ULTRASONIC GUIDED WAVE METHODS FOR THE
MATERIALS CHARACTERIZATION AND
DEFECT DETECTION

B. Boro Djordjevic
Materials and Sensors Technologies, Inc.
798 Cromwell Park Drive, Suite C
Glen Burnie, MD 21061, USA
bbd@mast-inc.com

ABSTRACT

Laser ultrasonic sources and guided wave sensing methods, using sub-wavelength miniature sensors, are utilized to nondestructively evaluate composite materials. These methods enable in-plane characterization of the ultrasonic signals directional velocities. Additionally, sensing of the guided wave modes changes, in the geometrically complex composite structures, enables detection of the material structural damage. Experimental data demonstrates reproducibility and feasibility of such tests to monitor and characterize development of micro structural damage in the composite materials.

Key words: Nondestructive Evaluation, Ultrasonic, Guided Waves, Composites, Material Properties

1. Introduction

Ultrasonic testing methods mostly use longitudinal waves with a majority of the test orientations in thickness direction. In the structural application for testing of materials such as composites, guided waves enable sensing of in-plane properties and rapid testing of large material areas without the need to pint-vise scan the structure. Laser ultrasonic sources are well adapted for in-plane testing methods. Laser ultrasonic source, guided wave methods, are very effective for the testing of complex composite materials structures. Using advanced ultrasonic transduction process, combined with the custom-made data acquisition, enabled reproducible measurements of the composite’s mechanical conditions that are not possible using conventional ultrasonic test approaches. By directional tracking and analysis of in-plane, in-plane, ultrasonic guided wave propagation, we mapped acoustic wave response in the composite materials. Such sensing of the ultrasonic guided waves enabled measurements of the materials properties and detection of the mechanical defect conditions. High accuracy directional velocity measurements facilitated very reproducible monitoring of the composite in plane directional material modulus as well as tracking of the progression in the material damage. With the aid of signal processing, experimental results show high sensitivity of the in-plane guided wave modes to characterize materials modulus and sense composite structural damage.
2. Experimental Design

Guided waves are directly influenced by in-plane mechanical condition of the material. Sensing changes in the guided wave propagation characteristics enables direct in-plane assessment of the mechanical condition of the material. Test configurations based on the traditional ultrasonic transducers and instrumentation cannot reproducibly generate and observe changes in the guided wave modes [1]. Ultrasonic testing of the structure, using guided waves in the X/Y plane is at lower frequencies than it is required for (Z-axis) through thickness longitudinal wave testing. Capture and interpretation of the guided wave propagating signals is more complex but readily processed via modern computers [2-4].

Fig. 1 illustrates the differences between conventional ultrasonic and in-plane guided wave test geometry. Ultrasonic sensor selection and data collection technology is critical to enable the guided wave testing. To enable reproducible guided wave measurements requires application of formed laser acoustical sources. Laser-optical ultrasonic receivers are ideal but because of complexity and cost, in practical tests, we used sub wavelength small aperture piezoelectric and line element transducers adapted for the guided wave test configurations. Miniature transducer technology, used for the guided wave testing, is available but in general is not used for the guided wave nondestructive testing (NDT) [5-9].

![Fig. 1: Schematic representation of the ultrasonic test directions for the characterization of the composite material using conventional versus guided wave emerging technology.](image)

Fig. 2 illustrates ultrasonic wave-fronts generated by the laser surface ultrasonic source. Depending on the material and laser source type, the directivity and intensity pattern of the wave-front signals is more complex. Constrained by material geometry boundaries these wave-fronts are converted into the guided wave modes. In addition to the longitudinal and shear waves, plate like structures support surface and plate waves that are very complex and exhibit dispersive mode behavior [10]. For the composite material characterization, we utilized a laser line source that is experimentally significantly more reproducible than conventional contact transducers. Additionally, the source timing is extremely consistent, providing better that 5 ns reproducibility of the time-zero source error. The signal sensing is via sub-wavelengths 1 to 2 mm broadband surface contact transducer responding to the surface displacement velocity. The sensing frequency bandwidth is from about 20 kHz to above 50 MHz with 250 MHz 12 bit digitizing instrumentation. The signal conditioning amplifiers are specifically designed for
extremely low noise, and very high linear dynamic range that meets capabilities of the 12 bit digitizing instrumentation. This configuration enables capture of all ultrasonic wave-fronts over significant and meaningful frequency test spectrum. This test setup does not modify local mechanical conditions such as in wedge or angle beam ultrasonic guided wave transducer settings. In addition, this test configuration does not filtered or exhibit sensing bias to the specific guided wave modes. Because of the small sensing aperture and very well defined laser source location, the experimental measurements can very accurately determine distance separation of the transmitter to receiver. With small time-zero source error and by accurate path measurements between source to receivers, it was possible to accurately and reproducibly measure ultrasonic wave-front arrival times. Depending on the exact experimental setups, the accuracy of the wave-front velocity can easily be measured to 0.1% or better.

![Diagram](image)

**Fig. 2:** Map of the wave-fronts generated by the laser surface ultrasonic excitation defining nomenclature and illustrating signal data collection configuration.

### 3. Experimental Procedures

The experimental measurements on the composite samples were grouped into two categories. First, the measurements of the ultrasonic signal velocity changes related to changes in the material properties and second, changes in the guided wave modes signals due to the structural defects or damage in the material. Fig. 3 illustrates fidelity of the ultrasonic signals analyzed for the velocity measurements associated with the head, first arrival signal representative of the longitudinal wave as indicated in the Fig. 2. This signal velocity is directly related to the composite material in plane modulus that is a critical consideration for the composite use and engineering design [10]. Loss of or inadequate modulus values are considered structural deficiencies.

Fig. 4 illustrates directional ultrasonic velocity profile for the head wave signal in the 20ply Graphite/Epoxy (Gr/E) composite panel. The square of the velocity is directly portioned to the directional modulus of the material. The mapping of the velocity readily, and in non-destructive manner, validates material directional stiffness properties. Because the head wave is non-
dispersive, the velocity measurements are thickness independent and consistently reproducible within the known error of the test measurement apparatus. These measurements can verify material directional properties such as the proper ply orientation and are sensitive to the material mechanical degradation such as fatigue, fiber damage, aging and chemical degradation, heat damage, or mechanical structural damage such as impact defects.

**Fig. 3:** Representative early arrival, longitudinal head wave, guided wave, signal from a Graphite fiber composite sample using single side laser generation and sub-wavelength receiver.

**Fig. 4:** Velocity profile of the head wave as function of direction in the unidirectional 20 ply Gr/E composite plate.
4. Data and Results

Experimental test demonstrations of the method are illustrated in Fig. 5 for the composite overwrap pressure vessel. Such bottles undergo cyclic pressurization fatigue and because of the high gas storage pressure can undergo catastrophic failures. Using described experimental procedures, the Gr/E bottles were characterized for the damage and loss of the modulus. The bottles were scanned as illustrated in Fig. 5 with guided waves propagating in the fiber direction.

![Testing Direction](image)

**Fig. 5:** Gr/Epoxy composite overwrap pressure bottle, guided wave test configuration and scan line direction.

The data was collected on the undamaged and fatigued bottles. Fig. 6 shows velocity profile for the undamaged (virgin) and fatigued (cycled) samples. The examples show both short time, early arrival, head wave signal and the longer, lower velocity, guided wave modes signal. The good material path shows distinct head wave, first arrival signature, and strongly defined, lower velocity, Lamb wave modes. The damaged path signal has total loss of head wave (note lower vertical amplitude scale) and a loss of distinct Lamb wave signals. In damaged zone, the distinct Lamb wave modes are converted into the low frequency structural flexure mode, characteristic of the overall bottle resonant response. Essentially, in the direction of the fibers there is a total local loss of modulus due to the local broken fibers. As a consequence of the cyclic fatigue, such fiber damage increases local stress, eventually initiating a catastrophic failure of the structure. Using these non-destructive tests, we can sense the early local damage of the composite microstructure before it becomes evident to the eye or leads to the in-service failure of the bottle.

![Image](image)

Fig. 7 is an example of a scan line plot of the head wave velocity for the cycled and undamaged bottle. The cycled sample shows an average increase in the velocity values and several locations of severe local damage (square points) as illustrated in the Fig 6 data. The velocity increase can be attributed to the residual strain of the pressure cycled bottle walls and is due to the compaction and rearrangement of the fiber bundles within the composite overwrap material. It is an early indicator of the composite microstructure change and it localizes early bottle damage.
Fig. 6: Ultrasonic guided wave signals for the good material and damaged material sections of the Gr/E composite overwrap vessel. Both, head wave early arrival signal and longer guided wave modes signals, are captured for the good and damaged composite material.

Fig 7: Modulus change and material damage plot of the Gr/E composite material on a scan line shown in Fig.5. The squares on the plot indicate scan location with a total loss of the signals due to the fiber breaks as shown in Fig. 6.

Guided wave modes, such as Lamb waves, redistribute over complex structural features such as geometrical stiffeners in the modern composite designs. Fig. 8 illustrates use of guided waves for the one sided structural damage testing in the hat stiffener geometry using in plane test configurations outlined in chapter 2 and 3. Schematically shown in Fig. 8, the hat stiffener discontinuity is sensed by tracking multi path Lamb wave signals. With the transmitted location and the receiving transducer locations as indicated on the drawing, the guide wave signals can
sense structural damage of the inaccessible hat section. The signals for the sensor 1 and 2 locations are representative of the undamaged stiffened composite panel. Damaged stiffener causes change in the lamb wave modes at the 2nd receive location while 1st sensor location shows no change confirming reproducibility of the test and indicates that only alternate hat stiffener path has changed. Such measurements, although complex, can be automated for the detection of the structural damage in the hidden structural components. Reproducibility of the signal source and broad coverage of all the guided wave signals is required for the successful use of this methodology.

**Fig 8:** Guided wave records for signals traversing the hat section of the undamaged hat wall and hat composite wall with slot damage. Ultrasonic guided wave tests transmitter and sensors are located on the outside structure surface. Y-axis represent relative amplitude and X-axis show time data sampled at 4 ns per point.

5. **Conclusions**

The above experimental tests demonstrate feasibility of the guided wave methods for the practical materials characterization and defect detection testing. Using laser sources and sub-wavelength miniature surface sensors, we have concluded that:

- Ultrasonic in-plane guided wave propagation is a complex process (especially in composites) but it can enable in-plane material properties characterization.
- Ultrasonic transduction process is critical for validity and quality of the in-plane test measurements.
- A reproducible and robust laser-generation and sub-wavelength transducer sensing methodology/technology has been developed and is required for the sensing of the materials properties.
- Laser ultrasonic guided waves tools enable reproducible one sided surface access measurements of the materials defects and complex geometry characterization. (Very useful)
- In-plane guided waves can measure mechanical modulus of the materials.
- Experimental tests confirmed the utility of the methodology for the composite materials properties sensing.

6. References