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Ultrasonic Guided Waves for Anomaly Detection in Aircraft Components

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ABSTRACT

Ultrasonic guided waves are considered for the testing of various components used in the aircraft industry. Natural wave guides are present on many aircraft components. Subsequently, guided waves can be used to test hard to access areas quite easily. Guided waves are also ideal for applications involving large areas of testing, as well as cases where direct access to a specific component is not possible. A test protocol for crack and anomaly testing in specific parts is developed. Phase velocity and frequency tuning are used to excite specific points on the dispersion curves. By exciting these so called transient resonant modes, it becomes possible to detect anomalies in different mechanical components and structures.

Cracks in helicopter blade models were detected with guided waves. Corrosion and cracks in multilayer media and cracks in landing gear models were also studied. Other investigated problems in this work involve the detection of fuselage wall thinning, the integrity of tear strap assemblies, the debonding of skin to core in honeycomb structures, and the debonding of joints, specifically lap splice joints.

Keywords: *ultrasonic guided waves, aircraft testing.*

INTRODUCTION

Guided waves are currently being explored for corrosion and crack detection in aircraft structures. Ultrasonic energy can be concentrated or guided to particular zones of interest, and information on the structure's condition obtained (Ditri et al., 1991). For an introduction to the phase velocity and tuning concept, see Shin and Rose (1998). Testing of a 747 tear strap is discussed by Rose and Barshinger (1997). General bonding issues with guided waves are previewed in Rose et al. (1995). Recent hidden corrosion detection and modeling efforts have also been discussed in previous work (Zhu et al., 1998; Rose et al, 1998; Zhu et al., 1998b; Rose et al., 1998). For general background and theoretical aspects of guided waves, see Rose (1999). Several sample problems are discussed in this paper including fuselage wall thinning, lap splice joint testing, tear strap testing, honeycomb structures, helicopter blades, and landing gears.

DATA ACQUISITION

Each point of the dispersion curves represents a different resonance pattern or guided wave mode and frequency. Each mode has specific attributes such as wave structure and energy distribution that make it unique. For example, some guided wave modes are sensitive to coatings, because the energy is concentrated on the surface. Other modes are sensitive to internal voids or cracks, others to surface cracks, and so on.

A complete guided wave test calls for flexibility in mode selection. A Matec tone burst system allows for frequency scanning. Piezocomposite transducers have a broadbanded bandwidth, which makes it possible to drive them at a frequency other than their central or natural one with the use of a tone burst unit. The unit outputs a gated sinusoid whose frequency and number of cycles can be controlled independently.

The other variable that needs to be controlled in a guided wave analysis is the phase velocity. This can be achieved by varying the incidence angle of the transducer, such as a piezocomposite transducer mounted on a variable-angle acrylic wedge. The angle of the wedge can be adjusted to activate different phase velocity lines in the dispersion curve (see Figure 1).

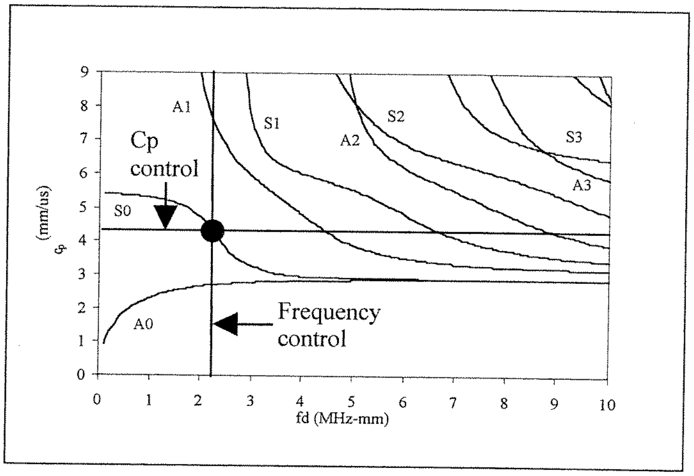

Figure 1 — Tuning process displayed on the dispersion curves.

By controlling both frequency and phase velocity, different guided wave modes can be excited. The understanding of the physics and mathematics of wave propagation theory are fundamental tools for mode selection. Observation and analysis of different resonance patterns, particle displacement profiles, and energy distribution diagrams make it possible to select modes that suit specific guided wave applications. The horizontal line controls the phase velocity, c_p, and the vertical line controls the frequency.

EXPERIMENTAL

Fuselage Wall Thinning

Fuselage wall thinning is a common phenomenon in aging aircraft. The fuselage, commonly made out of an aluminum alloy, degrades with time, resulting in a thinner structure. Guided waves offer a convenient NDT method for fuselage testing because they can travel long distances along the material. Consequently, large zones can be tested without having the necessity of moving the probe each time, avoiding traditional point by point testing. Since the aluminum skin of the fuselage is a natural wave guide, guided waves can travel from one point to another along curvatures and complex geometries.

Two transducers are placed on the surface, one acting as a transmitter and the other as a receiver. A guided wave is produced by setting the appropriate incidence angle and frequency. This guided wave, which is created due to the interference phenomena of longitudinal and shear modes bouncing inside the material, contains a

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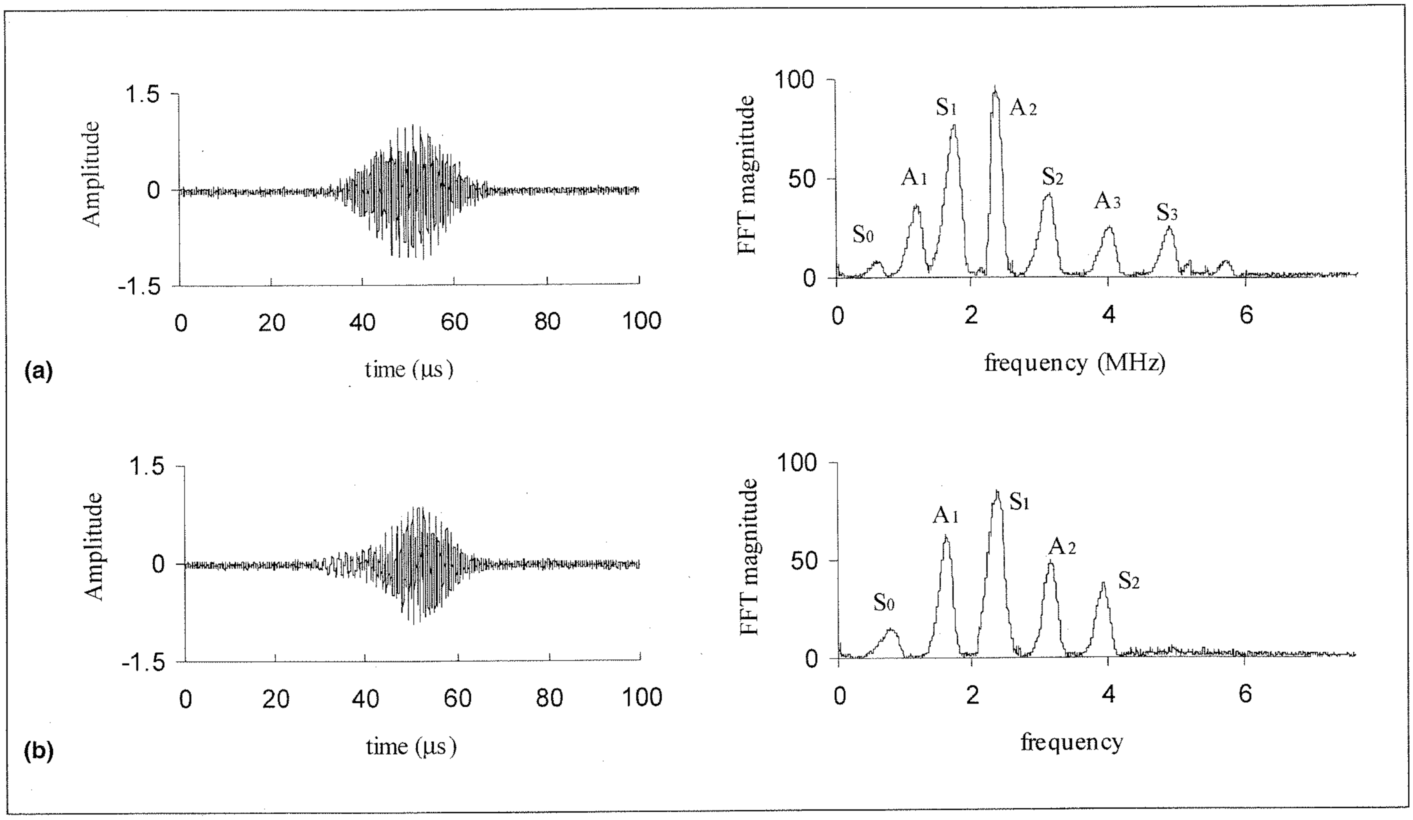

Figure 2 — Radio frequency signals and fast Fourier transforms recorded for two plates of different thickness.

band of frequencies. The superposition of these frequencies constitutes the guided wave as a whole. By looking at the frequency content of the signal it is possible to extract information about the guided wave being generated and its dependence on the thickness. A device can be used to generate a guided wave easily. The probe holds the two transducers at a fixed relative position, and the double spring arrangement allows for hopping, which allows the transducers to remain at a fixed distance and work on curved surfaces. Some sample results are shown in Figure 2 for two aluminum plates of different thickness. The signal and its corresponding fast Fourier transform are shown.

Either a shock excitation system or a tone burst with a few cycles can be used to excite a large area of the dispersion curves. The data presented here was obtained by using through transmission with 1.5 MHz transducers at an incidence angle of 31 degrees. The thicker plate can carry more modes since a larger *f-d* product and is excited on the dispersion curves.

The frequency thickness dependence can be evidenced by comparison of the fast Fourier transforms and the dispersion curves. The distance between peaks in megahertz measured on the fast Fourier transform is proportional to the distance in megahertz-millimeter measured on the dispersion curves along a horizontal line. The horizontal line is established through the incidence angle selected. So, by knowing the incidence angle and the natural frequency of the transducer, the thickness of a fuselage section can be determined by looking at the frequency content of the signal.

Lap Splice Joints

Lap splice joints, commonly found in the aircraft industry, are other structures that can be easily tested with guided waves. By using through transmission, the ultrasonic guided waves travel across the joint; a guided wave is generated by a transducer mounted on one of the plates. The wave then leaks into the bond and passes on to the other plate, where it is received by the other transducer. The amount of energy that leaks into the bond can be controlled by varying the incidence angle. Also by tuning frequency, different bonds can be tested on different plates with different thickness. Since a guided wave is composed of both in and out of plane modes, the test is very sensitive to adhesion problems. If the quality of the bond is poor, very little or no energy will leak into the bond, resulting in a low amplitude signal.

Although the testing strategy is simple, care must be taken to include tuning and not to select a mode and frequency with insufficient energy at the lower surface of body one, which would give a false indication of a poorly bonded lap splice joint. A double spring hopping probe can be used conveniently in the testing of lap splice joints. The springs on both sides of the probe provide the flexibility to test different joints and curvatures.

The results of a sample test are shown in Figure 3. The data presented here was obtained by using 1.5 MHz transducers in through

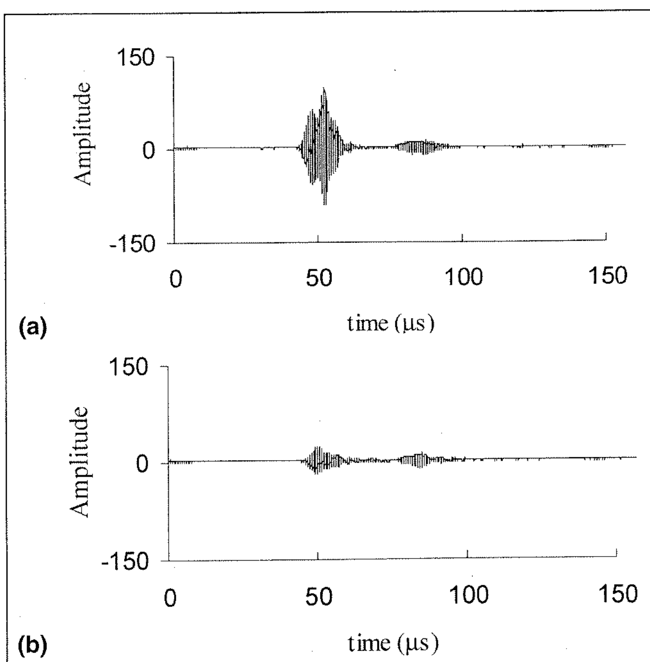

Figure 3 — Signal of a lap splice joint test showing good and poor results.

transmission mode driven with a tone burst system. An incidence angle of 31 degrees was used. A frequency close to the central frequency of the transducer displays nicely on screen. Shock excitation also works. Notice the difference in the signals recorded for a good bonded region and a poorly bonded one. The rivets do not cause any serious problem in data interpretation because a through transmission test mode is used for the testing. Note the severe reductions in amplitude for the poorly bonded case.

Tear Strap

Guided waves are also ideal for tear strap testing for many reasons. The skin of the aircraft is a natural wave guide and allows the energy to propagate efficiently. Since the tear strap is located on the inside part of the structure, access to it is not easy for traditional testing methods. Guided waves, on the other hand, show great flexibility. The energy can be launched from the outside part of the structure and forced into the inside by selecting a convenient resonance pattern. The pulse echo mode is used for this test protocol, and reflections of the strap are received on the oscilloscope. Again, one must use care to ensure that sufficient energy is available at the bottom of the skin.

A tear strap is usually bonded onto the inside surface of the skin. The results of a tear strap sample tested using guided waves are shown in Figure 4. Notice the multiple reflections obtained in the signal. They are due to the several edges of the specimen, including the free edge. By setting a gate on the signal it is possible to distinguish all the different echoes. Figure 4a shows the signal for a good bonded region. Notice the two sharp peaks inside the gate. In Figure 4b, the first edge of the strap is debonded; the first spike does not show up. Finally, Figure 4c shows the signal recorded for the totally debonded region. Notice how no reflections of the strap show up inside the gate. By frequency and angle tuning, different tear strap configurations may be tested. We try to obtain large echoes inside the gate, as illustrated. Pulse echo mode at a frequency of 1 MHz and an incidence angle of 45 degrees was used.

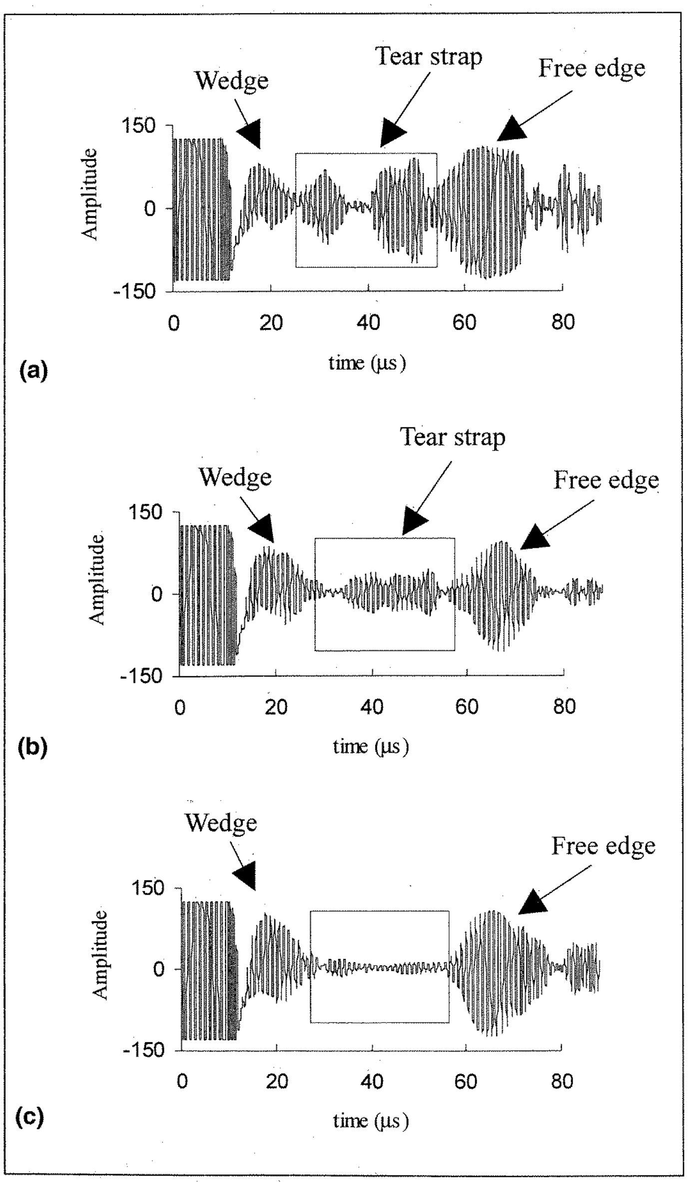

Figure 4 — Ultrasonic signals for a sample tear strap test (pulse echo).

Honeycomb Structures

Honeycomb structures lend themselves nicely to guided wave testing because the skin is a natural wave guide. Rather than carry out tedious point by point traditional longitudinal wave testing, which may not even have the sensitivity, guided waves can test larger zones. We control the amount of energy leakage into the core. Special modes have wave structures amenable to more or less leakage into the core.

Because of its relatively low weight to strength ratio, honeycomb is a very common structure used in the aircraft industry. This structure consists of two thin plates bonded together to a honeycomb core, with the use of an adhesive. The honeycomb core, as the word suggests, consists of a lightweight aluminum arranged in a hexagonal honeycomb fashion. The outer plates can consist of aluminum and/or some type of composite material, depending on the application. The final structure obtained possesses a very high stiffness and is very lightweight.

Honeycomb structures deteriorate after some cycles of operation, especially when subjected to certain environmental states. Corrosion of the core and adhesion problems between skin and core lead to debonding. This causes the structure to lose its properties, and, in some cases, catastrophic failure.

Ultrasonic guided waves have shown excellent results in the testing of honeycomb structures. Two ultrasonic probes are placed at some fixed distance from each other for through transmission. The guided wave generated by one transducer travels through the material and is then received by the other one. The ultrasonic signal can be displayed on an oscilloscope. Figure 5 shows the comparison

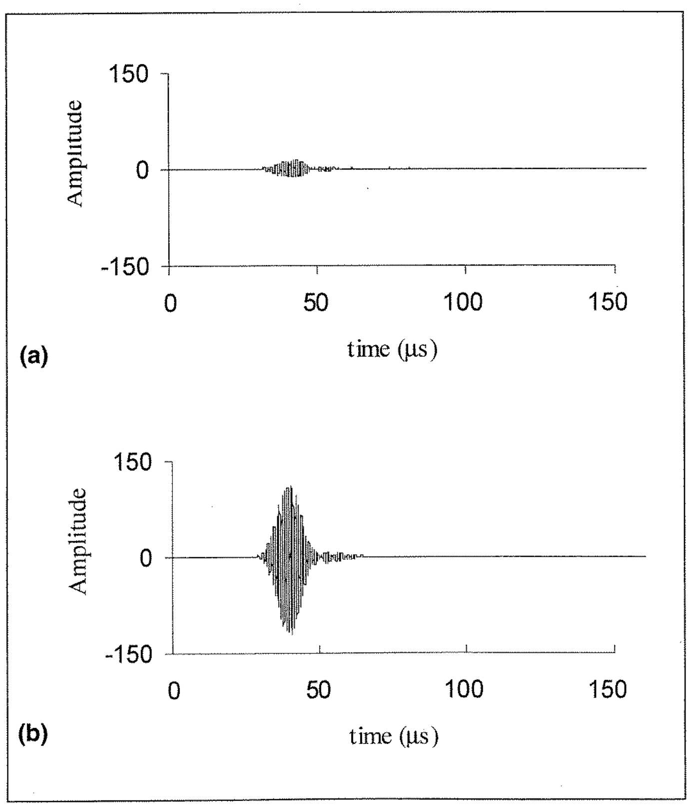

Figure 5 — Ultrasonic signals for a good and a bad skin to core bond in a honeycomb structure.

between a good and a bad bond. Through transmission mode with an incidence angle of 45 degrees and a frequency of 1.1 MHz was used. Notice that when the bond is good, the ultrasonic energy leaks into the core, resulting in a low amplitude signal. When the bond is poor, the guided wave travels with a high concentration of energy along the plate, and hence the received signal has bigger amplitude.

Helicopter Blades

The cracking of helicopter blades is another problem that can readily be tackled by guided waves. The ability of guided waves to travel long distances becomes the key factor when dealing with large areas of testing. By selecting the right frequency and angle, a special wave mode capable of traveling through the material without significant loss is generated. Hence, the whole length of the blade can be tested by placing the ultrasonic probe at a fixed position, where access is possible.

Traditional testing methods require the disassembly of components, which is expensive and laborious. Helicopters have to be parked in hangars for testing on a regular basis. Guided wave testing offers a solution to this problem, since the energy can be conveniently focused to specific regions of interest.

The cracks encountered in the field are transversely oriented, as shown in Figure 6. These small cracks can grow very rapidly, leading to sudden failure. The blades also have plastic covers on top of the aluminum that provide the aerodynamics for flying (see Figure 7). Current testing methods require the removal of these covers in order to have access to cracks occuring underneath. Guided waves are also capable of sneaking under these covers.

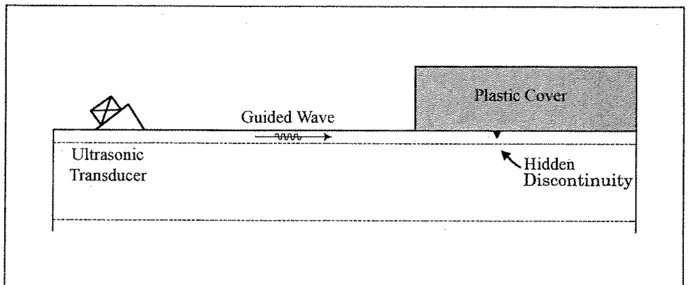

Figure 6 — Ultrasonic guided wave testing approach for finding hidden transverse cracks under the aerodynamic cover of a helicopter blade.

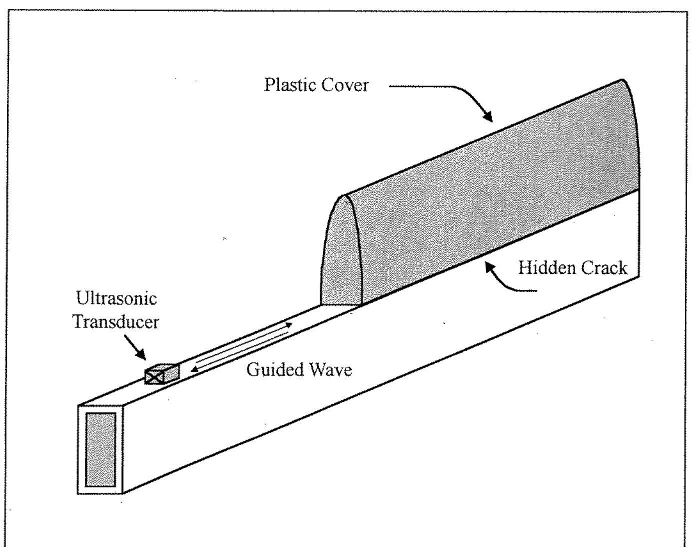

Figure 7 — Proposed guided wave testing technique for transverse cracking in a helicopter blade.

The length of the sample aluminum blade is 1.5 m (5 ft). The ultrasonic probe is placed on one end of the blade. The pulse echo mode is then used to create a guided wave that travels along the blade and comes back to the transducer when it encounters an anomaly. Once the guided wave mode is selected, the velocity of propagation (group velocity) is known. The time of flight can be measured, and the position of the crack can be determined with great accuracy. For calibration purposes, a reflection or echo from the end of the blade is first measured, as depicted in Figure 8a. The transducer is 0.76 m (2.5 ft) away from the end of the blade. The next step is to set up a gate on the screen and search for anomalies within it. Figure 8b shows a crack located 0.46 m (1.5 ft) away from the transducer. Since the group velocity is constant, the position of a crack can be easily located by proportionality. In other words, after calibration, the time scale on the screen is proportional to the length of the specimen.

Painted specimens were also studied since paint is used in the field to prevent corrosion. The ultrasonic signal generated in the painted specimen is shown in Figure 8c. The paint causes the signal to attenuate slightly, but the anomaly can still be detected. Figure 9a

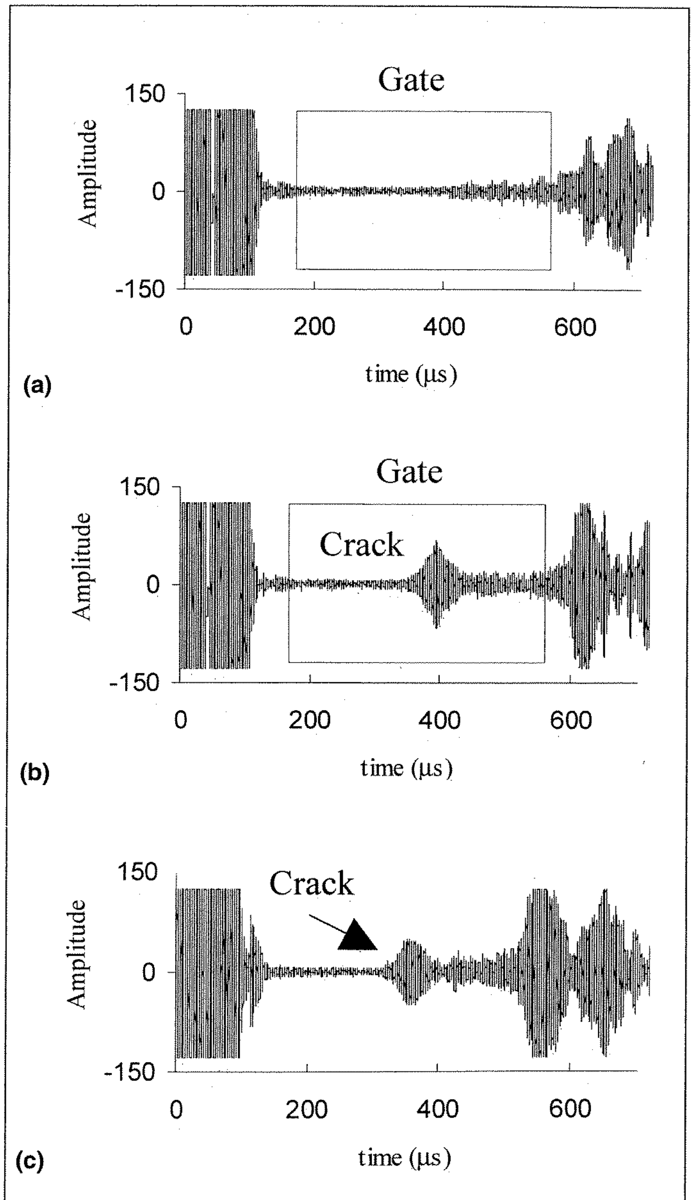

Figure 8 — Data recorded for a partial crack (0.46 m [1.5 ft] away): (a) reference signal showing an echo from the end of the blade (calibration for 0.76 m [2.5 ft]); (b) crack detected within the gate (0.46 m [1.5 ft] away from probe), same case as (b) for a painted specimen.

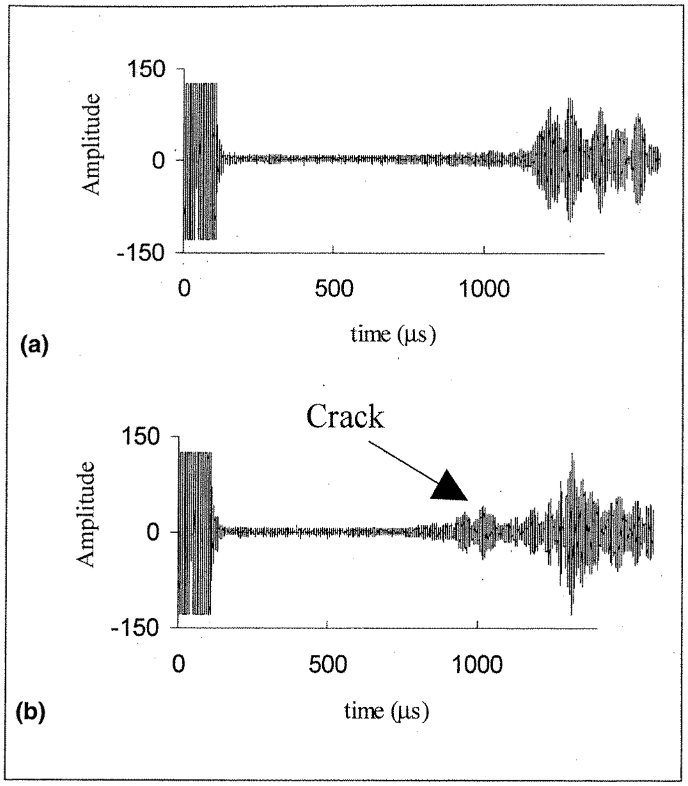

Figure 9 — Data recorded for a partial crack (1.2 m [4 ft] away): (a) reference signal showing an echo from the end of the blade, now at a different distance (calibration for 1.5 m [5 ft]); (b) crack detected within the gate (1.2 m [4 ft] away from probe).

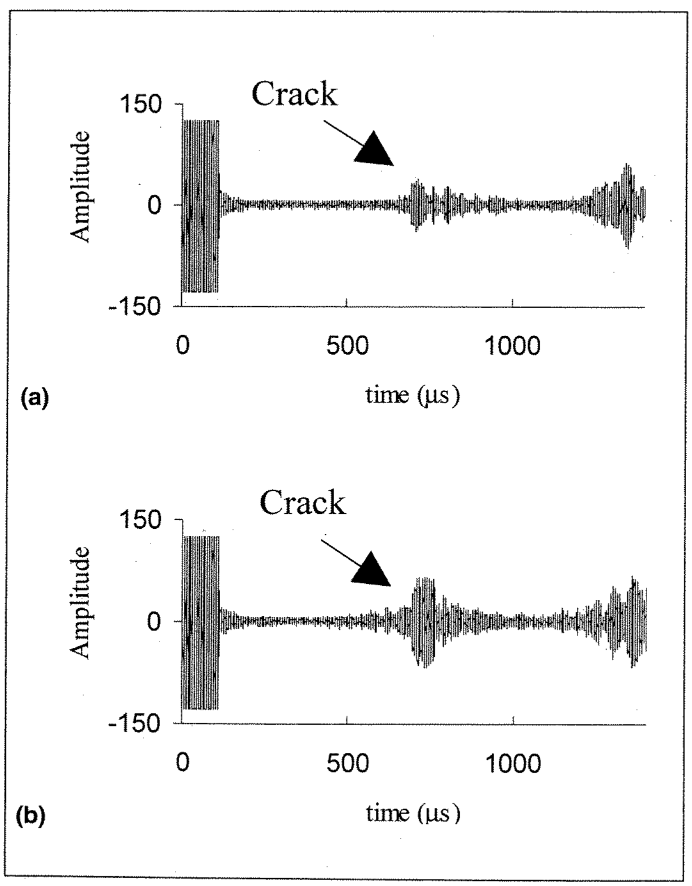

Figure 10 — Crack with and without the cover (0.9 m [3 ft] away).

is the reference signal when the transducer is placed at the end of the specimen. The crack is shown in Figure 9b. Sensitivity studies on crack size detectability must still be studied for the real helicopter blades.

The detection of a full crack is considered in Figure 10. This time the crack was placed underneath the aerodynamic cover. Signal a shows the crack under the cover. Signal b was taken without the cover. The acrylic cover used in this model was coupled to the aluminum with petroleum jelly and/or mineral oil, for comparison purposes. A conservative approach was used in this study since the coupling found in industry, achieved mostly by rivets, is easier to test. The signal received from the crack under the aerodynamic cover is attenuated, but the presence of the crack is still noticeable.

Since different crack sizes create different resonance patterns resulting in different wave modes, tuning of both frequency and angle are necessary to achieve a mode capable of showing the anomaly. Figure 11 shows the tuning process used in the detection of a partial crack. In the left column (a), the incidence angle was held fixed while the frequency was swept. In the right column (b), the frequency was held fixed while the angle was varied. These columns can be seen as the different frames of a continuous movie. By looking at the different frames, the best waveform occurs at a frequency of 1.19 MHz and an angle of 30 degrees.

Landing Gear

Landing gears, constantly being subjected to impact loading, need to be tested on a regular basis for the formation of cracks. Ultrasonic guided waves can be generated also for cylindrical geometries (Rose, 1999). Once again, the probe needs only to be placed at an accessible point and the frequency and angle tuned. A typical landing gear model consists of a smaller pipe screwed into a bigger one. Cracks tend to occur in the smaller pipe, close to the screw threads or even within them. Guided waves can be generated in a longitudinal fashion to look for cracks embedded in the threads, which would otherwise call for the disassembly of the structure.

In ultrasonic guided wave testing the ultrasonic transducer mounted on an acrylic wedge is placed some inches away from the threads. The wedge fits to the curvature of the tube. The pulse echo mode is used to generate a guided wave that travels longitudinally, parallel to the axis of the pipe. The setup for the test can be calibrated by obtaining an echo from a reflector with a known position, such as the threads of the pipe or its edge. Figure 12a shows the calibrating screen; an echo from the threads is located. Once the reference echo is located, a gate is placed on the signal. Reflections that occur inside the gate may correspond to cracks. Figure 12b shows the signal with the crack. These excellent results are acquired after appropriate phase velocity and frequency tuning to find the anomaly.

Once the setup is calibrated, the probe is scanned 360 degrees around the structure, looking for the formation of anomalies. This process was done in increments of 60 degrees. A frequency of 1.865 MHz and an incidence angle of 27 degrees were used. The crack is located at position *a* and the echo is shown in the corresponding waveform. Positions *b* and *f* show some evidence of the crack following the threads signal. This is due to beam spreading.

CONCLUSIONS

Many aircraft components are difficult to test with traditional techniques. Parts are inaccessible or have to be disassembled. The natural wave guide aspect of many structures makes guided wave testing possible. The applications of the phase velocity and frequency tuning process makes detection simple and straightforward. The wave resonance process of forcing returned echoes into a constructive interference mode makes signals easy to observe. Excellent results are shown for the detection of fuselage wall thinning, the integrity of tear strap assemblies, the debonding of skin to core in honeycomb structures, and the debonding of lap splice joints. Good results are also illustrated for transverse cracking in helicopter blades and cracking in landing gear assemblies.

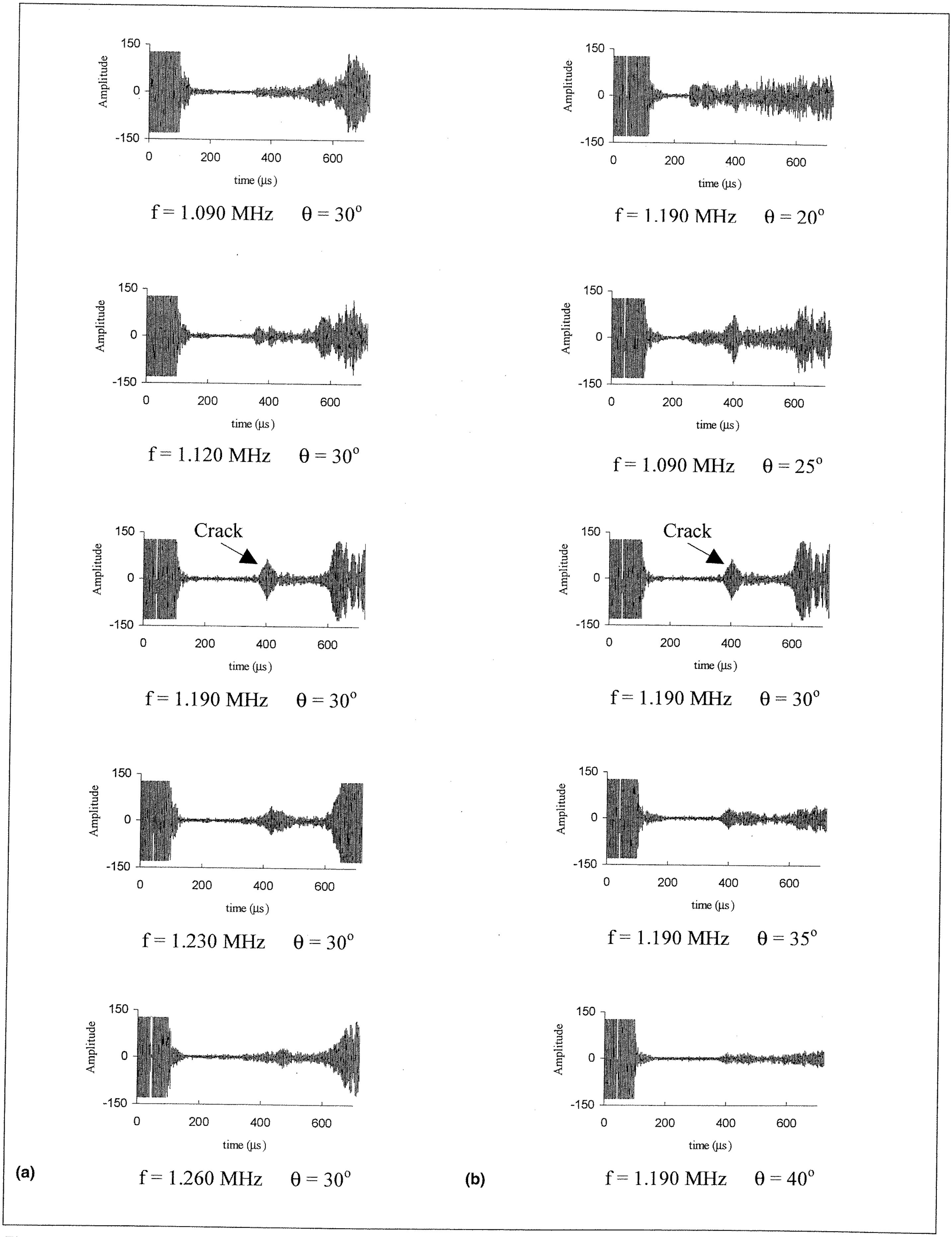

Figure 11 — An example of the phase velocity and frequency tuning process for optimal transverse crack detection in the helicopter blade simulation study (at f = 1.19 MHz, θ_i = 30 degrees).

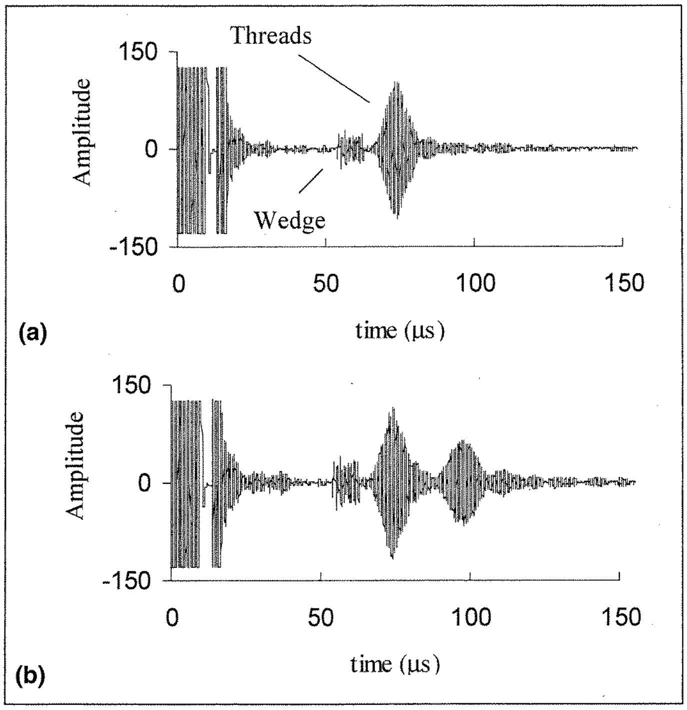

Figure 12 — Sample test results for a landing gear model; (a) calibrating signal; (b) signal showing a crack.

ACKNOWLEDGMENT

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ASNT Board of Directors Approves Motion to Build a Better Society by Doing Business Better

In order for the Society to maintain consistency in business negotiations, to make beneficial and solid decisions, and to maximize opportunities, ASNT's Board of Directors approved the following motion at its March 31, 2000 meeting in Birmingham, Alabama.

> For all business related interfaces with other societies, businesses or individuals, the contact shall be through the office of the Executive Director. These activities include, but are not limited to:
>
> - the establishment of AECs
> - contracts for services
> - alliances and/or partnerships with other societies and businesses worldwide
> - meeting cosponsorship requests distributor agreements
>
> At no time shall any volunteer member of ASNT be involved in the business negotiations of ASNT without the expressed invitation of the Executive Director.

This move, which protects the business of ASNT, has the unanimous support of the Board. If you have any questions regarding this motion, please do not hesitate to contact Executive Director Thom Passek.