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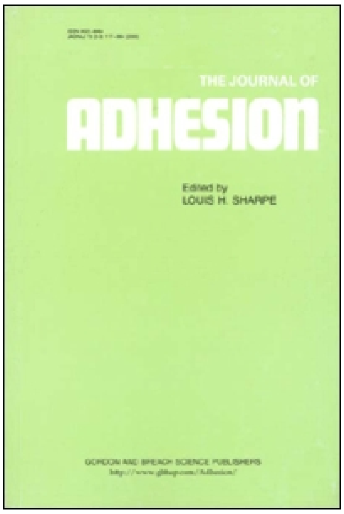

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J. L. Rose[a]; K. M. Rajana[a]; M. K. T. Hansch[a]
[a] The Pennsylvania State University, University Park, PA, USA

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Ultrasonic Guided Waves For NDE of Adhesively Bonded Structures*

J. L. ROSE, K. M. RAJANA and M. K. T. HANSCH

The Pennsylvania State University, 114 Hallowell Building, University Park, PA 16802, USA

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A rather sophisticated guided wave technology is introduced to solve a practical aging aircraft problem of delaminations and/or corrosion detection in either a lap splice joint or a tear strap. A Double Spring Hopping Probe is designed to achieve excellent contact on a curved aircraft structures. A guided wave resonance tuning concept for frequency is also discussed with respect to attaining reliable bond integrity measurements. A variety of experiments are discussed including experiments performed during the field trial on a Boeing 737-222 aircraft.

KEY WORDS: bond integrity; delamination detection; guided waves; Lamb waves

INTRODUCTION

Adhesively bonded metal-to-metal joints are used in many industries including, in particular, the aviation industry. The necessity of assuring solid bonds has led to several inspection techniques each with its own advantages and disadvantages.[1,2] One successful technique for inspecting adhesive bonds employs the use of ultrasound energy for the evaluation of bond quality. In principle, analysis of ultrasound waves after interaction with a bonded region will result in both qualitative and quantitative information regarding the bond.[3] Early attempts have utilized normal incident longitudinal and/or normal incident shear waves for inspecting the bondline, with shear waves providing improved sensitivity. Shear waves cause shearing forces along the adhesive-adherend interface thus improving sensitivity to bond quality.[4,5] Interface waves can provide us with an indication of strength and bond quality between the adhesive and the adherend, by introducing shear vibrations.[5] A promising method of introducing shear vibrations at the bondline is with the use of guided Lamb or horizontally-polarized (SH) waves.[6-8]

An interesting feature of using guided Lamb waves is the availability of two or more modes at any given product of frequency, f, and layer thickness, d. Following the development of the well-known Rayleigh-Lamb frequency equations and solving for the real roots, *i.e.*, the *phase velocities* for a given fd of the implicit transcendental functions, a set of classical dispersion curves can be obtained. Theoretical dispersion curves generated for an aluminum layer (with longitudinal and shear wave velocities of 6.3 and 3.1 mm/μ sec, respectively) are shown in Figure 1. The dispersion curves, based

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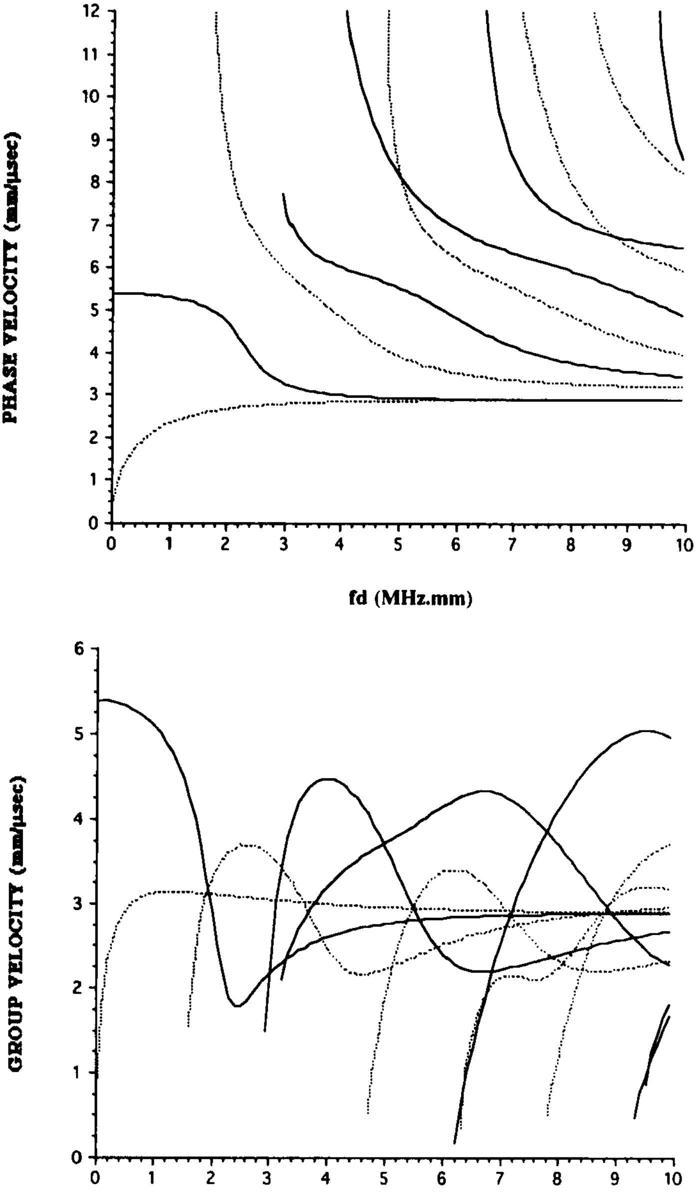


FIGURE 1 Phase and group velocity dispersion curves for aluminum single layer.

on analysis of the displacement distributions, can be identified as either symmetric or anti-symmetric. Symmetric modes have symmetric, in-plane displacement distributions about the midplane of the layer, while the anti-symmetric modes have anti-symmetric in-plane displacement distributions about the midplane of the layer. For an effective application of Lamb waves, two sets of dispersion curves are useful, namely phase velocity and group velocity. The phase velocity dispersion curves are useful for mode generation while the group velocity dispersion curves, for example, provide information on mode identification.

The utility of guided waves for the investigation of adhesive bonds is reviewed in this paper. Emphasis is on the development of a *Double Spring Hopping Probe* (DSHP) for data collection on bonded structures. The experimental results presented in this paper make use of the fundamental symmetric mode, S_0, at 1.455 MHz and the anti-symmetric mode, A_1, at 3.525 MHz. After several experiments on laboratory standard specimens, an opportunity was presented by the Federal Aviation Administration (FAA) to test the DSHP on the Boeing 737-222 test bed at the Aging Aircraft NDI Validation Center (AANC), Sandia National Laboratories, in Albuquerque, NM, USA. Many portions of the aircraft were tested and excellent results were obtained on lap splice joints and tear straps with delamination and corrosion.

DOUBLE SPRING HOPPING PROBE

Experimental results recently reported by the authors for guided wave inspection of bondlines made use of computer-controlled scanners.[7] However, it was required that a hand-held probe for random inspection of a bondline region of at least three square inches (6.45 cm^2) at one time be developed. The DSHP developed at the University Park campus of the Pennsylvania State University meets these requirements. The DSHP was designed to implement the guided wave concepts studied in this work with emphasis placed on the delamination problem. A description of the probe design is discussed in this section. Figure 2 shows the probe on an aircraft panel. This version, while fulfilling all initial requirements on flat structures, will also provide controlled flexibility on curved surfaces. In addition, the transducer holder design allows us to interchange transducers so that different central frequencies and bandwidths can be employed.

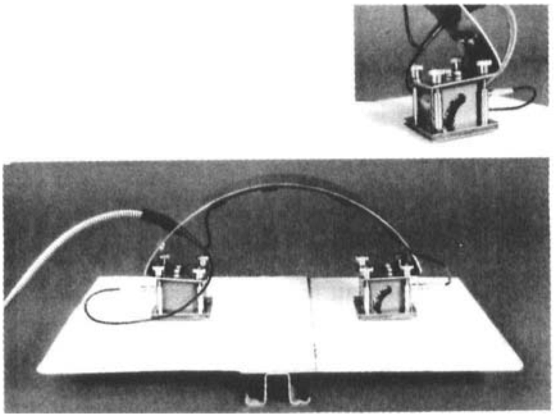


FIGURE 2 Photograph of DSHP showing variable angle beam probe and double spring holder.

Transducers

A pair of broadbanded variable angle beam transducers, manufactured by Krautkramer Branson, Lewistown, PA, USA, with element dimensions of 8 × 9 mm (0.31 × 0.35 inch) with 4.0 and 2.0 MHz central frequencies were employed. These transducers offer a great advantage over other off-the-shelf versions by eliminating the number of interfaces encountered by the UT wave before it strikes the skin of the aircraft. The transducer is housed in a metallic housing with a Plexiglas® delay block. Since frequency selection is critical for the Lamb wave technique, these transducers are equipped with piezocomposite elements. Unlike the traditional piezo ceramic element, the piezo composite is made of thin ceramic rods embedded in epoxy, thus forming a connectivity pattern of 1–3.[10] As such, these transducers offer excellent response to toneburst excitation. A function generator and a gated amplifier combination allows one to excite the transducers at chosen frequencies within the bandwidth limit. The piezo-composite element itself is housed in a fluid-filled chamber within a Plexiglas housing. The angle of incidence of the sound wave can be varied enabling one to obtain different phase velocities by using an angle adjustment on the housing. Worn out contact surface soles of the Plexiglas housing are also replaceable. The transducer is shown in Figure 2.

Double Spring Handle and Transducer Holders

As illustrated in Figure 2, the handle is made of spring steel which is fastened to the transducer holders *via* a softened spring steel. Force applied by the operator on the handle will enable the Plexiglas sole to contact the specimen in a two-step process. First, the soft spring allows the transducers to adjust to the specimen's face. Second, continued application of force by the operator redistributes the reaction forces thus enabling a good contact of the Plexiglas sole to the specimen. The softened spring connects the holders to the handle (Figure 2). The cables are drawn from one side along the inner surface of the handle and are protected in a flexible metallic sheath. The holders secure the position of the transducers during inspection and are provided with easy access screws for replacement. This arrangement reduces errors due to any transducer misalignment.

Bond Inspection on Laboratory Standards Using DSHP

It was demonstrated by Rose *et al.*[6,7] that the amplitudes of various Lamb wave modes showed good sensitivity to bond quality. The mode choice is based on an analysis of displacement distributions.[8] Sensitivity of the chosen modes to the bond quality in a pitch-catch arrangement employing the DSHP is demonstrated in this section. A tone burst excitation is used to generate effectively the modes of our choice. A block diagram of the experimental setup is shown in Figure 3. The continuous wave generated by a Hewlett-Packard function generator is gated by a Matec gated amplifier. This serves as an input for final amplification by the Matec power amplifier. Both the input and output RF-waveforms are monitored on a dual channel LeCroy oscilloscope. An NCR 486 computer is used for data acquisition from the scope. Using this setup two sets of specimens were studied.

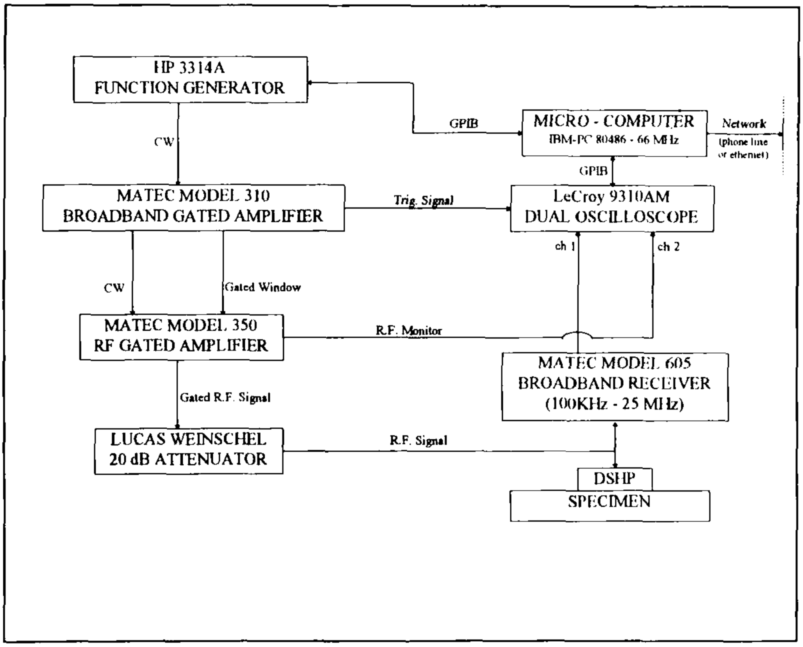


FIGURE 3 A block diagram of the tone burst excitation system.

The first specimen is a laboratory standard that simulates a lap splice joint, fabricated using two 1.0 mm (0.039 inch) thick aluminum plates which are adhesively bonded and riveted together. Overlap of the aluminum sheets was 76.2 mm (3 inches) and the rows of rivets were spaced at 25.4 mm (1 inch) intervals. The incident angle of the transducers was adjusted to 31° and the excitation frequency was tuned to 3.525 MHz using a Hewlett-Packard function generator. The DSHP was then placed on the single layer on each side of the bonded region. In order to confirm that the generated mode was indeed A_1, the group velocity was measured and compared with the theoretical value. Phase matching between two signals collected at differential distances was used to obtain the experimental value of 3.06 mm/μsec. Comparatively, the theoretical value is 3.08 mm/μsec yielding an error of just 0.65%.

The second specimen studied was an actual aircraft panel from the belly section of an aged commercial aircraft. The fundamental symmetric mode at 1.455 MHz, generated at a 30° angle of incidence, was used, employing transducers with 2.0 MHz center frequency. The experimental value of group velocity was measured as 4.379 mm/μsec. The theoretical value is 4.302 mm/μsec, yielding an error of 1.70%.

EXPERIMENTAL RESULTS

Figure 4 presents the loss in transmitted amplitude at each position on the specimen, with a schematic of the specimen on the right. The strip between the edge and the first

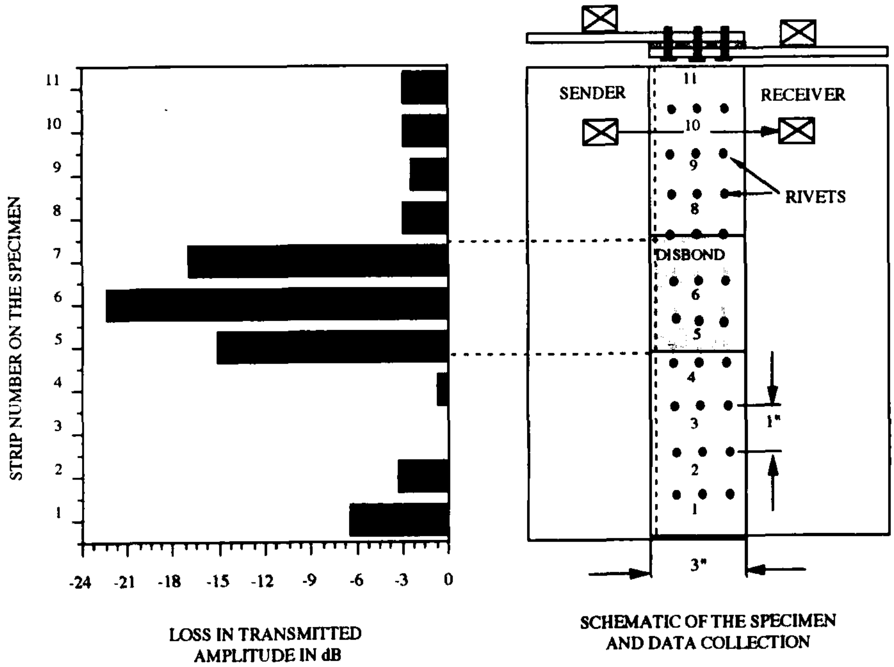


FIGURE 4 Sample results using DSHP showing 20 dB sensitivity for disbonds.

row of rivets is marked as 1, between the first and the second row of rivets as 2, and so on up to 11. Along strips 5–7 no adhesive is used, to simulate a disbonded region. Good adhesion is characterized by efficient energy transfer across the bond, and in this specimen the region across the third strip showed maximum transmission representing a perfect bond. Hence, this strip is used as a reference and the transmitted amplitudes across the rest of the strips are normalized and presented as a loss in transmission in a dB scale. The mean for the regions where there is good transmission of ultrasonic energy is around 2.5 dB. Strip 6 showed maximum loss in transmission (22.5 dB) and hence the sensitivity of the Lamb waves for disbond detection employing DSHP is approximately 20 dB.

In the second set of experiments that was performed on the aircraft panel from the belly section of an aged commercial aircraft, the goal was to detect a missing tear strap and lack of adhesion between the tear strap and the first layer. The tear strap is crucial to fuselage integrity, as it diverts the crack front from propagating along the entire lap slice joint, thus causing a local failure only. The specimen was taken from an aircraft with natural curvature and multiple coats of paint. It was demonstrated by the authors that the presence of paint on the aluminum skin will influence every mode to a certain extent, but the S_0 mode is least affected.[11] The angle of incidence was adjusted to 30° to generate S_0 at 1.455 MHz using a transducer with 2.0 MHz central frequency. Good adhesion between the tear strap and top layer is associated with a loss of transmitted amplitude due to the fact that the energy leaks into the tear strap. Sample RF-waveforms for a well-bonded region and a disbonded region are presented in Figure 5.

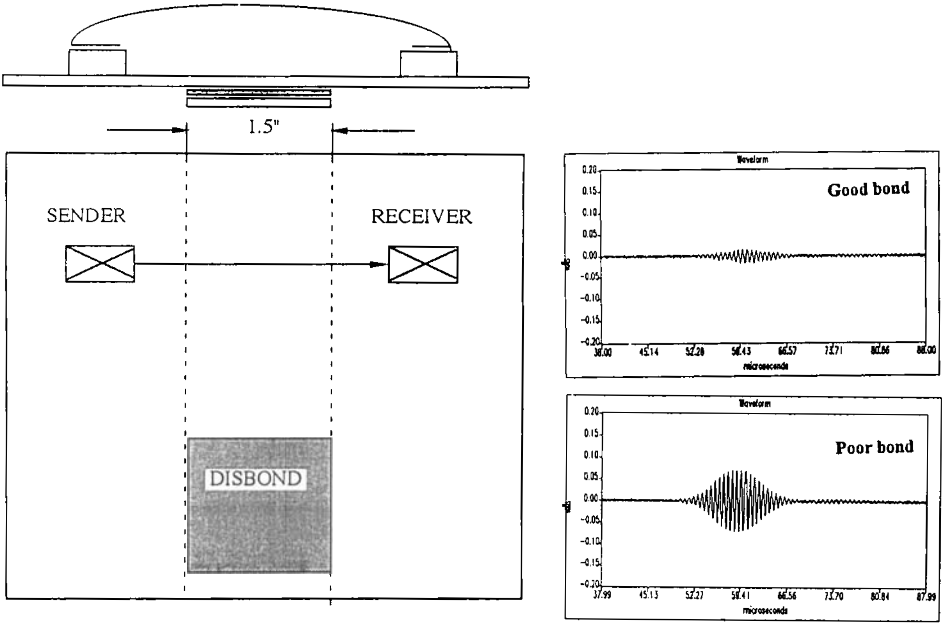


FIGURE 5 Sample RF-waveforms acquired on a aircraft panel of an aged aircraft showing lack of adhesion between the tear strap and first layer. (14 dB sensitivity for poor bonds).

The disbonded region showed a 14 dB improvement using the amplitude of the signal acquired along the good region as reference.

BOND INSPECTION USING THE DSHP DURING FIELD TRIALS

Success on laboratory standards and service damaged panels has led to a field test in Albuquerque, NM, USA. Presented in Figure 6 is the DSHP inspecting a lap splice

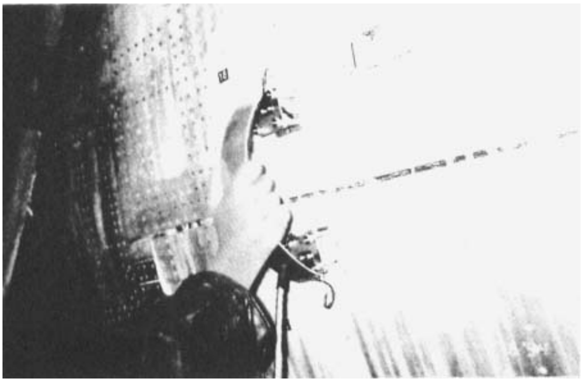
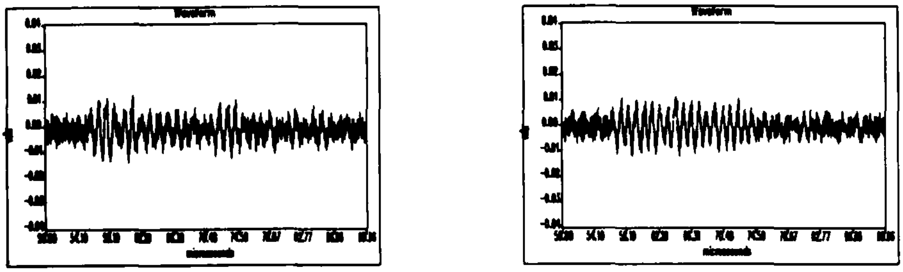
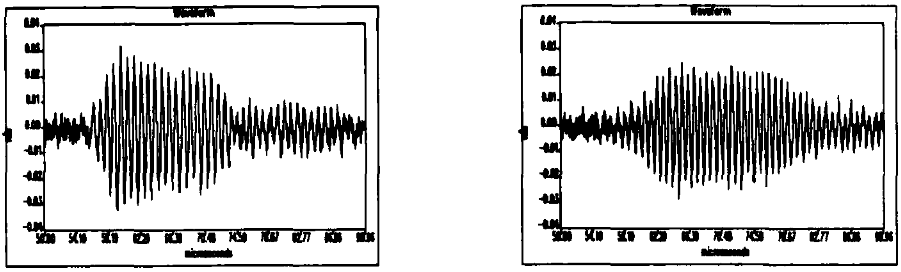


FIGURE 6 Testing a lap splice joint of a Boeing 737-222 using Double Spring Hopping Probe.



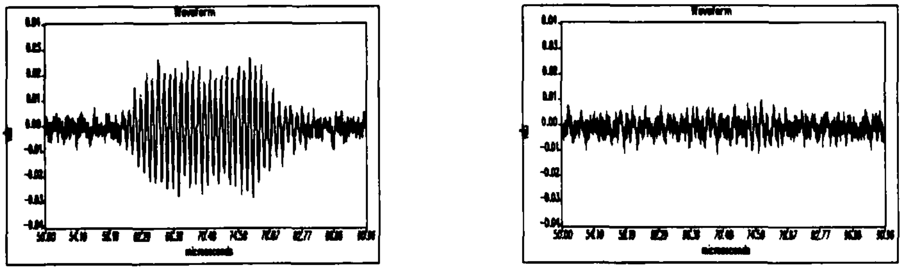
FREQUENCY = 0.875 MHz

FREQUENCY = 1.000 MHz



FREQUENCY = 1.125 MHz

FREQUENCY = 1.250 MHz

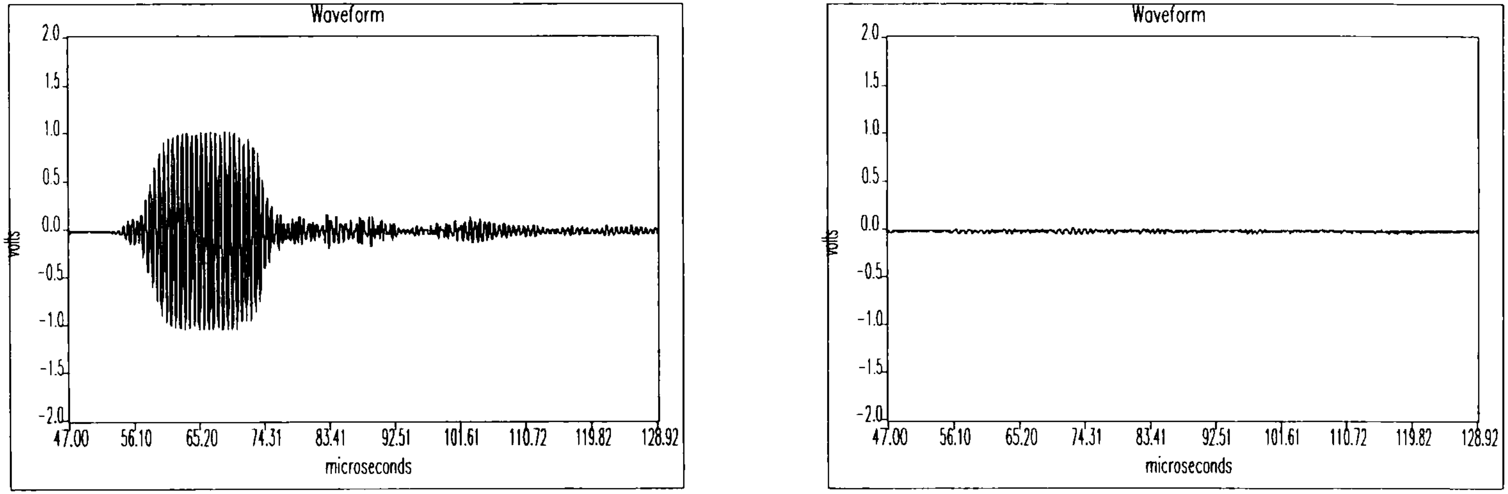


FREQUENCY = 1.375 MHz

FREQUENCY = 1.500 MHz

FIGURE 7 Influence of the frequency perturbation in the vicinity of S_0 mode.

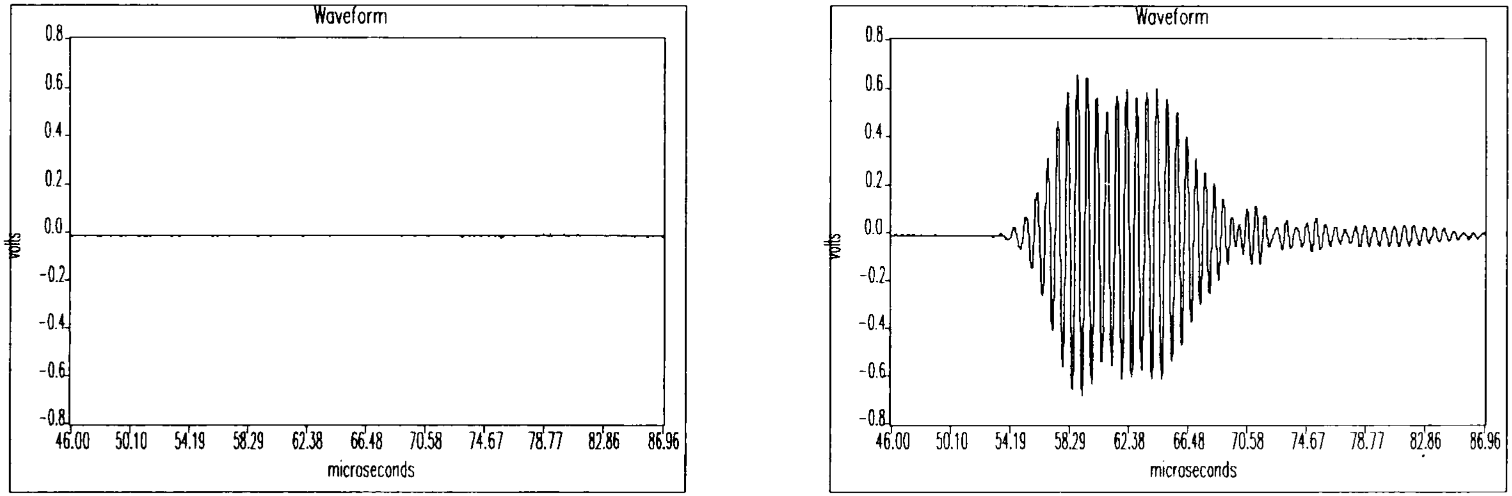
joint of a Boeing 732–222. The angle of incidence of the transducers was adjusted to 31° and the excitation frequency was tuned to 1.38 MHz using a function generator. One of the major goals of our work efforts during the field trials at the Sandia National Laboratories, was the evaluation of various lap splice joints and tear straps over the entire aircraft. The basic goal for this work was to generate a specific Lamb wave mode on one side of the lap splice joint, and then to propagate across a well-bonded structure,



a. Good bond

b. Poor bond

FIGURE 8 Sample RF-waveforms from a lap splice joint.



a. Good bond

b. Poor bond

FIGURE 9 Sample RF-waveforms from a bonded tear strap.

despite any mode conversion and energy transmission loss that might occur. If, for some reason, delamination or corrosion were present that would produce air gaps and inefficient energy transmission, then, indeed, regardless of the mode generated on the sending side of the lap splice, an insufficient amount of energy would travel across the joint. A resonance tuning or calibration techniques were employed in a pitch-catch configuration across a region tested to be defect free by other techniques. If the system under interrogation were to be asymmetric, *e.g.*, due to different plate thickness, angle adjustment would be necessary on the receiving side.[12] The results describing this frequency perturbation or calibration technique is shown in Figure 7. Note that the signal-to-noise ratio (SNR) was poor for the waveform characteristic at a 0.875 MHz frequency. If the calibration were not performed, this signal might be the one used to look at the wave transmission across the lap joint, thus giving misleading results. The SNR improves progressively as the frequency is increased to 1.375 MHz. Finally, at 1.375 MHz, for this specimen and system geometry, the best SNR was obtained. However, a further increase in frequency will result in a poor SNR as illustrated by the RF-waveforms. It may be pointed out that if the bond quality were to be poor, irrespective of the excitation frequency the SNR will be low.

Experimental results obtained by the guided wave approach using the DSHP were compared with the data obtained using optical D-sight[13] techniques provided to us by AANC at the Sandia National Laboratory. In most cases, excellent agreement is achieved along all 147 data sets acquired at random sections over the entire airplane. The DSHP showed excellent high flexibility in adapting to the curve surface of the aircraft skin without losing coupling. Sample results acquired from a good region and a poorly-bonded region of a lap splice joint are shown in Figure 8. The detection of corroded tear straps and of a lack of adhesion between the tear strap and the first layer is also studied. Good adhesion between the tear strap and top layer is associated with a loss of transmitted signal amplitude, while a lack of adhesion and missing tear strap results in improved transmission. Sample results are presented in Figure 9.

CONCLUSIONS

Preliminary test results using the DSHP for disbond detection in adhesively-bonded joints have been presented. Versatility of the Lamb wave technique and implementation of the DSHP to handle different specimen geometries is demonstrated. Painted structures often rapidly attenuate higher order modes, but the fundamental symmetric mode has penetration power and good sensitivity to defect detection. For disbond detection in through transmission, the sensitivity is in the range of 20 to 33 dB. Proof of the inspection capability of the portable hand held guided wave probe assembly, DSHP, has been demonstrated in a number of different test situations. The DSHP performed well while interrogating both lap splice and tear straps. The curvature variations along the length of the aircraft from nose to tail was handled well. Excellent results were obtained along the lap splice of the aircraft and the areas of severe corrosion were clearly pointed out. Plate thinning due to corrosion and cracks in the first and second layers was also detected using the S_0 mode. Additional work to handle structural variations on the aircraft must be carried out.

Acknowledgments

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