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ABSTRACT

Bonding of composite structures is regularly used in aerospace industry to restore structural integrity in repair or assemble sub-structures. This structural feature is prone to degradation with improper installation or disbond when submitted to fatigue or extreme strains. Therefore, non-destructive evaluation (NDE) should be considered to inspect adhesive bonded joints. In comparision with traditional NDE, a built-in structural health monitoring (SHM) would be more desirable to save the inspection cost as well as improve safety. The objective of this research is to evaluate integrity of composite bonded joints using guided wave propagation technique. Two carbon fiber reinforced polymer (CFRP) are bonded together using adhesive film and artificial disbond is introduced by a circular Teflon tape. A rectangular piezoceramic is used to generate plane guided waves and non-contact measurement is performed using 3-D Laser Doppler Vibrometer to extract the required information for evaluation of quality of bond line. Results have shown that the joint can be charactized using guided wave behavior; and reflection and transmision coefficients for incident A_0 and S_0 modes are extracted in order to design the final SHM system.

KEYWORDS : Composite bonded joint, Composite repair, Giuded wave propagation, Structural Health Monitoring(SHM), Disbond detection

INTRODUCTION

The use of composite materials in commercial aircraft primary structures has dramatically increased from nearly 5% in 1970 (Airbus 300) to about 50% in 2010 (Airbus 350, Boeing 787). This shift is primarily due to the tailorability of composite materials, which are lighter, stronger and can resist corrosion and fatigue damage better than traditional aluminum alloys. Despite enhancements in terms of specific strength and stiffness, susceptibility to hidden damage in composites is still a major point of concern. These types of damage in composite structures can significantly jeopardize their performance and safety with little advanced warning. The recognition of safety, integrity and durability as the principal priorities for engineered structures and materials has led to intensive research and development in the field of non-destructive evaluation (NDE) techniques. Over the last 50 years, NDE techniques (radioscopy, ultrasonic, shearography, etc.) have attained maturity in engineering practice, playing a significant role in evaluating the durability of engineered structures and are usually conducted at regular scheduled intervals during the lifetime of structures. However, they cannot provide efficient access to appropriate sections of the structures in a real-time manner and provide limited information about structural integrity. NDE techniques are now being retrofitted, with the aim of continuous/real-time and automated surveillance of the overall integrity of structures through consideration of working condition updates and structural ageing. This technology is termed structural health monitoring (SHM).

SHM is a major area of interest for the aerospace community, especially considering aging aircraft where the growing maintenance costs, estimated at $10.4 billion worldwide annually, can reduce their economic life. SHM systems replace scheduled maintenance with as-needed maintenance, thus save the cost of unnecessary maintenance, on one hand, and prevent unscheduled maintenance, on the other hand. It has been demonstrated that an effective SHM technique can reduce the total maintenance cost compared to traditional NDE approaches by more than 30% for an aircraft fleet [1]. It has been shown that life of the F-18 of the Canadian Air Force could be extended by 12 years, by monitoring the operational loads, thus leading to savings of 400 million Canadian dollars [2].

The objective of the proposed research is to provide SHM design criteria for disbond detection in composite bonded joints and repairs by developing a standard process to experimentally characterize guided wave propagation.

1 INSPECTION USING ULTRASONIC WAVES

1.1 Propagation of guided waves

Among different approaches of SHM, guided wave propagation has been proposed for effective monitoring of composite joint since it is fast, repeatable, sensitive to small damages and low cost [3]. The wave propagation methods usually make use of piezoelectric transducers to generate propagating waves and measure the signature of the echoes or change in the propagation characteristics that may be influenced by any inhomogeneity.

Guided waves (Lamb waves) were first described by H. Lamb [4] for homogeneous isotropic materials. They are ultrasonic waves that are guided between two parallel free surfaces, such as the upper and lower surfaces of a plate. Lamb waves can propagate in symmetrical or anti-symmetrical mode with respect to the neutral axis of the plate (Figure 1). Symmetric (S_i) modes predominantly have radial in-plane displacement of particles, Figure 1(a), while anti-symmetric (A_i) modes mostly have out-of-plane displacement, Figure 1(b). Therefore, a symmetric wave mode is often described as “compressional”, showing thickness bulging and contracting; and an anti-symmetric mode is known as “flexural” [3], presenting constant-thickness flexing, though higher-order anti-symmetric modes have increasingly complex through-thickness displacements

(a) (b)

Figure 1. Schematic illustrating the motion pattern of Lamb waves in a solid, (a) Symmetric mode and (b) Anti-symmetric mode.

Lamb waves are dispersive, and their velocities are dependent on wave frequency and plate thickness. This phenomenon is referred to as dispersion. Some literature papers have considered wave propagation in structures without concerning the interaction with the damage investigate the wave speed, (phase (C_p) and group (C_g) velocities [5]), its dispersion, attenuation with distance, slowness profile [6], and sensor arrangements and configuration [7] as well as material and geometry of structures.

In isotropic plates, Lamb waves travel with the same velocity in all directions and the wave front forms a circle. However, that is not the case in anisotropic materials such as fibre-reinforced composites, where the wave velocity is influenced by the direction of propagation [6].

1.2 Interaction of waves with damage

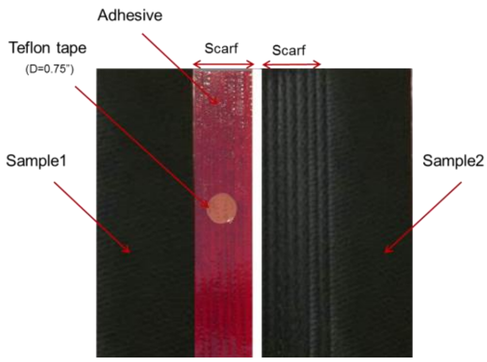
Interaction of Lamb waves with structural damage can significantly influence their propagation, such as reflection, transmission and mode conversion; and different locations and severity of damage can cause unique scattering phenomena. For instance, when incident S_0 mode encounters a delamination, a new wave mode, is generated, in addition to the transmitted and reflected S_0 waves. Differences in the location and severity of damage may produce unique energy scattering patterns [8]. From the changes in the amplitude ratio of the reflected waves and the arrival time (in the time domain analysis) of the new mode, it was found that this system can be used to evaluate the delamination length quantitatively [9].

For delamination [10, 11], impact-induced delamination [12-14], matrix cracks [15], thermal and fatigue effects [16], it has been shown that each discontinuity affects the wave scattering parameters. The location of damage can be determined by measuring the arrival time of scattered waves and its size is evaluated by degree of attenuation. However, guided wave propagation in bonded structures [17] was not investigated in detail, despite the fact that these features are very common in aircraft structures. The comparison between guided wave approach and other conventional approaches shows that the current commercial use of SHM system based on guided wave propagation still requires additional research to be optimized for damage detection of disbands in bonded composite structures [18].

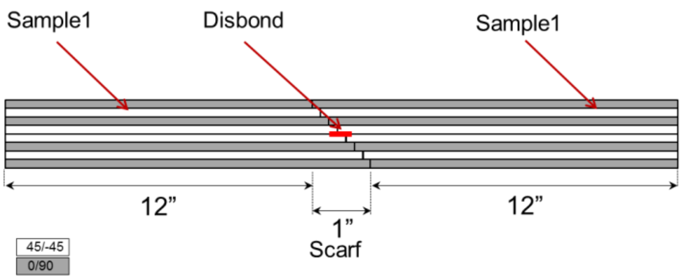
2 EXPERIMENTAL METHODOLOGY

2.1 Structure under consideration

Scarf or stepped joint are usually preferred for repair over external patches because of the excellent level of recovery of strength and minimum surface change in the outer-mould line. This configuration can be also typical representative for bonded assembly structures in aerospace industry. In this paper, two scarf panels made of OOA prepreg (Newport woven 321) with a quasi-isotropic layup $[0/90/-45/45]_{2s}$ are attached using adhesive film: Cytec FM® 300-2M. The total thickness of the sample is approximately 2.4 mm and the angle of the scarf is about 6 deg, such that 8 layers steps of 3 mm are used in order to form each sample (Figure 2).



(a)



(b)

Figure 2. Bonded joint configuration(a) two stepped samples (b) schematic view of the bonded samples

A circular disbond (0.75 inch diameter) is also introduced during manufacturing using Teflon tape (Figure 2). Since the Teflon is placed on the adhesive, and subsequently two samples attached together, the location of the defect is in the middle through thickness.

2.2 Experimental setup and validation in the composite plate

In order to characterize the wave behavior in the bonded structures independently on the actuator and avoid complex geometrical spread, a plane guided wave generator has been specially designed. For this purpose, two identical rectangular piezoceramics (5x50 mm) have been mounted in a clamped system, as described in Figure 3. This allows controlling independently the symmetrical and anti-symmetrical generation of guided wave in the structure. The generation of plane wave through rectangular piezoceramics allows directive generation and avoids geometrical spread of the wave as in the case of circular piezoceramics, such that the attenuation in the propagation direction is directly related to the damping in the material.

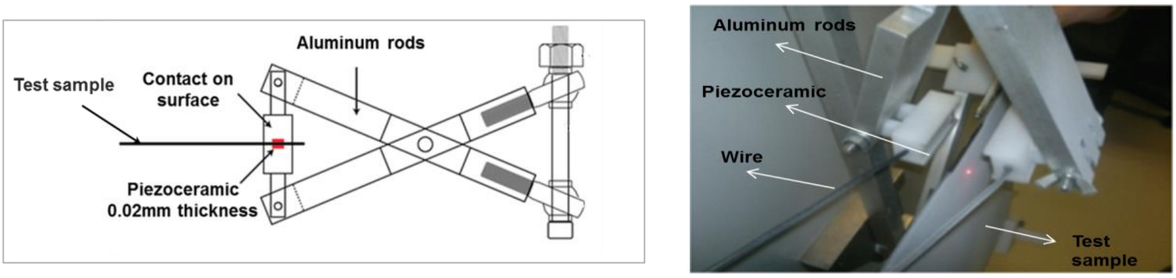


Figure 3. Schematic and actual illustration of the piezoceramic element.

Non-contact measurement of the in-plane and out-of plane velocity is performed using a 3-D Laser Doppler Vibrometer (PSV-500, Polytec GmbH, Waldbronn, Germany), as presented in Figure 4. The measurements of the transfer function between actuator voltage and the measured velocity over the 3 directions are taken over a linear grid of 300 points and the propagation characteristics are extracted using spatial Fourier transform as described in [19]. The space between two adjacent points is set at 0.5 mm in order to describe accurately the wave propagation up to 500 kHz, ensuring at least 5 points per wavelength.

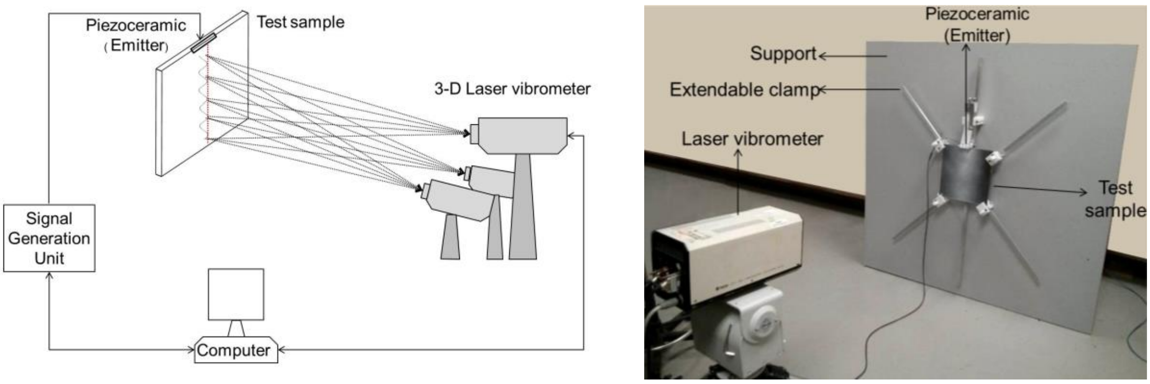


Figure 4. Schematic and actual illustration of the experimental set up.

Figure 5 presents the resulting Frequency/Wavenumber (f/k) transform for the 3 components of the velocity field and for a propagation following the x direction when the two co-localized piezoceramics are in phase (symmetrical excitation) and out-of phase (anti-symmetrical excitation). In this figure, it can be seen that S0 mode is amplified when considering symmetrical excitation and is mostly observed on the x component of the velocity. Also, as expected, A0 mode is naturally amplified when driving the 2 actuators out-of phase and is more observed in the z- component of the velocity field (out-of plane velocity). Damping is then extracted for each frequency by using a best fit model (damped sinusoid) and will be used for determination of reflection and transmission coefficients.

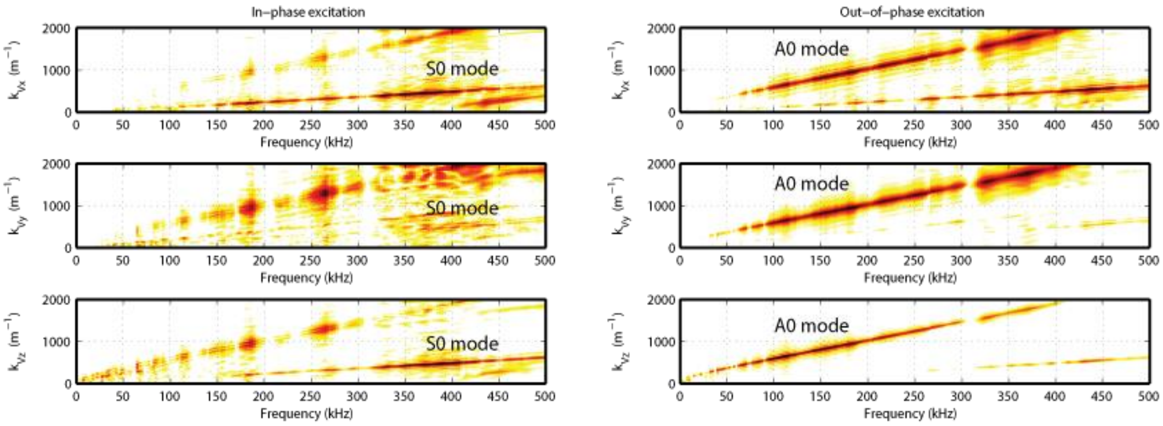
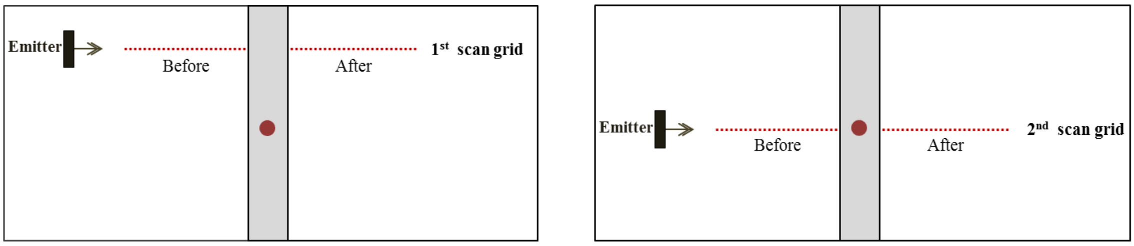


Figure 5. Frequency/Wavenumber transform for a propagating wave in the composite plate. Components in the x- (top), y- (middle) and z- direction (bottom) are presented in the case of in-phase excitation (left) and out-of phase excitation (right).

2.1 Reflection and transmission through the joint

The same procedure is used for characterization of guided waves through the joint. In this case, spatial Fourier transform is perform over a linear grid before and after the joint as presented in Figure 6. The same grid length and element spacing is used in order to obtain quantitative measurement of the reflected and transmitted energy at the joint section.



(a) (b)

Figure 6. Two linear scanning grid (a) pristine joint (b) joint with disbond

Mode reflection is performed by measuring the ratio of the incident amplitude over reflected amplitude on the (k,w) transform spectrums. The velocity in the x- direction is used for reflection and transmission of the S_0 mode while the out-of plane component (z direction) is used for characterization of the A_0 mode. The damping occurring in the bare plate is compensated in order to obtain the real energy reflection coefficient from the joint. Transmission is then estimated by computing the ratio of incident and transmitted wave energy and compensating by the damping through the joint.

Figure 7 shows the reflection and transmission of the guided waves with respect to frequency for the first scan grid (pristine joint) as presented in Figure 6(a). The reflection and transmission results are presented in light grey and a smoothed version is indicated in solid red or blue. The results show that S_0 is better transmitted through the joint, since it is less influenced by viscoelastic effect of adhesive. On the other hand, anti-symmetric mode is less transmitted and reflected rather than symmetric mode, since out-of-plane motion of particles is more attenuated upon encountering the adhesive. A small reflection peak is observed at 355 kHz and correlated with a reduction of transmission coefficient which corresponds to a wavenumber of approximately 1700 m^{-1}. This corresponds to a wavelength of 3.2 mm, which is approximately same as the length of increments steps between two adjacent prepreg layers. Thus, a reflection at the tip of each layer is observed and adding of each layer leads to the apparition of this reflection peak around 355 kHz.

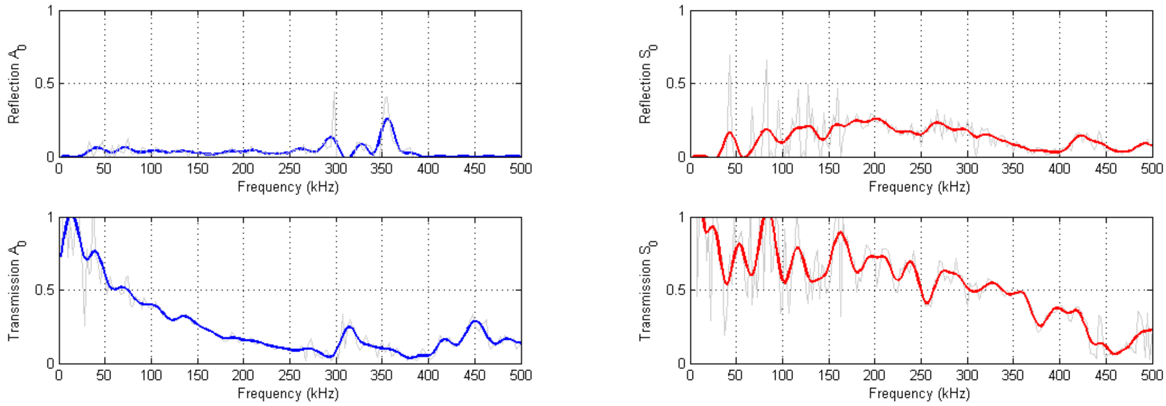


Figure 7. Joint characterization by reflection (top) and transmission (bottom) coefficients of A_0 (left) and S_0 (right) modes

The second scan was performed over a linear grid including the disbonded area; see Figure 6(b). The reflection and transmission coefficients are plotted with respect to the frequency in Figure 8. It is observed that the disbond decreases the transmission level in low frequencies for A_0 and S_0. Moreover, again the anti- symmetric mode is more attenuated by the presence of the disbond rather than symmetric mode. Therefore, the level of reflection and transmission of A_0 decreased and the peak around 355 kHz is no longer observed due to the presence of the disbond. Thus, for SHM system based on guided wave, the change of A_0 mode in transmission below 250 kHz and change of reflection coefficient around 355 kHz are potential modes and frequency ranges.

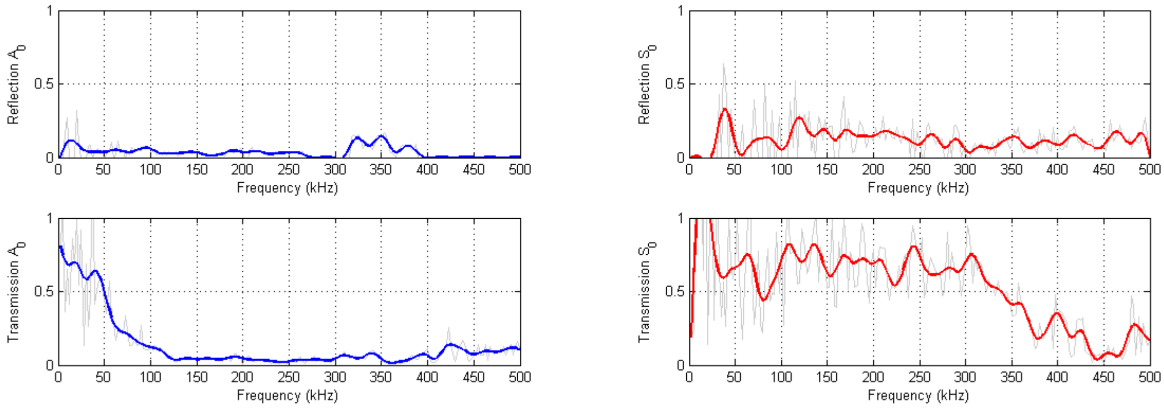


Figure 8. Disbond characterization by reflection (top) and transmission (bottom) coefficients of A_0 (left) and S_0 modes (right)

3 CONCLUSION

This research uses experimental methodology to investigate the propagation and interaction of guided waves in multi-layered composite bonded joint. The robustness of the set-up first validated for a simple composite plate and dispersion curve was extracted using spatial Fourier Transform. Concerning the bonded joint, the reflection and transmission coefficients are presented with respect to incident mode and frequency. Results show that guided wave propagation is affected by the joint and symmetric mode is more transmitted rather than anti-symmetric mode. The level of reflection and transmission of symmetric and anti-symmetric mode are different for pristine joint and disbonded area. Extension to oblique incident fields and diffraction patterns is left for future work.

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