GUIDED WAVE NON-CONTACT ULTRASONIC FOR NDE

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Abstract: Non-contact ultrasonic, enables rapid testing of structures using ultrasonic tests that are not possible via conventional contact transducers. This paper reports on laser ultrasonic and air/gas coupled ultrasonic measurements that are performed remotely, do not require direct access to test area, do not need traditional ultrasonic coupling and do not have traditional C-scan fixture requirements [1-4]. This hybrid non-contact ultrasonic transduction system extends ultrasonic measurements to test configurations and ultrasonic wave-modes that are difficult to perform using conventional technology. A Lamb wave or surface acoustical wave can be directed to reach regions of structure not accessible using conventional ultrasonic transducers. Analysis of recorded signals from a single test allows assessments of the defects or material condition. The experimental results demonstrate that such testing techniques can perform the inspection from only one side of the structure. Because there is no requirement for a coupling medium to transmit the ultrasound, and traveling stress waves cover larger area, the material or structure can be inspected remotely and at higher test speed then by conventional contact ultrasonic methods. These non-contact ultrasonic methods have potential for in-situ evaluation of components and structures for presence of corrosion, cracks and fatigue damage in metals and composites. Experimental tests reported below show feasibility of the technology to support periodic life service inspections.

Introduction: Figure 1 and 2 illustrate ultrasonic wave generation via laser light. High-energy, nanosecond pulsed laser illumination of the material surface generates ultrasonic stress waves. The shape, frequency and propagation direction of laser generated ultrasonic waves is controlled by illumination pattern of the laser light. Such acoustical sources are very flexible and enable generation of plate waves (Lamb waves) or surface acoustical waves (Rayleigh waves). Stress waves propagation is effected by material properties, presence of the defects or corrosion. In the hybrid ultrasonic test configuration the stress waves are detected by an air-coupled capacitance transducer [5-6].

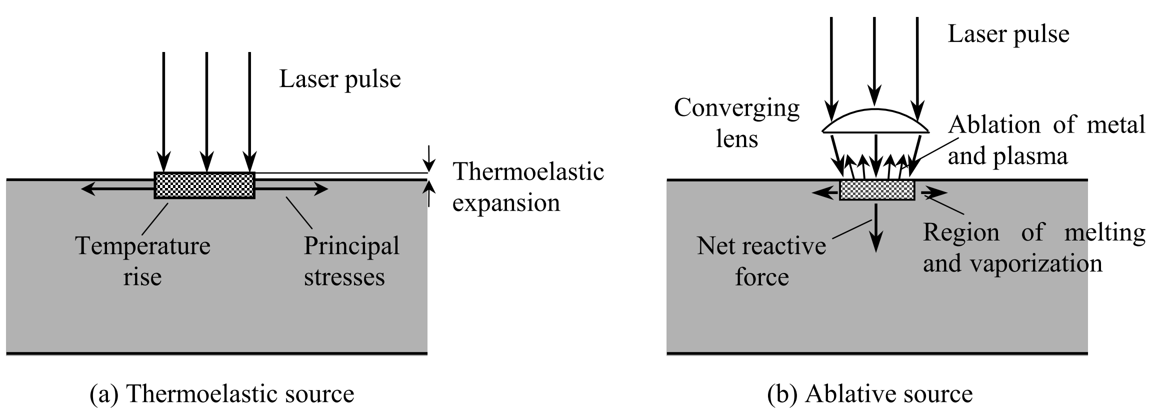

Figure 1. Ultrasonic wave generation in (a) thermoelastic regime and (b) ablative regime.

Signal recorded from a single test as shown in Figure 3 allows assessments of the structural and material integrity between the test points. Test configuration can be in bi-static (separate transmitter and receiver points) or mono-static (pulse echo with transmitter and receiver

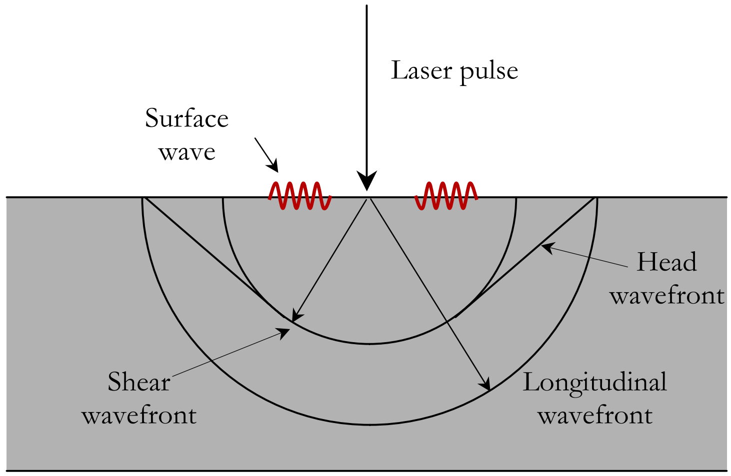

Figure 2. Waves generated by a laser pulse incident on an infinite half-space of solid.

collocated). Presence of cracks, cross-section change, presence of corrosion, delaminations and other defects modulate propagating stress wave and are detected without the need to point wise scan complete surface of the part. Analysis of ultrasonic signals enables deduction of the material condition between test points. The experimental results demonstrate that such testing techniques can perform the inspection from only one side of the structure. Because there is no requirement for a coupling medium to transmit the ultrasound, the structure can be inspected remotely and at higher test speeds then by conventional contact ultrasonic methods or scanning imaging methods such as ultrasonic C-scan. More technology development is required to fully develop, implement and engineer this approach in support of the practical service inspections of the structures.

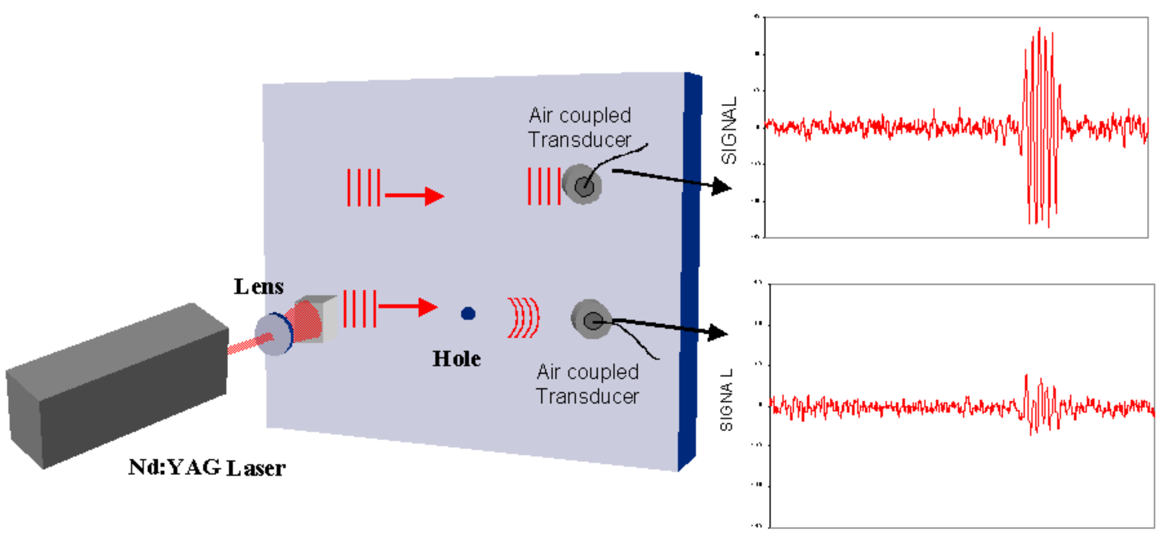

Figure 3. Diagram of the hybrid ultrasonic test configuration using laser generation and air coupled detection. This configuration allows large separation between laser generation and air coupled detection points and uses Lamb wave or surface acoustic signals for non-contact inspection. The set-up is adaptable for pulse echo or pitch-catch test configurations. Ultrasonic signals shown in figure are from an aluminum plate measured over good area and the area of a plate with a hole. For practical non-contact applications and for lower cost, it is more convenient to combine laser generation and air-coupled transducer detection.[7-8]

For a large area testing such as an aircraft wing, contact ultrasonic testing is time consuming. To develop a rapid and more efficient testing technique it is advantageous to perform non-contact ultrasonic measurements that do not require ultrasonic coupling or sophisticated scanning. The plate geometry of many aircraft surfaces readily supports Lamb waves that are hard to induce using conventional transducers and are not commonly used for NDE. Structural and materials testing is possible using Lamb waves (Fig.4). Propagating wave types are better suited for larger area inspection requirements but are less developed than conventional C-scan approach. Both, surface and plate stress wave modes are very sensitive to material integrity, presence of discontinuities (cracks, fatigue induced flaws, and corrosion) or plate thickness changes [9-10]. Even very small mechanical discontinuity or geometry change will influence the propagation characteristic of the guided waves. These effects are measured as mode changes, frequency shifts or filtering, reflection and diffraction of new ultrasonic modes or overall distortion of the original ultrasonic signals. By capturing and analyzing these changes we can deduct the mechanical features of the material that is causing the ultrasonic signal change and interactions.

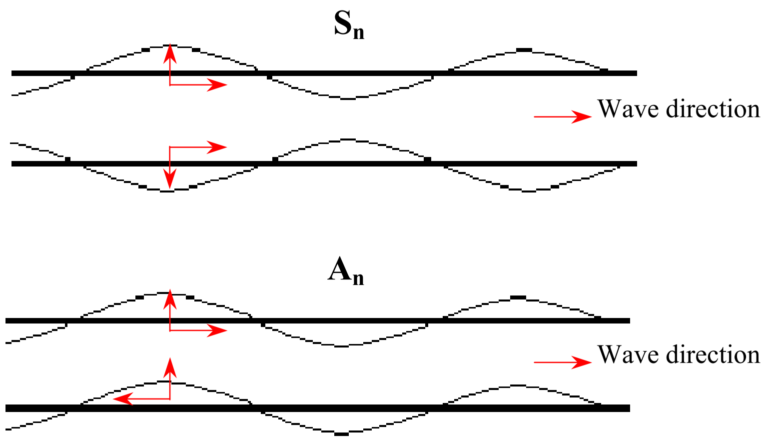

Figure 4. Displacement characteristics of symmetric (S_n) and antisymmetric (A_n) Lamb modes. These modes readily propagate over a long distance in the plate like structures.

Results: Non-contact ultrasonic tests are performed using laser generation and air-coupled transducer detection. A Q-switched Nd:YAG laser forms a light pattern via lens or transmission mask to generate a selected wave mode. These signals propagate along the plate (skin), interact with defects and are detected by an air-coupled capacitance transducer [11-12]. Figure 5 illustrates the detail laser illumination for stress wave generation configured for honeycomb panel testing.

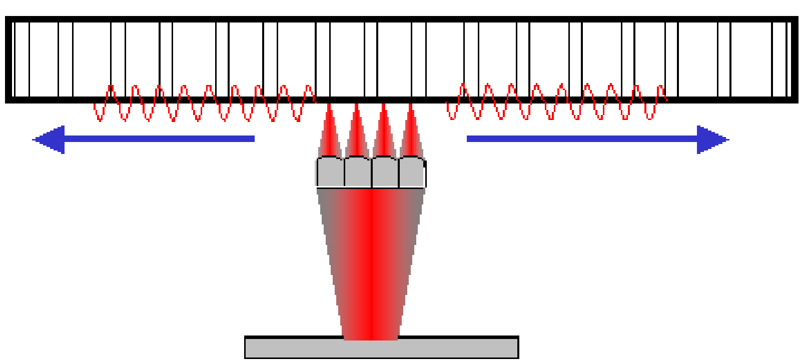

Figure 5. Controlled frequency laser ultrasonic set up for testing large area honeycomb panels .

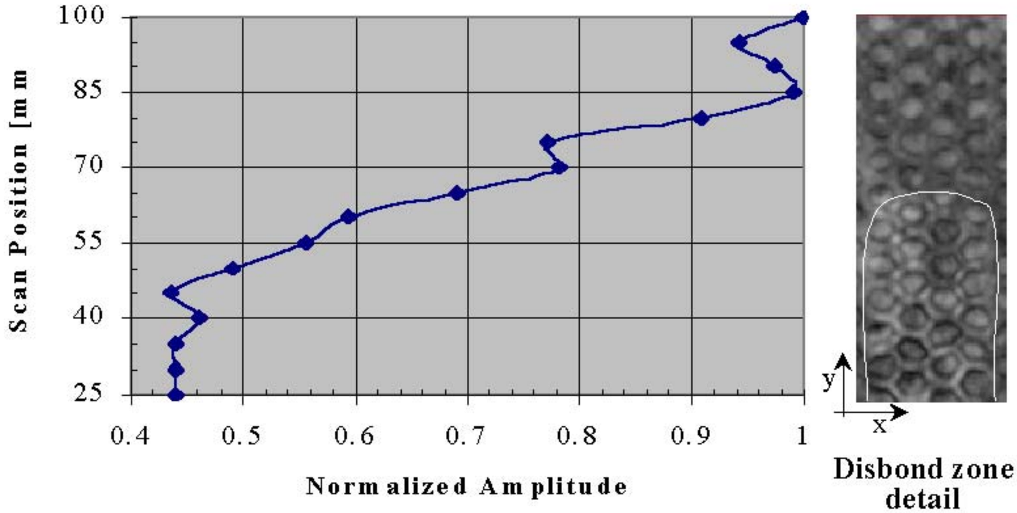

Figure 6. Normalized Lamb wave (A_0) signal amplitude as a function of the position along the disbond zone for a honeycomb panel test sample. Disbond detail from Fig. 7.

The signal change due to core disbond in honeycomb panel is shown in Fig. 6. Amplitude of Lamb wave in panel skin changes over 50% between disbond and good honeycomb bond area.
In contrast, pulse echo ultrasonic C-scan shown in Figure 7 does not significantly changed even at acoustical microscope resolutions using 5MHz ultrasonic test signal. The area of disbond cells is outlined in a white line on the scan for a better location of the defect area.

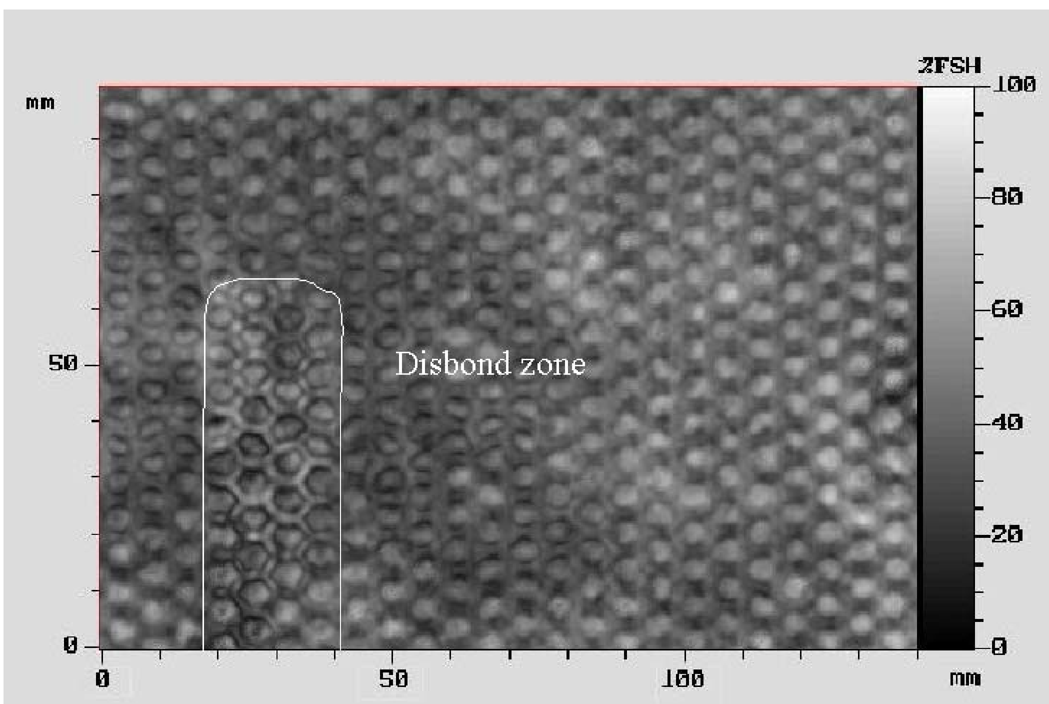

Figure 7. Barely detectable honeycomb disbond area scanned in pulse echo configuration using 5MHz acoustical microscope C-scan.

These non-contact ultrasonic methods are adapted for Lamb and surface wave testing for approximately 100 kHz to 2 MHz frequency range. Lamb wave modes are very efficient for global inspection of plates like structures or lap joints because they propagate through the whole material or joint area. However, Lamb waves are multimode and dispersive and it is desirable to track the modes or generate a single Lamb mode so that changes in the received wave signals may be attributed to the material condition [13-14]. Figure 8 is a diagram of lamb wave modes that were modeled for 1.6 mm aluminum panel. Complex stress wave signal; such as shown in Figure 10 can be analyzed using a wavelet transforms that give better signal analysis results than traditional frequency spectrum processing. Wavelet analysis enables signal energy allocation to modes that are defined in time-frequency plot. Thus, it is relatively easy to observe mode changes due to presence of defects and plate geometrical changes that affect plate stress wave propagation. To generate a controlled Lamb wave mode using lasers, we utilize a spatial light modulation technique illustrated in Figure 3 and 5. Non-contact ultrasonic configuration enables ultrasonic guided wave detection of defect and materials characterization minimizing effects of obstructions and interfering surface irregularities or protrusion. Wavelet analysis of signals enables evaluation of the thickness reduction due to corrosion, or defect detection over full sound path, minimizing scanning requirements. This ultrasonic inspection approach overcomes the drawbacks of conventional C-scan imaging and/or contact methods that require point-wise access to all test areas.

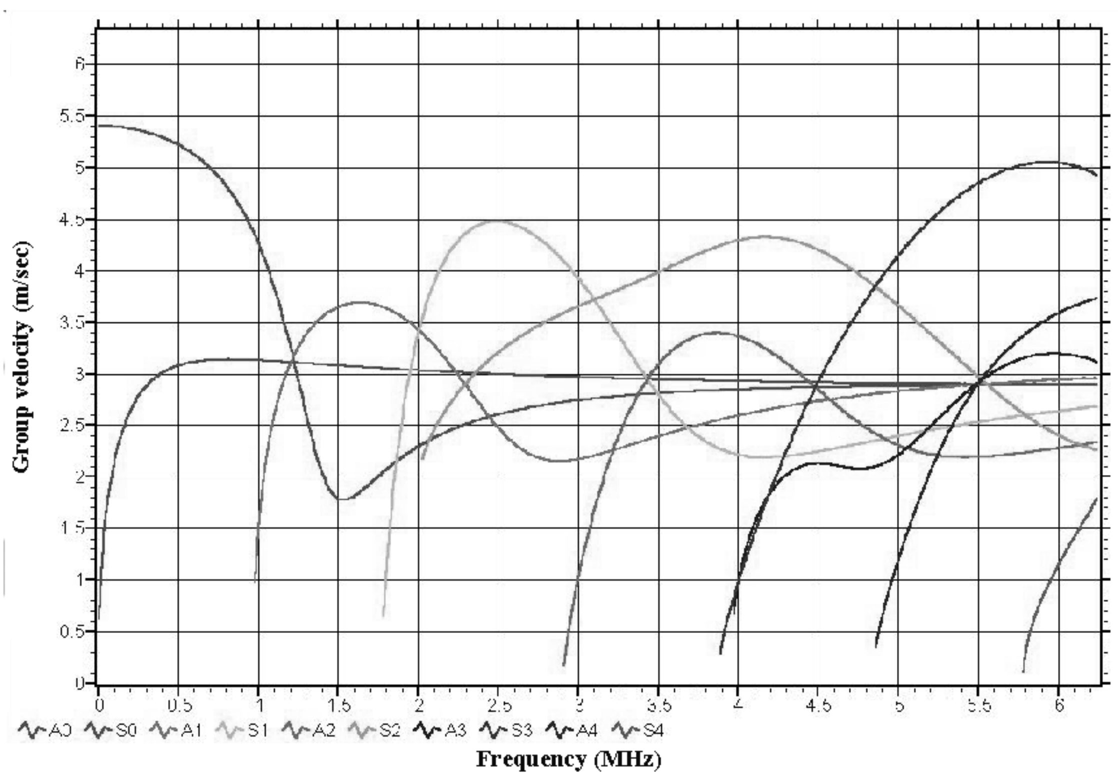

Figure 8. Lamb wave modes for 1.6 mm thick aluminum plate typical of aircraft skins

Lamb wave ultrasonic tests are performed on a selection of samples and configurations that demonstrate the signal changes due to different sample configurations or reference defects. Figures 9 and 10 illustrate effect of crack defect on propagating Lamb waves. The crack modifies Lamb waves by converting energy of lower frequency modes into higher order Lamb modes.

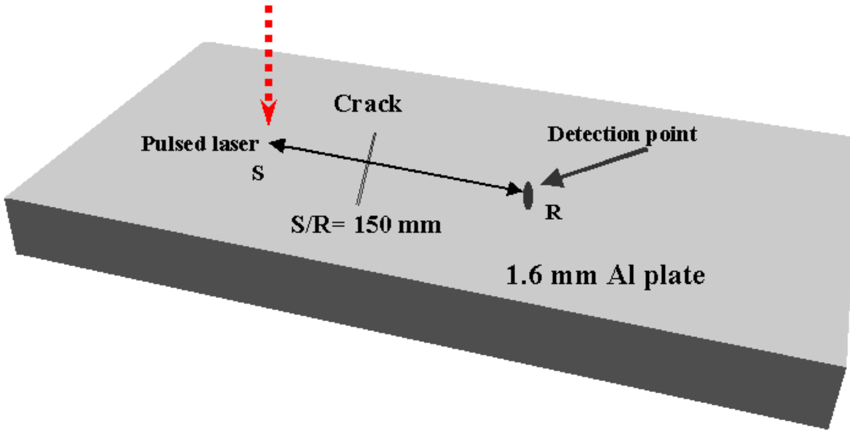

Figure 9. Schematic of the experimental test setup for non-contact ultrasonic crack detection.

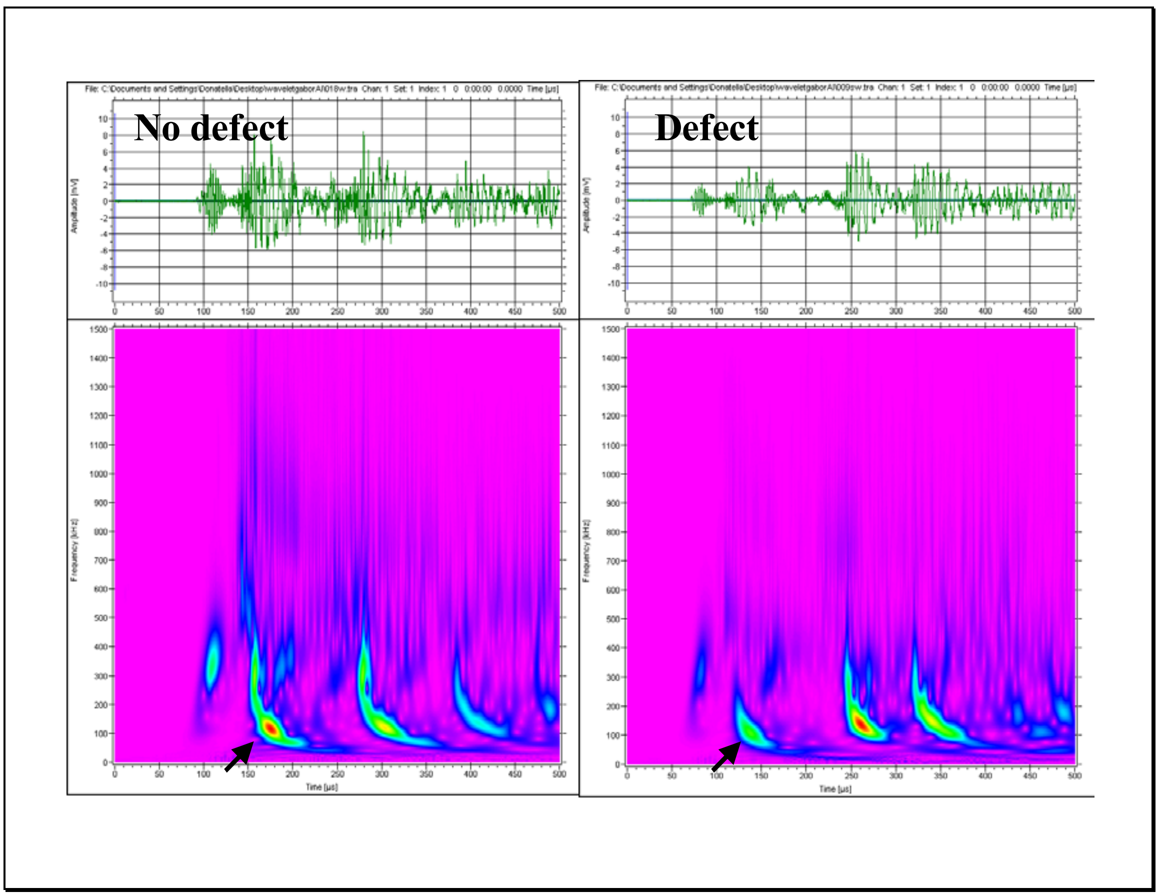

Figure 10. Lamb wave signal changes due to presence of skin crack. The wavelet modal analysis diagrams show a loss of energy in lower frequency mode and corresponding ultrasonic energy shift to higher modes when crack discontinuity is present in the sample. An arrow highlights the lower mode in the diagrams. Horizontal axes represent relative time and vertical axis frequency.

Figure 11 is an example of Lamb waves changes due to presence of partial crack in the plate. Any cross-section reduction due to crack in the plate-like-structure changes the mechanical boundary and geometry of the plate. This geometry change mandates the interaction with the ultrasonic plate stress waves. Thus, Lamb ultrasonic signal waveforms are modified due to creation of different wave modes in a damaged region of the sample. This response is difficult to discern by examination of direct ultrasonic waveform signal. However, using advanced signal analysis such as wavelet analysis, the changes in modes are readily observed.

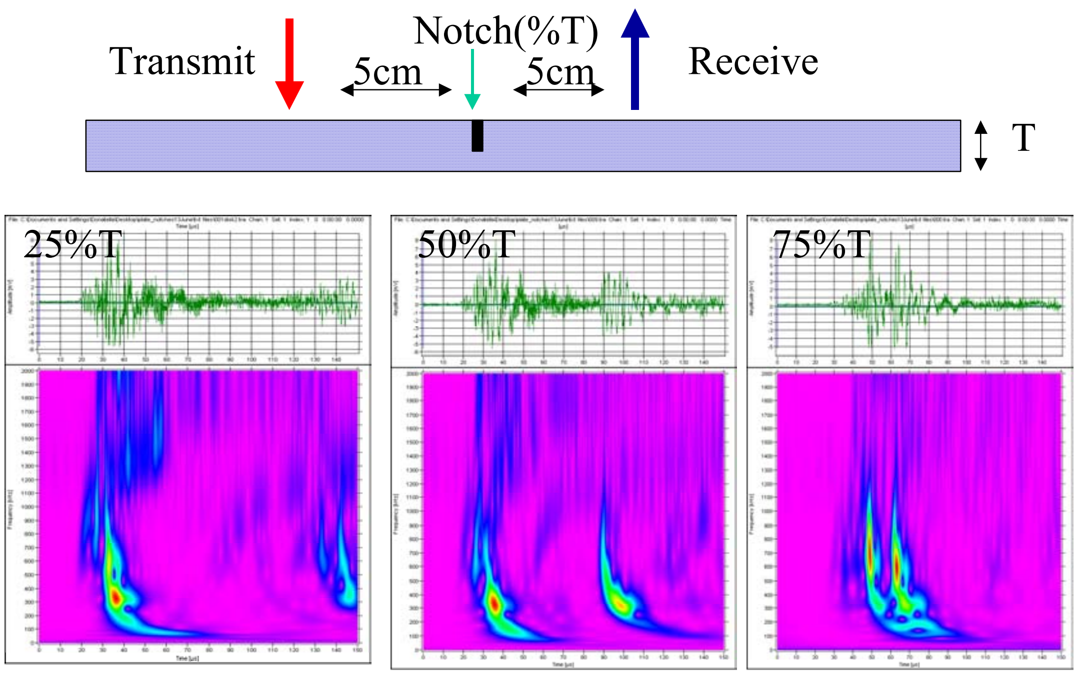

Figure 11. Ultrasonic signal amplitude transmission level for different depth of the notch (crack) in plate with thickness T. The wavelet diagrams show significant shifts in modes and mode energy that are influenced by presence of crack like discontinuity. The results indicate the ability to analytically estimate crack depth using the wavelet signal analysis information

Discussion: The experimental results on the above panels demonstrate potential to employ this approach for inspection of different plate like structures. We have performed tests on composite and metal samples typical of aged aircraft frames that contained corrosion, disbonds or riveted lap splice. In these ultrasonic tests, the received signal amplitude patterns are more complex, but reflect the mechanical integrity of the structures. A better data base and more advanced analysis of the signals is required for reliable classification of the measurements. At this point, it is impossible to predict ultimate test sensitivity of this methodology to disbonds, mechanical material properties degradation and corrosion or crack size. However, this approach offers very rapid screening for overall structural conditions and the test appears to be very sensitive to any mechanical irregularity.

Conclusions: Using hybrid ultrasonic configuration, we have demonstrated a remote ultrasonic inspection methodology to investigated integrity of structures including, metal skins and adhesively bonded components. This enabling technology is based on laser ultrasonic and air-coupled ultrasonic transduction methods and the approach is feasible for field implementation. Laser generation and air-coupled reception can be packaged as a compact remote sensor test head for the development of non-contact ultrasonic testing. Significant advantage of the approach is ability to examine large areas of material without a need for extensive scanning. Laser ultrasonic transduction extends ultrasonic measurements to test configurations and wave-modes that are difficult to perform using conventional technology. The hybrid test configuration allows for truly non-contact and remote inspections and incorporates laser light modulation technique for controlled generation of acoustic waves. Experimental results from the samples show that non-contact ultrasonic methodology using guided waves is sensitive to presence of defect and changes in plate thickness. The tests can be performed with a single line scan, covering large areas by monitoring propagation characteristics of acoustical signals and using wavelet analysis of ultrasonic waveforms.

The experimental results demonstrate that the new, non-contact ultrasonic testing methods have potential for evaluation of components that are not feasible using conventional NDE configurations. Additional work is planed to establish limits in detection of cracks or corrosion in different type of components and test methods using the hybrid laser/air-transducer ultrasonic system configuration.

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