various damage configurations using an array of eight surface-mounted piezoelectric elements. Two different methods were used to measure the response of the structure to the excitation, firstly one piezeolement was used as the actuator and the remaining seven as sensors to obtain the frequency response functions of the beam at various locations. A total of 56 transfer functions were obtained covering all actuator–sensor combinations using each piezoelement as the actuator in turn. For the second set of tests the piezoelements were used as micro-tappers in turn and the microphone was used to obtain the acoustic response directly over each actuator. A total of eight transfer functions were obtained for each beam.

It was found that the presence of the delaminations, manifested in the reduction of the natural frequencies, could be clearly detected using any actuator–sensor pair and acoustic response recorded at any non-nodal location on the beam even at actuator–sensor pair and non-nodal locations remote from the damage. Changes to the frequency responses were dependent on the damage configuration. Hence, if a large damage database is available either from high-fidelity structural modelling or extensive experimental testing, global damage characterisation can be achieved using only a small number of actuators and sensors.

However, where a damage database is unavailable, global detection cannot be achieved. In this case, damage characterisation may be based on the detection of localised damage-induced features in the form of secondary vibrations within the delaminated region. It was found that when both the actuator and sensor were in the close vicinity of the damage, large additional peaks in the frequency responses could be detected as a result of those secondary vibrations. Hence, the response of the actuator–sensor pairs can be compared with each other for the identification of damaged regions. This technique is more versatile in its application than global detection schemes, although an extensive optimised actuator/sensor network is required to cover a large structure.

PZT and microphone sensors systems are both suitable for application to an in-situ SHM system. The acoustic response was in general more sensitive to changes in the power spectrum as a result of the damage. This is due to the additional vibrational modes measured by the acoustic microphone. Microphone based sensor systems have the advantage that the sensors are not in contact with the structure and thus do not degrade due to fatigue stresses. The advantage of the PZT actuator–sensor system is that the PZT can alternate between the actuator and sensor function thus minimizing system components.

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