Inspection of Bonded Repair Patches in Aircraft using Ultrasonic Guided Waves

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Abstract
Aircraft structures subject to service loads and chemical environments develop structural weaknesses like cracks, corrosion etc. In order to mitigate the resulting reduction in the useful service life of aircrafts, repairs are done in the form of adhesively bonding plates e.g. titanium plates bonded to aluminum fuselage. Typical of adhesive joints, these bonded repair patches also have interfacial (adhesive) or bulk (cohesive) weaknesses in the joint. Nondestructive inspection of these structures is required to ensure the quality of the repair patches. A systematic approach for the inspection of adhesive repair patches is demonstrated in this work. Among the multiple mode and frequency combinations possible in a structure, defect sensitive guided wave modes were selected from theoretical studies and verified successfully on epoxy bonded titanium-aluminum samples with simulated adhesive and cohesive weaknesses.

1. Introduction

Aircraft structures are subject to fatigue loading and chemical environments while in service leading to the formation of cracks, corrosion etc. In order to mitigate the resulting reduction in useful service life of aircrafts, repairs are done. Adhesively bonding metal or composite patches to the damaged surface of aircraft, after appropriate surface treatment, can improve the stiffness of the weakened part [1]. The adhesive bonding used is susceptible to interfacial (or adhesive) and bulk (or cohesive) defects, making nondestructive inspection essential in order to ascertain the quality of repairs. Practical cases of adhesive repairs can be found in the literature [2,3].

Recently, researchers have demonstrated a method for health monitoring of repairs using strain gages bonded to the aircraft skin and repair patch [2]. The ratio of strains was used to detect debonding between the skin and the repair patch.

Ultrasonic wave propagation through structures is dependent on the material elastic properties. Ultrasound provides a nondestructive means of adhesive bond quality assessment. Pilarski and Rose [4,5] have shown the importance of generating shear at the interface between the adhesive and adherend. This was an improvement of the bulk wave approach that needed very high frequencies (> 10 MHz).

Ultrasonic guided waves are special kinds of waves propagating primarily under the influence of the geometry and boundary conditions of a waveguide. They are characterized by dispersion which is captured in the form of phase and group velocity variation with frequency [4]. Rose and co-workers [6] have successfully demonstrated mode selection principles by employing modes from the overlap between dispersion curves of the individual plate that form the adhesive bond.

This study comprehends the progress made in mode selection for inspection of defects in an adhesive joint - titanium patch bonded to aluminum aircraft skin using epoxy. Bonded samples were prepared with controlled interfacial conditions simulating adhesive and cohesive weaknesses. Using the modes selected from the theoretical study, experiments were performed using wedge mounted piezoelectric transducers. With the collected waveforms the different conditions of weakness in the bond were identified successfully.

2. Guided wave mode selection

Ultrasonic guided wave dispersion curves provide the theoretically possible phase velocity and frequency combinations that can exist in a structure having free boundaries. The Lamb wave phase velocity and group velocity dispersion curves for a typical adhesive repair patch - epoxy (0.66 mm thick) bonded Titanium (1.6002 mm), Aluminum (3.175 mm) joint – is shown in Fig. 1. At every point on the phase velocity dispersion curves, the bonded geometry shows a unique cross-sectional vibration pattern – termed as the wavestructure. Since the repair patch geometry under study is not mid-plane symmetric, the modes are referred by numbers rather than the conventional Antisymmetric (A) or Symmetric (S) notation.

Each point on a dispersion curve has a unique wavestructure and it holds the potential to solve different inspection problems. In the literature there have been instances [6] where the guided wave mode selection has been carried out to address different defect detection scenarios.

In this work, the adhesive or interfacial defects possible at the aluminum-epoxy interface and also the cohesive or
bulk weakness in the epoxy layer are studied. In order to inspect the interfacial weaknesses at the aluminum-epoxy interface in the bonded repair patch, the in-plane displacement at that interface was used as the criterion. Figure 2 shows in grayscale the normalized interfacial in-plane displacement value superimposed on the guided wave modes.

In addition to the interfacial in-plane displacement feature, in order to simplify the interpretation of the experimentally measurements waveform, it is mostly preferred to have minimum number of modes excited within the structure. The guided wave mode selected should also have a smaller wavelength to improve sensitivity to smaller defects. The mode 18 (from Fig. 1), identified with an arrow in Fig. 2, at a higher phase velocity range (14-16 km/s) was thus selected for inspection of the bonded joint.

4. Experimental work and results

There are various techniques for exciting guided waves in structures for experimental work viz. acrylic wedge, oblique incidence in a water immersion mode, or a comb transducer with or without time delays. A variable angle acrylic wedge arrangement was adopted due to its ease of implementation and flexibility to generate guided wave modes at different phase velocities.

The mode identified in Fig. 2 (mode 18) was generated using a variable angle beam acrylic wedge set to an incidence angle of 10°.

3. Preparation of samples with simulated defects

In order to verify the theoretical work, small repair patch samples – i.e. epoxy bonded Titanium-Aluminum joint were created. Aerospace grade sheet epoxy – EA9696 was used as the adhesive. Defects were introduced at controlled depths in order to study the wave propagation across cohesive and adhesive weaknesses. Aluminum (3.175 mm) and Titanium (1.6002 mm) plate samples were polished using abrasive disc pads, cleaned with acetone followed by coating with sol-gel and water based primer.

For each repair patch, two epoxy layers were stacked between the prepared faces of the Aluminum and Titanium plates and cured under vacuum conditions with the application of appropriate pressure and temperature inside an autoclave. Square defects with 0.5” sides were introduced at the Aluminum-epoxy interface for creating adhesive weakness and between the layers of epoxy to create cohesive weakness. A folded strip of teflon was also suitably placed for creating both adhesive and cohesive weaknesses in the repair patch. A bubble wrap was used to create another instance of adhesive weakness.

Fig. 1 : Phase velocity and group velocity dispersion curves for bonded repair patch: Aluminum (3.175 mm)-Epoxy (0.66 mm)-Titanium (1.6002 mm). The guided wave modes are numbers in sequential order.

Fig. 2 : Normalized in-plane displacement value is shown superimposed over the dispersion curves for titanium-epoxy-aluminum joint. The arrow on top of the figure indicates the mode 18 – that has one of the highest in-plane displacements at the aluminum-epoxy interface.

Fig. 3 : Energy transmission from frequency sweep experiments using variable angle acrylic wedges adjusted to 10° incidence and reception angle in pitch-catch mode.
angle of 10°. Experiments were performed by arranging the wedge mounted transducers (2.25 MHz, and 12.7 mm in diameter) in pitch-catch configuration and varying the excitation frequency from 1 MHz to 3 MHz in steps of 50 kHz. The RF signals collected were squared and summed to obtain an energy quantity for each excitation signal in the range of frequencies 1 MHz and 3 MHz at 50 kHz intervals. A comparison of the variation in the transmitted energy quantity obtained from the frequency sweep experiments is shown in Fig. 3.

It can be observed from the Fig. 3 that the range of excitation frequencies - 2 to 2.5 MHz, with incidence and reception angles of 10°, is sensitive to the adhesive and cohesive defects simulated in the bonded repair patch samples. The transmission is maximum in the case of a good bond and minimum in the case of a cohesively weak bond. The energy transmission in the adhesive weakness cases lies between the two extremes. The variable angle wedges were replaced by small fixed angle wedges having the same incidence angle (10°), thus reducing the number of contacting interfaces between each of the transducers and the bonded plate by one from the initial count of three.

The signals collected in pitch-catch mode across the simulated defects using a pair of 2.25 MHz, 6.7 mm diameter commercial transducers mounted on fixed angle wedges is shown in Fig. 4. The pulse input to the transmitter was a tone burst cosine pulse at 2.5 MHz. The RF signals from Fig. 4 clearly show that the guided wave mode selected from the theoretical study was able to distinguish between the different cases of interface conditions simulated and a good joint among the repair patch samples fabricated.

Commercially available 2.25 MHz transducers were used as transmitter and receiver and tone burst input was supplied to the transmitter.

Conclusions

In this work, a promising systematic approach to selection of guided wave modes for the inspection of adhesive and cohesive weaknesses in an adhesively bonded repair patch, comprised of epoxy bonded aluminum and titanium repair patch, is presented. One of the guided wave modes with large in-plane displacement at the aluminum-epoxy interface in a titanium-epoxy-aluminum bonded joint was selected for the inspection. Several repair patch samples - epoxy bonded aluminum-titanium plates - were fabricated in the lab with simulated interfacial weakness conditions. Acrylic angle beam wedges set to an angle of 10°, with 2.25 MHz transducer mounted on top was found to be able to generate interface sensitive mode in the bonded repair patch. Using a matching receiver, it was possible to distinguish between the good and bad repairs.

References