APPLICATION OF ADVANCED NON-CONTACT ULTRASOUND FOR COMPOSITE MATERIAL QUALIFICATION

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ABSTRACT

Uncured and continuously produced materials cannot afford exposure to a device via contact nor be immersed in liquid coupling. This makes conventional contact and immersion ultrasound unsuitable for inspection. However, ultrasound is highly desirable for inspection of uncured composites as amplitude and time of flight measurements often reveal vital properties. Non-contact (air-coupled) ultrasound has improved to a level of efficiency comparable to conventional ultrasound, usable at frequencies from 30 kHz to 5 MHz. As such, it can be used to relate signal measurements directly to material properties in materials such as fiber-based composite prepreg and most cured and uncured composites. A safe and non-destructive measurement process of relatively low cost, non-contact ultrasound presents opportunities to lower cost, reduce and identify waste, and improve production efficiency and materials quality.

Direct relationships exist between ultrasonic amplitude in non-contact through transmission and key properties such as porosity, delamination, homogeneity and other defects and metrics in composites. By converting amplitude and velocity measurements into material property values through characterization formulas (i.e. moisture content = [ultrasonic amplitude * x] + y), one can apply standard methods of manufacturing process control to hold production processes within desired control limits with real-time feedback. Mapping such measurements to webline material positions allows direct identification of sections of undesirable material, reducing waste and improving manufacturing yields by avoiding unnecessary disposal of uninspected sections. Utilizing multiple points of measurement (multiple channels) in the cross-web direction allows for up to 100% inspection and high accuracy of spatial identification on finished products.

1. INTRODUCTION

Ultrasound Testing (UT) is a popular and effective method of non-destructive materials analysis. However, conventional UT has certain limitations, primarily the need for coupling liquid or direct contact with the test material. Such limitations have prompted the desire for air-coupled or Non-Contact Ultrasound testing (NCU), which can be directly applied to high volume inspection, supporting manufacturing quality control (QC) processes. For a long period though, NCU has proved challenging due to inefficient coupling between ultrasonic transducers and air. Inefficient air coupling prohibits ultrasonic signals from propagating through air and into materials, thus making meaningful analysis a near impossibility. However, over recent years, improvements to air coupling in ultrasound have opened up the ability to propagate and detect ultrasonic signals comparable to those achieved in immersion ultrasound. Further improvements have even increased the frequencies of efficient air transmission to include a wide range from 30 kHz to 5 MHz. Efficient NCU in this frequency range provides applicability for a wide variety of composite materials. We will review actual composite quality measurements resulting from improvements to NCU and discuss the applicability to production QC within composite manufacturing.

1.1 Non-Contact Ultrasonic Advancements

As mentioned above, core product improvements to ultrasonic transducers have opened the door for efficient air coupling. One of the key improvements is proper matching between piezoelectric material (the heart of an ultrasonic transducer) and air.



Figure 1: Ultrasonic Transducer Composition.

A schematic of an ultrasonic transducer is depicted in Figure 1, above. From this image, we can see that a piezoelectric transducer can be composed of the following elements: Piezoelectric material, transition layers, matching layers, and sometimes damping and electrical matching. The piezoelectric material is the primary element, which makes the key conversion from electrical to mechanical energy, and vice versa. However, it is the transition and matching to the test medium (i.e. air) which is of key importance. In this section of the transducer, we are able to affect the efficiency of acoustic propagation into the desired medium. These advancements have opened the door to possibilities which we will now discuss.

1.2 Composite Material Analysis

Composite manufacturing volumes have reached new heights and quality control is ever more important. As composites are expensive and difficult to reproduce, non-destructive testing (NDT) is preferred over other destructive methods. Ultrasound has often been a favored method of NDT as it is safe and reliable. However, conventional UT is often not applicable to high volume manufacturing QC as immersion or contact is required. The advancement of NCU can now allow us to inspect high volumes, even 100%, of manufactured parts.

Composite materials which can be analyzed using NCU include the following: Prepreg, honeycomb composites (Nomex and aluminum core), GFRP, CFRP, and C-C composites. Defects and non-uniformities include porosity and density variation, delamination, foreign object detection, cracks, holes, and more.

2. EXPERIMENTATION

2.1 Types of analyses conducted

NCU is primarily applied in through transmission, requiring access from both sides, but can also be used in pitch-catch mode (same side), and pulse-echo for surface measurements.



Figure 2: Representation of through transmission analysis upon test material.

As seen in Figure 2 above, we can obtain reflection and tranmission signals from an ultrasonic wave, in an ideal condition. For the purpose of testing composite materials, we will mainly focus on the first signal, representing direct transmission. Measurement in through transmission can be conducted within different domains of measurement. These include attenuation (inverse transmismittance), time, and frequency. The strength of the transmission signal is a measure of attenuation or transmismittance, while its occurance in time is a measure of time of flight through a material. To observe in the frequency domain, we can perform an FFT of a time plot and record various values, such as peak frequency and bandwidth. As we will later see, the attenuation and time of flight of the main transmission signal will reveal a significant amount of information relevant to composite quality.

2.1.1 Material Transmittance

The transmittance of a material can be measured by relating the strength of its main transmission signal relative to that through air alone as depicted in Figure 3, below.



Figure 3: Representation of transmittance

Where T_a and T_c are measured in dB, the transmittance of material, *m*, can be represented as follows: $T_m = T_c - T_a$. The transmittance of the material is a representation of how easily it allows ultrasound to pass through it. As our experimental results will show, this can be used to determine whether or not a defect, such as delamination, is present, as well as porosity in certain instances.

2.1.2 Material Velocity

Another key metric is material velocity. Like transmittance, the velocity can be directly related to important material properties. This technique is depicted in Figure 4, below.



Figure 4: Representation of Velocity and thickness

In instances where the material thickness is known, velocity can be calculated as follows:

 $V_{m} = \frac{d_{m}}{t_{am} - (t_{a} - t_{c})}$ $t_{am} = \frac{d_{m}}{V_{a}}$ $d_{m} = \text{material thickness}$ $t_{am} = \text{time of flight in air corresponding to } d_{m}$ $t_{a} = \text{time of flight in air}$ $t_{c} = \text{time of flight in air + material}$ V = air ultrasound velocity

If material thickness is unknown, velocity is calculated as follows:

$$V_{m} = \frac{d_{m}}{t_{am} - (t_{a} - t_{c})} \qquad \qquad d_{m} = V_{a} \times t_{am}$$

$$t_{am} = t_{a} - \left(\frac{t_{1} + t_{2}}{2}\right) \qquad \qquad t1 = \text{round trip time of flight from}$$

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2.2 Test Conditions

In addition to domains of measurement, we also have the option to analyze materials under different base conditions, including transducer frequency, size, and focus. With advancements, as previously described, we can analyze materials at frequencies as low as 30 kHz and as high as 5 MHz in non-contact mode. The sizes of such transducers can vary from as low as 1 or 2mm active diameter to as high as 100mm active diameter or more (frequency dependent). Certain materials and applications are well suited for higher frequencies, these would include high resolution (detectability of small material property variances) requirements. However, such materials may need to be relatively thin, especially at very high NCU frequencies, such as 3-5 MHz and receptive to high frequency ultrasound. Highly attenuative and thick materials, such as concrete and certain composites, are often best analyzed at lower frequencies, such as 50 kHz to 500 kHz. In the following section we will observe results upon composite materials measured under various test condutions and across different domains of analysis.

3. RESULTS

While non-contact ultrasound has only recently begun practice across various industries in manufacturing conditions, a large amount of data have been collected through analysis of composites and other materials. Such tests have been conducted across the frequency range mentioned above in both the velocity and attenuation domains. In the following sections we will explore variations in material properties and correlations developed against ultrasonic units of measurement. Such results will allow us to draw conclusions upon which conditions are ideal for certain applications and materials, enabling for detection during manufacturing processes for quality control.

3.1 Direct Transmission in NCU

In order to demonstrate the variation in material detectability under different frequencies, we can turn our attention to a test material of PMMA (acrylic) which was analyzed at the frequencies of 200 kHz, 500 kHz, 1 MHz and 2 MHz in through transmission NCU.



Figure 5: Detectability as a function of frequency.

As observed in Figure 5, above, the detectability of drilled holes in acrylic material vary significantly with the frequency measured. We can visually see that the results at 500 kHz exhibit the ideal condition for detection of the induced defects within this material. When encountering new applications for NCU, such trials must be conducted in order to experimentally confirm the best fequency for analysis.

3.2 NCU Transducers Acoustic Profile

The images in Figure 6 below exhibit characteristics of high efficiency NCU transducers in ambient air. These data were collected in direct transmission mode and the transducer specifications and ambient air level are listed under each plot. The blue trace represents the A-scan in time while the red trace is the frequency profile.





Figure 6: Characteristics of transducers in air at various frequencies (50 kHz to 4 MHz).

The data in Figure 6 demonstrate that ultrasonic signals in air can be produced efficiently at a large range of frequencies. Perhaps especially impressive is the propogation of NCU in air at 4 MHz as shown in the

final trace of the above figure. Similar results are achieved at 5 MHz using both planar and focused transducers.

3.3 Materials Analysis

After determining ideal frequency and transducer conditions for certain composites, we can perform X-Y scans to create 2-dimensional images (C-scans) on various materials.



Figure 7: Composite materials analyzed using NCU.

Figure 7 represents materials successfully analyzed using NCU. These materials include CFRP, GFRP, prepregs, C-C composites, foam core sandwich composites, honeycomb core composites, wood composites, and more. We will now explore results from analysis upon select materials.

3.3.1 Honeycomb and Foam Core Panels



Figure 8: C-scan images of various honeycomb composites.

The above honeycomb panel images shown in Figure 8 depict various conditions and defects. The upper left image and bottom right image contain spots (circular and square) in blue which represent core defects. The upper right and lower left images depict delamination between the skin and core sections. The blue areas represent poor lamination/bond and red areas represent good bonding. The thickness of the core sections vary from half an inch to 2 inches.



Figure 9: High resolution imaging of CFRP skin Al Honeycomb Core (25mm thick) with fine embedded defects and broken honeycombs imaged with focused 200 kHz transducers.

Using high resolution ultrasound with small spot size transducers (Figure 9), we can resolve detail including individual honeycomb cells and small defects.



Figure 10: Honeycomb panel analyzed at 200 kHz with planar transducers (left) and point focused transducers (right).

Figure 10, above, demonstrates the effect of using focused and unfocused transducers upon the same material sample. The sample analyzed is a 25 mm thick honeycomb panel with delamination defects of varying size and a recessed core on the right side. The image to the left represents analysis conducted with planar transducers at 200 kHz, while the image to the right was created using focused transducers, also at 200 kHz. While both analyses can detect all embedded defects, the visual difference between the two samples is stark. The focused analysis resolves variation in the material to a much finer spatial resolution. Depending upon the desired information, either analysis could be useful. For example, if the variation within individual cells is an undesirable artifact of the analysis, a planar set of transducers may be preferred. However, if visual representation of individual cells is preferred then focused analysis can be advantageous.



CFRP skins foam core sandwich Figure 11: C-scan images of foam core composites.

Foam has traditionally posed difficulty for measurement using ultrasound, but success with high efficiency NCU has opened up new possibilities. In Figure 11 we can observe internal defects within foam core sandwich panels. Blue areas represent high porosity defects.

3.3.2 C-C Composites

Carbon-Carbon composites are traditionally difficult to to analyze under various conditions, including ultrasound, due to high attenuation. However, with efficient through transmission ultrasound at relativly low frequency (between 100 kHz and 500 kHz), substantial progress has been achieved.



2D Carbon-Carbon Airplane and Automobile Disc Brakes

Jumbo aircraft disc brake Formula 1 car disc brake Figure 12: Images of C-C Disk Brake Composites.

In Figure 12, above, the representative images show extreme delamination within the central portion of a C-C aircraft disk brake (left). The blue and dark blue areas represent low signal amplitude in the attenuation domain, which is attributed to poor bonding between layers.

Non-Uniform Bond

Quality

Carbon-Carbon Plates for Oven Fixtures

Major Delamination

Well Bonded Layers

Figure 13: Images of C-C Oven Fixture Composites.

Figure 13 depicts C-scan images of C-C composites used as high temperature oven fixtures. Using NCU, we can identify relevant defects in the C-C plates. In the above image, major delamination was recorded in the left-most part, noticeable in the dark blue regions. In addition, uneven bonding was observed in the center unit as compared to a defect free sample on the right.

3.3.3 CFRP (Carbon Fiber Reinforced Plastic) Composites

Bonding between layers within CFRP panels is a key quality metric. NCU is largely receptive to bond quality, as poor bonding highly attenuates signal amplitude.



Figure 14: CFRP composite with embedded defects (4mm thick) with line scan to the right.

As seen in Figure 14, various embedded defects within CFRP are easily detected using NCU. While the upper image represents the C-scan, the lower plots are line scans through selected sections of the material. The upper and lower line scans pass through the defective portions while the middle represents the more uniform central section of the material.



Figure 15: CFRP composites with varying porosity (4mm thick) with line scan to the right.

NCU is also highly sensitive to porosity variation. In Figure 15 we observe a notable difference between samples of higher porosity (left) and lower porosity (right). Increased porosity tends to attenuate ultrasonic signals more heavily.



Figure 16: High resolution C-scan images of CFRP lamiantes with embedded defects (6mm thick).

High resolution NCU allows for detection of small embedded defects within materials, such as CFRP lamiantes. Figure 16 demonstrates the detection of defects smaller than 1mm in thickness. These results were obtained using focused ultrasound at 500 kHz.

3.3.4 Carbon Fiber Prepreg

A key ingredient material for aerostructures, the quality of carbon fiber prepreg is of great importance. Traditional ultrasonic detection methods, such as contact and immersion, are not applicable due to the adverse effect upon uncured prepreg from direct contact or water exposure. For this reason, NCU is a desirable method for quality measurements.



Figure 17: C-scan images of aerospace prepreg material with detects and varying resin content.

Figure 17 represents images of aerospace prepreg material. The left image contains overt defects (red spots) and lower porosity (blue regions). The right image does not contain defects and is of relatively normal porosity. To validate the correlation between ultrasonic amplitude in carbon fiber prepreg and material impregnation level, an experiment involving a secondary test method was used. Two samples of expected variation in porosity were measured using NCU. Results from these measurements are seen below in Figure 18. Sample A exhibited higher ultrasonic applitude than Sample B with readings ranging from 0 to -10 dB and -20 to -25 dB, respectively.



Figure 18: NCU scans of sections of unidirectional prepreg with expected differences in impregnation level.

Following the measurements in NCU, the samples were evaluated under a secondary, destructive, method of water pickup. During the water pickup test, the samples are immersed in water for a period of time under controlled conditions. The samples are weighed prior to water exposure and immediately after. It is expected that any increase in weight is due to porosity or inverse impregnation within the prepreg material. This is caused by "soaking" of water within material that is not fully impregnated.

| Sample | NCU Amplitude | W1 (g) | W2 (g) | WPU (%) |
|--------|------------------------|--------|--------|---------|
| А | High (0 dB to -10 dB) | 2.977 | 3.086 | 3.7% |
| В | Low (-20 dB to -25 dB) | 3.022 | 3.558 | 17.7% |

Table 1: Water pick-up test results of unidirectional prepreg specimens

Table 1 represents the results from water pickup upon the prepreg samples from Figure 14, where W1 represents the weight prior to water pickup, W2, after water pickup, and WPU being the change in weight

on a percentage basis. From these results, we see that Sample A, which exhibited higher ultrasonic amplitude has a smaller change in weight as compared to Sample B, which exhibited lower ultrasonic amplitude. These results seem to validate the claim that lower amplitude of prepreg in NCU represents lower impregnation, and vice-versa.



Figure 19: C-scan images of wind turbine blade prepreg material with wave defect.



Figure 20: C-scan images of wind turbine blade prepreg material with multiple defects: Fuzzball (left and center and dry region (right)

Figures 19 and 20 depict carbon fiber prepreg for wind turbine blades with various defects. The image from Figure 19 represents a wave defect, in blue towards the left side. As can be verified in the photograph of the actual material, this wave defect (or fiber misplacement) is clearly detected using NCU. Figure 20 represents two images depicting a "fuzzball" defect (left and center), which is a misplacement of fiber in a circular ball. The right image within Figure 20 contains a dry region in blue towards the lower section. While unanticpated during manufacturing, it was confirmed that this section is notably more porous than the surrounding area.

3.4 Manufacturing Quality Control

While NCU has demonstrated applicability for measurement of key material characteristics, such as porosity, delamination, and foreign objects, it presents a unique opportunity to serve as a safe, reliable, and cost effective quality control method. 2-dimensional imaging, recording key NCU values such as transmittance or velocity, is a preferred output for quality control measurements. Such images can be produced using X-Y scanning as well as multi-channel static arrays.

3.4.1 X-Y Scanning

For high resolution imaging, X-Y scanning can provide a large amount of detail in a cost-effective manner. In its simplest form, as seen in Figure 21 below, X-Y scanning consists of a motion control system capable of moving a transmitting and receiving transducer across a test material in two axes to create a 2D image at the desired resolution.



Figure 21: Example of X-Y Scanning system for 2D image creation.

Depending upon throughput requirements, NCU X-Y imaging can be a powerful method of quality control, creating detailed images with statistical processing capability for quick accept/reject decisions. It also allows for human operators to visually process C-scans to determine if defects or non-uniformities may be present within products.



Figure 22: Sample of imaging and statistical processing capable with X-Y scanning.

In Figure 22 we see an example of the kind of statistical analysis which can be pulled from X-Y imaging. These include general measures such as average, minimum, maximum, standard deviation for a C-scan as well as histograms and line scans across desired areas. While X-Y scanning can provide detailed information, QC for high throughput applications are sometimes well served using static array imaging systems.

3.4.2 Multi-Channel Arrays

Continuous inspection during manufacturing can be best suited using multi-channel arrays in NCU. Each channel in the array can produce a line scan or rolling C-scan to provide constant and instanteous feedback. The spatial resolution is determined by the number of channels and their spacing relative to each other.



Figure 23: 32-channel multi-element non-contact ultrasonic array.

Each production application may require a different configuration of ultrasonic transducers in a multichannel array. Figure 23 provides an example of a 32-channel array, arranged in a brick pattern for continuous coverage during webline manufacturing. This particular example consists of 500 kHz ultrasonic transducer elements, each with dimensions of 19 mm x 19 mm active area as receivers (visible on the lower portion of the photograph). The transmitting unit is a large oversize transducer with dimensions of 4 cm x 25 cm. The transmitter transmits ultrasonic energy across all receiving elements but the image resolution is determined by the receiver array pattern.

In addition to a brick pattern, transducer arrays can also be constructed in linear form. While continuous coverage is not obtained, the effectiveness of a linear set of trasnducers can often provide enough information.



Figure 24: Representation of a linear array pattern.

In Figure 24 we see a linear pattern comprised of multiple channels per transducer pair. In this case several pairs of transducers can be set up alongside each other and depending upon the coverage area and size of element, more or less pairs can be used. Like the previous brick pattern example, the transmitting units are oversized to cover the area of the receiving transducer arrays.

For continuous inspection, we can choose to measure the ultrasonic signal in either or multiple domains as mentioned earlier: Attenuation, velocity, or frequency. In order to measure the desired value, we gate the A-scan of the signal (as was done to create the above C-scans) and continuously record the metric of choice.



Figure 25: Representation of a linear array pattern.

For continuous inspection, we can choose to measure the ultrasonic signal in one or multiple domains (attenuation, time, or frequency) simultaeneously. In order to measure the desired value, we use data from the A-scan of the signal (as was done to create the above C-scans) and continuously record the metric of choice. Figure 25 depicts a rolling line scan for a single channel during continuous acquisition.

4. CONCLUSIONS

Through significant advancements in non-contact ultrasonic technology, inspection opportunities to support quality control in manufacturing are now possible across a number of products in the composites industry. As demonstrated above, measurements such as porosity, density, delamination, and more can be achieved through NCU. Based upon the nature of the desired measurement, this can be accomplished at frequencies between 30 kHz and 5 MHz through X-Y scanning or by use of multi-channel arrays for continuous inspection. Continuous inspection provides beneficial feedback during manufacturing and full information regarding product quality following fabrication. While a number of materials have been analyzed, the technology is relatively new and there are a multitude of materials an applications which have yet to be explored. Further work is required and a number of industrial applications should be pursued using non-contact ultrasound for the purpose of production quality control.

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