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NDE FOR PROGNOSTIC STRUCTURAL CHARACTERIZATION

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ABSTRACT

Probing material degradation and properties change to anticipate stages of damage can be achieved using advanced in-situ and hybrid non-contact remote ultrasonic sensing including laser generation and air-coupled detection arrangements. The sensing technology is based on application of guided waves such as plate (Lamb waves) or surface waves (Rayleigh waves) for direct material interrogation that can be performed over long range and on geometrically complex components. Signal processing such as Wavelet analysis of recorded signals from a single test enables assessments of the material condition. Experimental results demonstrate that such testing techniques can perform the inspection from only one side of the structure and have potential to estimate elastic modulai of the material. Such ultrasonic sensing configurations make nondestructive test technology feasible to support structural integrity assessment and life service inspections of metal, bonded or composite based structures.

Keywords: NDE, Ultrasonic, Prognostic, Guided waves, Structural integrity, Sensors

1. Introduction

New materials application and the performance improvement of modern structures and platforms are progressing at ever-faster pace. However, the management of operational life, service needs, damage assessment and overall structural state is undefined and inadequate to enable an informed technical and cost effective lifetime system management. Significant gains in effectiveness can be achieved if current structural and material integrity management tools can be improved and augmented by Nondestructive Evaluation (NDE) prognostic tools that will measure and predict the materials degradation, structural damage and potential failure risks.

Prognostic models must be based on a global-local strategy that connects and integrates: i) dynamic and environmental load histories of the structural system ii) in-situ characterization of damage and material allowables using advanced NDE sensor data, and iii) multi-scale mechanism-driven models of material damage, from incipient micro-structural degradation to development of crack initiation and crack growth and propagation. Figure 1 is representative of material damage diagram illustrating stages of materials damages from micro, to macro, to structural domains. From incipient material conditions the damage in composites and in metals is initiated at a scale where micro-structural material features play prominent roles. Early damage (Stage 1) leads to microstructure changes such as plastic deformation or physical material changes that can include intragranular micro-cracking or loss of interfacial cohesion/adhesion among the constituents. In second stage (Stage 2), micro-defects coalesce and grow, resulting in macroscopic failure zones which appear in the form of discrete deformation, micro voids, micro-cracks that cause average deterioration of stiffness and strength properties. The third stage (Stage 3) the micro-damage coalesces into transitional micro- to macro- structure significant cracks (order of gain size or microstructure repeat feature dimensions). The fourth stage (Stage 4) encompasses macro crack and damage zone formations that are directly influenced by material global strains. Damage growth, fatigue and failure prediction understanding for Stage 4 are fairly mature, whereas considerable debate is still ongoing regarding the principal driving forces for low and high cycle fatigue in earlier stages of damage evolution. In general, Stage 4 damage is considered to be at the current limit of NDE sensing and detection.

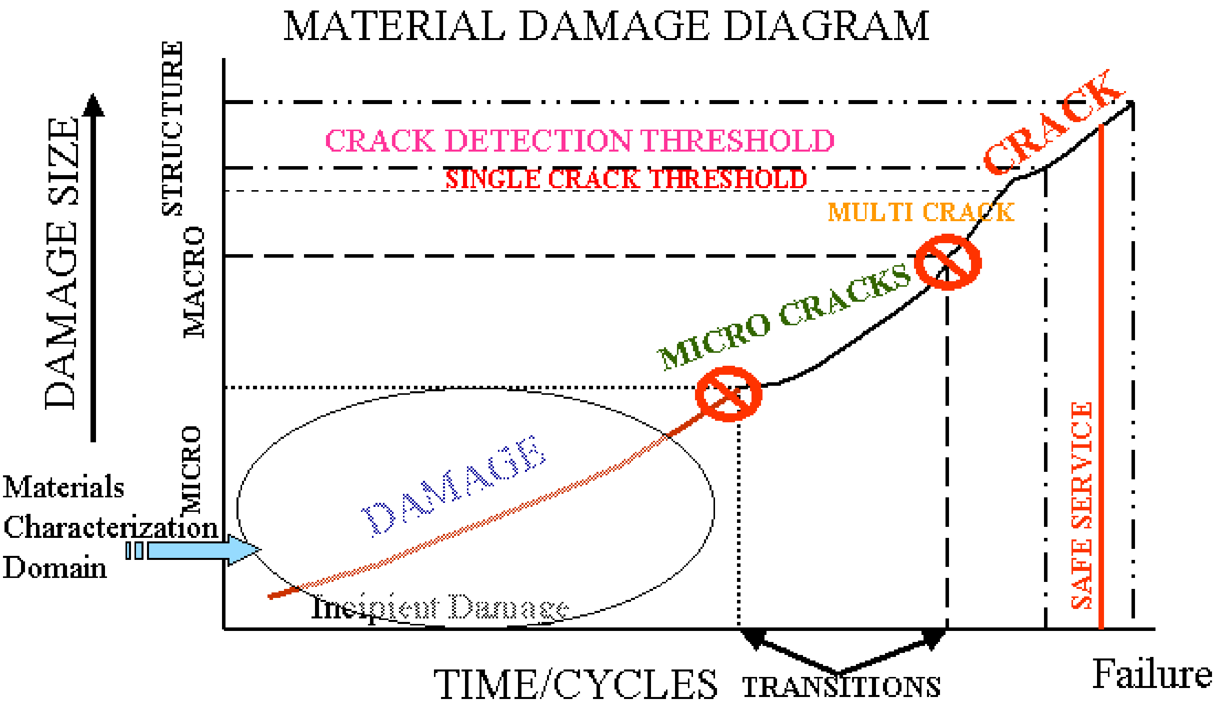


Fig. 1: Materials damage time/cycle diagram illustrating different regions and types of damage in the lifetime of the structural material.

Recent developments in the real-time, in-situ or remote ultrasound sensing and related signal processing make possible high resolution interrogation of materials damage at the micro-structural level described by stage 1 to 3 conditions, significantly before macro-crack Stage 4 material damage levels.

2. Technical Approach

2.1 Ultrasonic Materials Evaluation and Sensing

Ultrasonic stress waves are known to be sensitive to the material properties and micro-structural characteristics. The speed of ultrasonic wave depends on the moduli and density of a material. Ultrasonic attenuation, a loss of ultrasonic wave amplitude, is influenced by factors such as grain size, grain anisotropy and inelastic effects related to microstructure grain details. In composite, micro-structural geometry, matrix material cure, fiber to resin ratio or periodicity of the fiber lay-up influence the attenuation of the stress waves. Ultrasonic methods are used to study the bulk aggregate material inelastic and elastic responses. New ultrasonic transduction methods such as lasers or in-situ sensors (Fig. 2) have broadened the ability to investigate micro-structural characteristics.

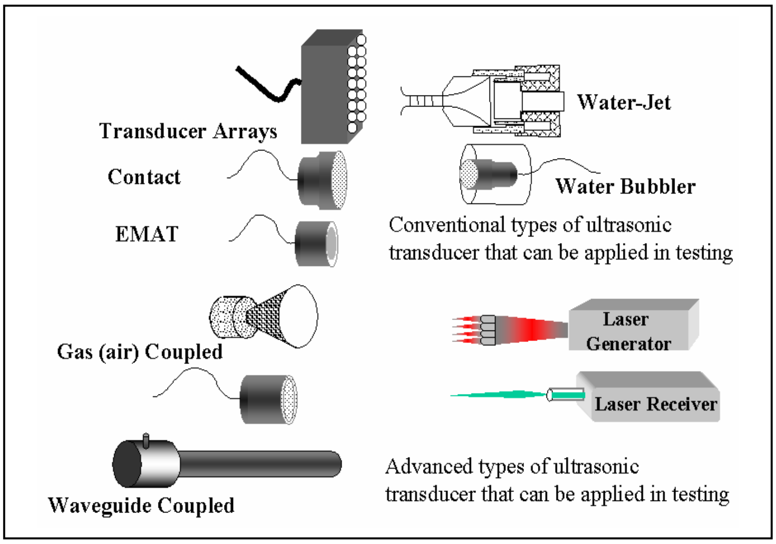


Fig. 2: Schematic diagram showing various conventional and non-contact remote ultrasonic transduction sensors. Conventional sensors require physical contact or attachment to structure and cannot be used on moving components. Non-contact, remote laser and gas-coupled devices combined with guided stress wave modes can interrogate obstructed or moving components.

The behavior of micro-structural features in materials is fundamental to the understanding of materials performance and failure. In metals, the grain boundaries directly influence the material's strength, fatigue, and creep performance. Although it is impractical to measure changes for the individual grain boundaries, ultrasonic methods can sense accumulation of damage in material regions that undergo a micro-structural change. In composite materials, micro-mechanics changes are highly dependent on the local micro-structure. Stress induced micro-structural damage is usually distributed over a larger material volume reflecting the complex aspects of the performance of a material.
Fatigue loads create sufficiently large damaged zones to create a material layers with a stiffness and density that are distinct from those of the surrounding grains. These changes affect the linear as well as the non-linear elastic responses to ultrasonic stress waves. As early as 1956, Truell *et al.* [1] observed changes in the ultrasonic attenuation as a function of fatigue cycles on polycrystalline aluminum. They found that attenuation was nearly constant during the early stages of fatigue, then showed a gradual increase during the intermediate stages, and then increased very rapidly prior to fracture. Researchers at Johns Hopkins University performed studies in the early 70's [2] and found that ultrasound can predict the onset of fatigue damage before the initiation of cracking. At that time, these findings were impossible to implement in practice because of the complexity of required instrumentation and the lack of computer power. With the advent of modern data capture and data mining technologies and improved ultrasonic sensing, such NDE measurements are feasible for development of prognostic characterization.

2.2 Non-contact Ultrasonic Transduction

Spatially formed laser-sources for ultrasound generation enable improved control of the stress wave timing, directivity, acoustical energy partitioning in stress wave modes and waveform shape. The remote and non-contact laser acoustical sources are very flexible and enable generation of plate (Lamb waves) or surface waves (Rayleigh waves) that cannot be generated using conventional contact transducers [3-6]. Guided wave modes combined with advanced signal analysis enable single impulse testing and characterization of large area or volume of the structural materials.
Figure 3 illustrates a formed, high-energy, nanosecond pulsed, laser illumination of the material surface that generates ultrasonic stress waves. The shape, frequency and propagation direction of

ultrasonic waves is controlled by intensity and illumination pattern of the laser light [7]. Such acoustical sources are flexible and enable very efficient generation of guided acoustical waves.

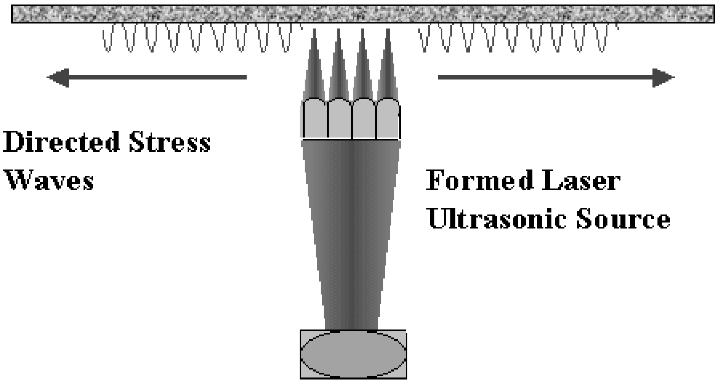


Fig. 3: Schematic diagram of the Formed Laser Light Ultrasonic Source enabling generation of controlled guided ultrasonic stress waves.

Figure 4 illustrates hybrid non-contact ultrasonic test configuration where the stress waves are detected by a remote air-coupled capacitance transducer [8-9]. Test configuration can be in bi-static (separate transmitter and receiver points) or mono-static (pulse echo with transmitter and receiver collocated). Signals recorded from a bi-static test as shown in Figure 4 allow assessments of the structural and material integrity between the test points as well as estimate of material elastic modulus. As configured, guided wave inspection can be performed from only one side of the structure and structural degradation can be detected without the need to point wise scan complete surface of the part. Because there is no requirement for a coupling medium to transmit the ultrasound, the structure can be tested remotely over complex geometries and at higher test speeds not achievable by the contact ultrasonic methods or ultrasonic scan imaging methods such as ultrasonic C-scan.

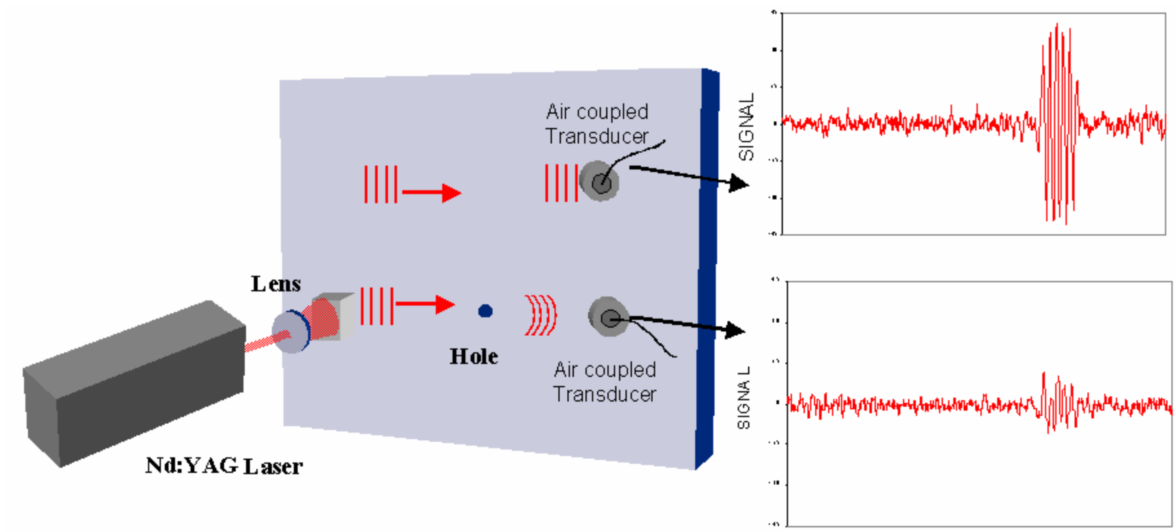


Fig. 4: Diagram of the hybrid ultrasonic test configuration using laser generation and air coupled detection. This configuration allows large separation between laser generation and air coupled detection points and uses Lamb wave or surface acoustic signals for non-contact inspection. The set-up is adaptable for pulse echo or pitch-catch test configurations. The reference ultrasonic signals shown in the figure are from an aluminum plate measured over good area and the area of a plate with a hole. Separation between transmitter and receiver can be as small as a few centimeters to more than a meter.

The plate-like geometry of many civil, transportation, or aircraft structures readily supports Lamb waves that can propagate over long distances. Guided mode ultrasonic 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 overall material integrity[10,11]. Very small mechanical change, material discontinuity or geometry change will influence the propagation characteristic of the guided waves. These effects are measured as mode changes, frequency shifts or frequency filtering, reflection and diffraction to 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 modification and interactions.[12,13]
Because of the laser source reproducibility and short initiating impulse of less than 10ns, it is possible to establish reproducible "0" time at close or better than 1ns. This enables very accurate ultrasonic signal propagation timing and thus high fidelity measurements of ultrasonic velocity that is direct indicator of material mechanical modulai. In its simplest isotropic form, velocity (V) is related to modulus (E) and density (ρ) by relation:

$$V=(E/\rho)^{1/2} \quad (1)$$

The relationship equations for the guided waves are more complex and additional complexity is introduced by anisotropic composite properties [14,15]. However, by measuring ultrasonic waves velocity, one can always estimate the elastic constants of the material.

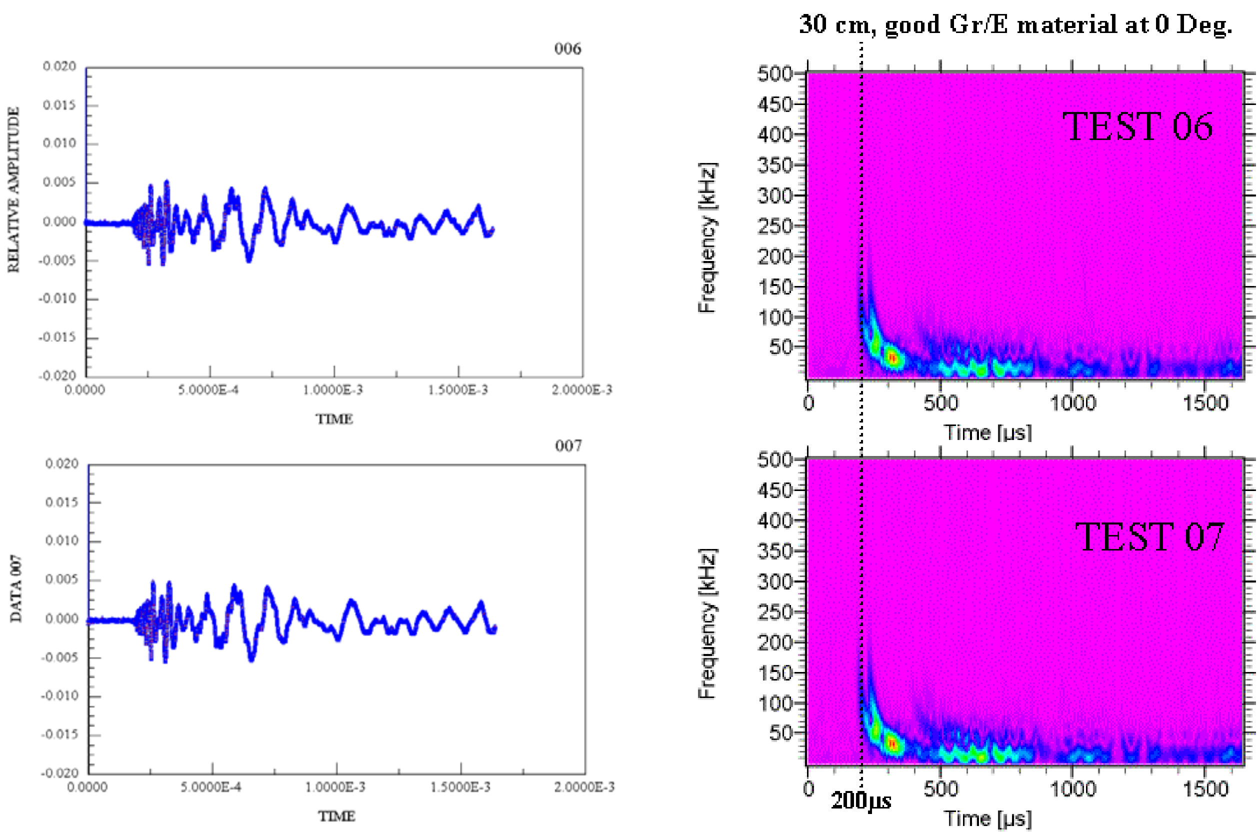


Fig. 5: Two independent test signals demonstrate the reproducibility of the measurements. Ultrasonic path was 30 cm from source to receiver in a bi-static test configuration. The ultrasonic time-amplitude signals are processed by wavelet algorithms and mapped on the time-frequency intensity plot. The signals time domain plot and wavelet transform in the frequency-time domain are identical.

2.3 Signal Processing

In many current ultrasonic NDE applications, the unprocessed time-domain signal offers sufficient fidelity to locate flaws. However, the characterization of a material property damage, defect resolution or automated analysis requires further signal processing. Complex stress wave signals such as shown in Figure 4, can be analyzed using a wavelet transforms that give better signal analysis results than traditional frequency spectrum processing. [16,17]. Wavelet analysis enables processing of dispersive ultrasonic signals by energy allocation to modes that are defined in time-frequency plot. Thus, it is possible to observe mode changes due to presence of material properties change, geometrical changes that affect stress wave propagation and presence of defects such as cracks. Figure 5 illustrates the reproducibility of the wavelet analysis data for two guided wave measurements in good area of a composite panel. Separating ultrasonic signals by arrival times, frequency content and amplitude enables recognition of the signatures of the material mechanical properties or specific features of the defect conditions.

3. Sensing Material Damage

Signal processing of the complete waveforms of the traveling ultrasonic waves enhances information about all material features encountered in the path. By deconvolving this information via wavelet analysis, one can perform full analysis of signals for all three functional parameters: frequency, time and energy.

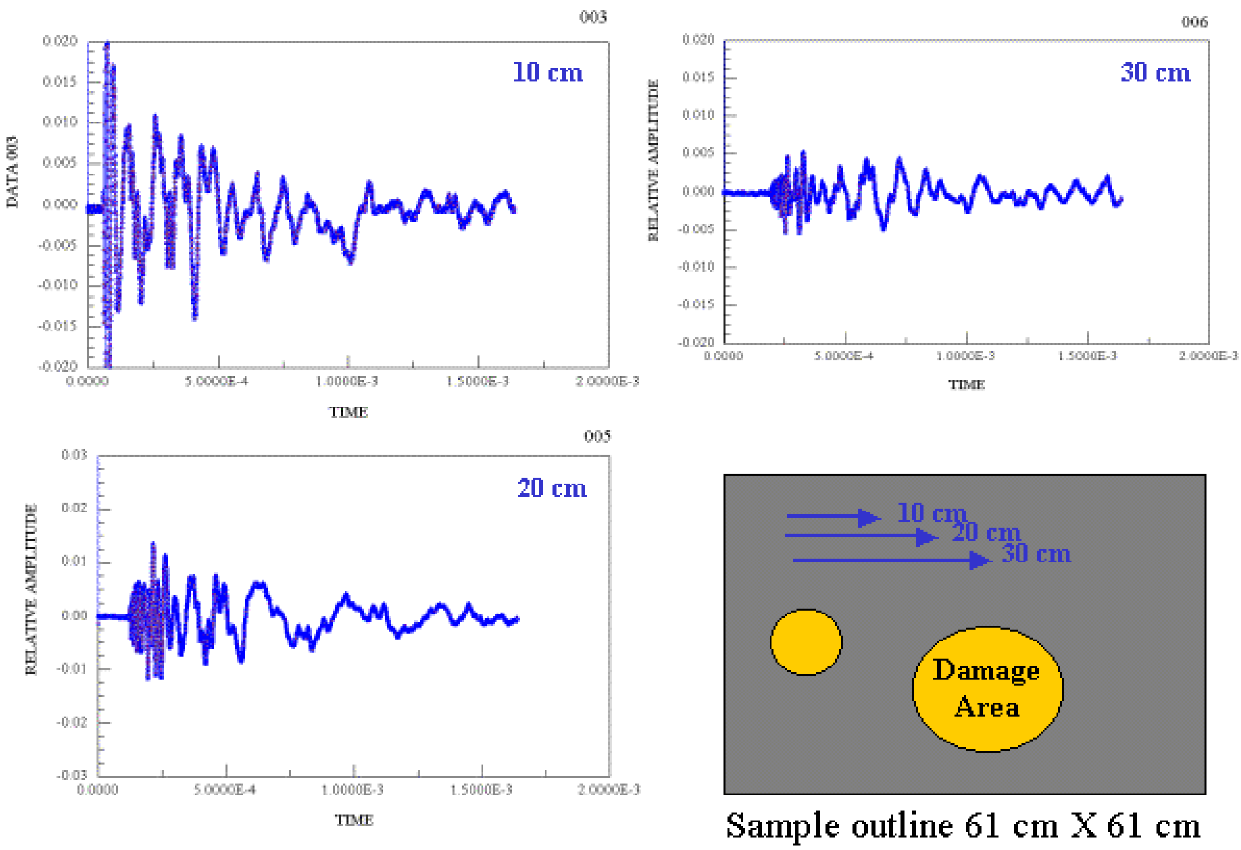
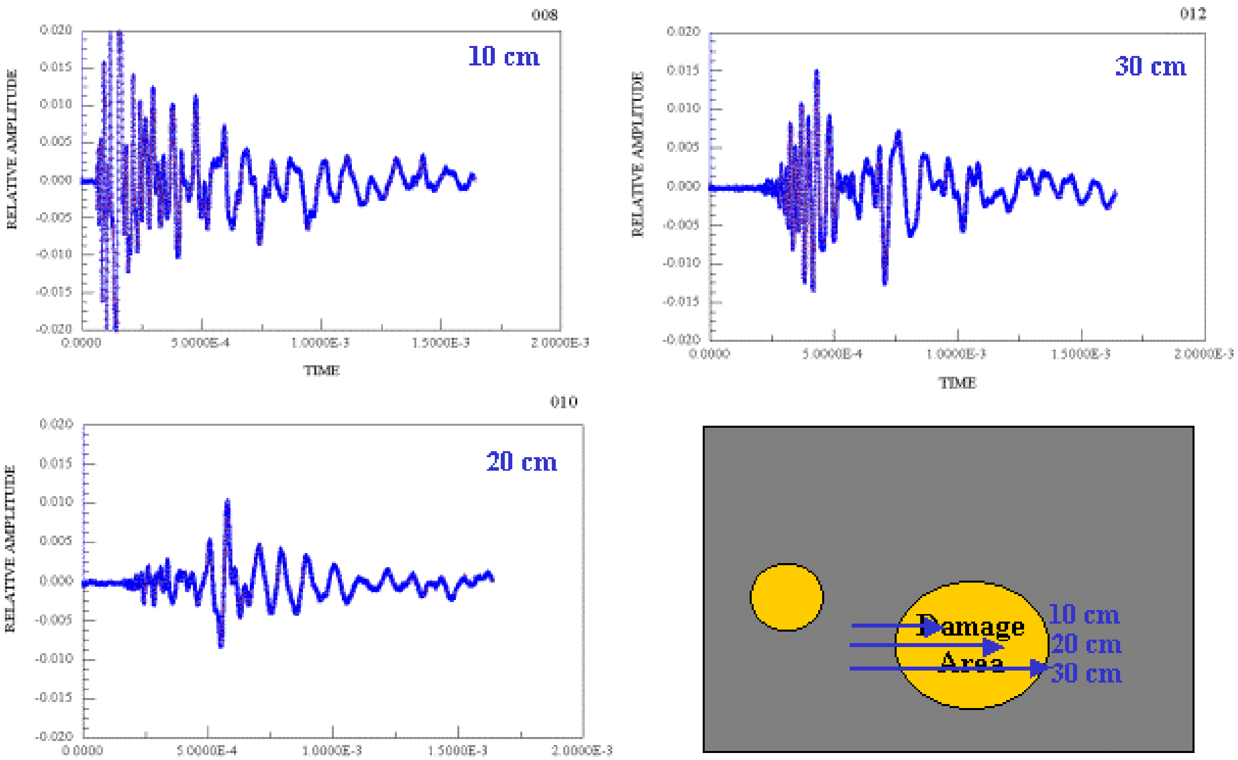


Fig. 6: Time amplitude records of ultrasonic guided wave signals for a composite panel over good material. Test configuration geometry as illustrated in figure 4 with bi-static transducer configuration. Signals captured for the transmitter-receiver separations of 10cm, 20cm and 30 cm.

An example of such application is demonstrated by a guided wave tests performed on the 5-play Graphite/Epoxy composite panel that sustained lightening damage. Figures 6 and 7 are ultrasonic test records of the guided wave signals in a god and damaged area of the Gr/Ep composite panel. Ultrasonic test were performed over path length of 10 cm, 20 cm and 30 cm. The un-damaged and damaged material areas are not readily observed and conventional ultrasonic nondestructive tests are not reliable in sensing extend of the material damage.



Sample outline 61 cm X 61 cm

Fig. 7: Time amplitude records of ultrasonic guided wave signals for a composite panel over lightening strike damage. Test configuration as illustrated in figure 4 with bi-static transducer configuration. Signals captured for the transmitter-receiver separations of 10, 20 and 30 cm.

Figure 8 shows an example of the wavelet modal analysis that separates the complex ultrasonic signal into the characteristic stress-wave plate modes. The diagram “fingerprints” ultrasonic signal with information that is not discernable by direct examinations of the ultrasonic signal amplitude-time record as shown in Figure 6 and 7. Signal over good are changes for longer travel path as higher frequencies are lost and energy is converted to lower frequency slower velocity mode. Figure 7 illustrates the signals from the waves just entering damage, plate wave signal at the center of the damaged and signal from the modes that crossed the damage region. Wavelet diagram in Figure 8 show the difference in modes between good material and damaged area. Transmitted modes in the damaged area are characteristic of locally modified material properties and thickness of the plate. From wavelet diagram, it is readily discernable that significant energy is transferred across the damage but the modes, energy, and ultrasonic frequency are shifted. Lamb wave modes propagating in damaged area are at lower frequency and are traveling slower than the modes in good area. This change is attributed to loss of mechanical integrity of the resin and fiber/resin bonding that reduces part stiffness and creates local stiffness change. A Lamb wave signal is very sensitive to this material condition change.
These non-contact ultrasonic methods are adapted for Lamb and surface wave testing in frequency range of approximately 100 kHz to 2 MHz using air coupled receivers and can be

extended above 20 MHz using in-situ or contact sensors. Lamb wave modes are very efficient for global inspection of plates like structures because they propagate through the whole material area. [13-14].

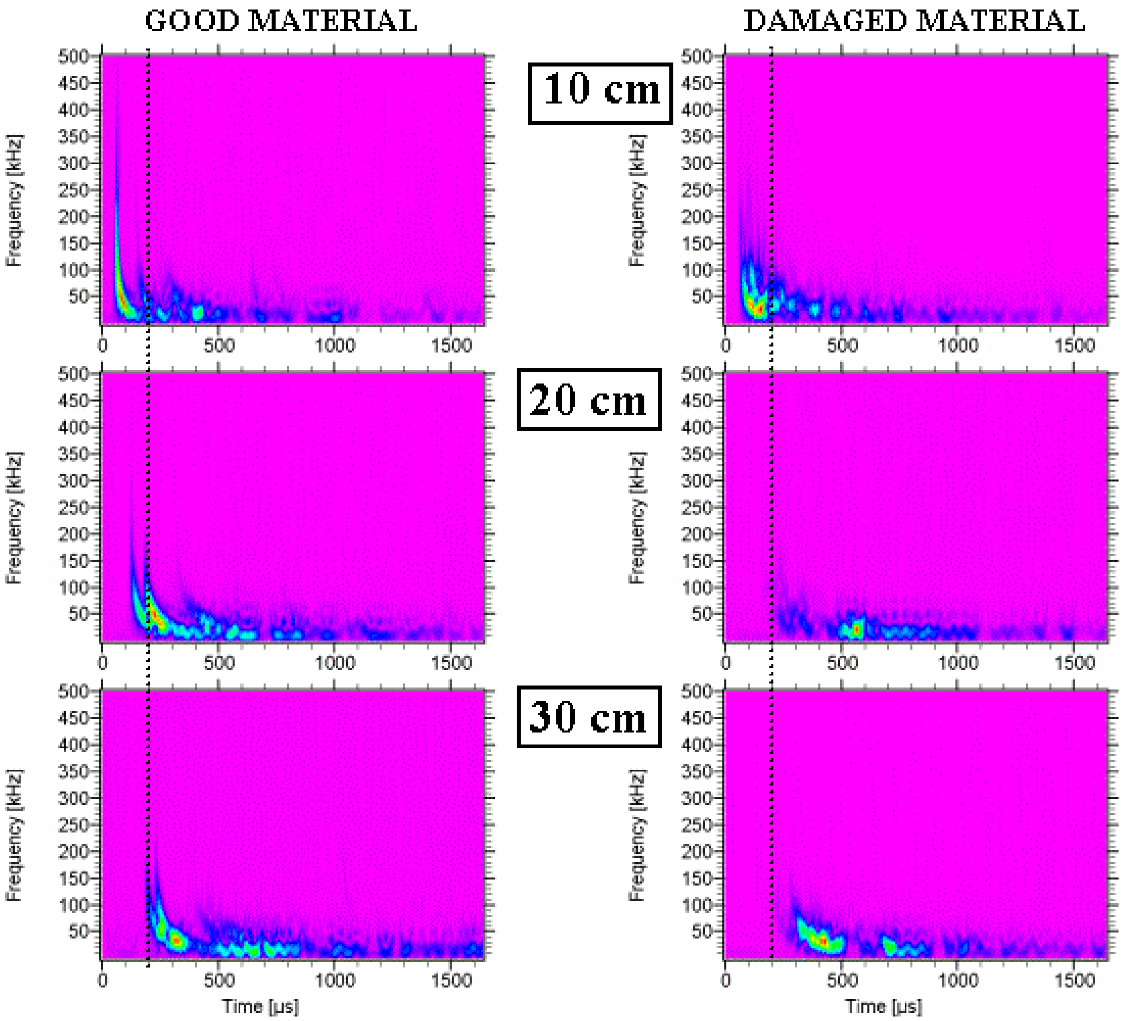


Fig. 8: The complex waveforms captured by transducers shown in Fig. 7 and 8 are analyzed and plotted in 3 dimensions. Time (X-axis), frequency (Y-axis) and energy (shade of gray) parameters are separated via the wavelet modal analysis. The wavelet diagrams show shift to lower frequency and later arrival time for modes crossing damaged areas of the Gr/Ep plate.

The experimental results on the damaged panel 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 database and more advanced analysis of thesignals are 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 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. Guided wave ultrasonic methods have potential for in-situ evaluation of components and structures for presence of corrosion, fatigue damage, impact damage, environmental damage, mechanical damage, incipient cracks generation and other micro-structural degradation events.

4. Conclusions

Guided wave ultrasonic tests can be very sensitive to materials properties. This enabling sensing technology is based on laser ultrasonic and air-coupled ultrasonic transduction methods or in-situ sensors. The sensing approach is feasible for field implementation. The tests can be performed by monitoring propagation characteristics of acoustical signals and interpreted using wavelet analysis without a need for the extensive point-to-point scanning. The hybrid test configuration allows for truly non-contact and remote inspections and incorporates laser light modulation technique for controlled generation of guided acoustic waves. Additional work is planed to establish limits in detection of damage such as micro-cracks or loss of material stiffness due to fatigue. These ultrasonic measurements can be extended for civil, transportation and aerospace service and applied for a range of materials and structural tests.

5. References

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