ABSTRACT

The Use of Non-Destructive Testing with High-Frequency

Ultrasound on Curved Carbon Fiber Laminates

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Carbon fiber composites have continued to become more frequent in major industries such as Aerospace and Automotive, due to their high strength-to-weight ratios. Traditional destructive testing is not always applicable as it renders the part useless for its intended purpose. Therefore, non-destructive testing is necessary to keep the part in place for its intended application. Up to this point, non-destructive testing with high-frequency ultrasound has only occurred on flat composites. Due to the prevalence of curved composites in industry, this thesis focuses on using high-frequency ultrasound A-scan and C-scan techniques to perfect a procedure to scan a curved Carbon Fiber Composite. This thesis conveys this developed technique to scan a curved carbon fiber laminate using ultrasound A-scan and C-scan techniques and presents a study to convey its feasibility.

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THE USE OF NON-DESTRUCTIVE TESTING WITH HIGH-FREQUENCY ULTRASOUND ON CURVED CARBON FIBER LAMINATES

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By

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CHAPTER ONE

Introduction

1.1 Research Motivation and Objective

In recent years, laminated carbon fiber composites have become increasingly popular as companies seek stronger alternatives, with decreased weight compared to traditional engineering materials such as aluminum and different types of steels. Specifically carbon fiber laminated composites have become popular in the athletic, automotive and aerospace industries. The main advantages laminated carbon fiber composites offer over aluminum and steel is their increased strength to weight ratios along with the ability to increase strengths along desired directions. However, this increased strength does not come without its drawbacks. The main drawback is the complexity of the manufacturing process, which results in increased materials, engineering and fabrication costs. Several commonly employed techniques involve the manual layup of the lamina which, leads to greater variability between each part, thus introducing quality control issues [1]. Therefore, non-destructive testing is needed to ensure the part was manufactured to the design specification.

Besides being useful for quality control non-destructive testing can be used to determine the unknown ply stack orientation and sequence of a carbon fiber laminate. Knowing these qualities is especially useful for determining materialistic properties of the carbon fiber laminate. Current research efforts in ply detection have been applied to flat carbon fiber laminates. The following thesis expands upon the work of Stair [1] and Vo [2] by introducing an ultrasonic technique that incorporates A-scan and C-scan data for curved carbon fiber laminates. In this effort methods and results are presented see an individual carbon fiber tow within a curved carbon fiber laminate.

1.2 Thesis Overview

Chapter Two begins with a brief discussion on the applications, benefits, and recent trends of carbon fiber reinforced laminates over materials such as aluminum and steel. After this a brief discussion on the laminate manufacturing techniques used for this thesis will be presented. The discussion transitions to the introduction of various industrially accepted methods of non-destructive techniques and applications, with a special focus on ultrasound techniques. Finally, the fundamental basics of ultrasound technology and specific examples of its use in industry will be presented.

Chapter Three presents an overview of the entire process beginning with the pre-scan of the curved carbon fiber laminate and ending with the ultrasonic C-scan. This chapter will focus on the scanning methods for a curved carbon fiber laminate stack using A-scan and C-scan ultrasound techniques as well as the modifications that were made to the already existing system and scanning algorithms. The methodology will be presented along with an in-depth discussion of how the system is controlled through an in-house LabVIEW program along with an integrated in-house MATLAB program.

Chapter Four will outline the study that was then undertaken to confirm the successes of the modifications discussed in Chapter Three, as well as the ultrasound C-scan Data processing developed by Stair [1]. Finally, the manufacturing methods used to create curved carbon fiber laminates will be presented in detail, including how to replicate the process. The main limitations for the manufacturing process are only a small number can be manufactured at a time, it can be difficult to achieve smooth surface finishes and releasing the part from the mold can also be challenging.

Chapter Five provides a discussion of the results from chapter four, the difficulties and limitations of this methodology and potential future work. This includes but is not limited to, improving and eliminating the limitations, as well modifying the set-up to be able to scan two degrees of curvature, instead of only one. Future work will also include streamlining the process to make curved carbon fiber laminates so that it is more efficient, creates a smoother surface and creates less waste. Specifically, the proposed tool and methodology may provide a mechanism to see an individual carbon fiber tow in a curved carbon fiber laminate up to five lamina thick.

CHAPTER TWO

Literature Review

This chapter includes a brief overview of composites, the rise in need for non-destructive testing and applications for composites. It will also include a discussion on different laminate manufacturing techniques, specifically the Vacuum Assisted Resin Transfer Molding method. This chapter will also provide a summary of the fundamentals of ultrasonic analysis as well as discuss the fundamentals of and current state of affairs for ultrasonic technology. Finally, different non-destructive testing techniques will be presented and discussed.

2.1 Composites Introduction

In order to develop products, that are stronger and lighter, industries such as aerospace, automotive and athletic industries are using carbon fiber reinforced products more and more prevalently in their products [1]. Recent examples of products with these composites in them include the Boeing 787 Dreamliner, Lamborghini Sesto Elemento and various golf clubs and tennis rackets [3, 4]. These are just a few examples of products with carbon fiber reinforced laminates in them as there are many others that exist in everyday life.

Figure 1: Left is Lamborghini Sesto Elemento and right is the Boeing 787 Dreamliner [3]

The prices of these composites vary substantially and depend on the type of fiber as well as manufacturing method used. [1]. A good example of this would be a boat hull made out of fiberglass would be much cheaper than a wing of a Boeing Dreamliner 787, made out of carbon fiber [1]. Most large volume and large scale manufacturing methods involve combining chopped fibers in a polymer, often in the form of a pellet. This pellet can then melted and injected or compression molded into parts [5]. Another popular method of manufacturing involves coating a composite fiber in either a thermoplastic or thermoset resin or wrapping the fiber around a piece of tooling or mold [1]. Thermoset resins are activated using a chemical catalyst or through the addition of heat. After the resin hardens, thus adding a polymer matrix, the part and mold can be separated, leaving only the completed part. The manufacturing method used in this study involves cutting plies from carbon fiber fabric and lying them on a curved tool and allowing them to chemically cure. After this process, the final manufactured part is called a carbon fiber reinforced composite.

While these carbon fiber composites have higher strength-to-weight ratios than traditional metals, the advanced manufacturing process creates additional difficulties, as the final material properties are heavily influenced during this process. Carbon fiber laminate properties, are determined by the ply type, amount of plies, and the orientation of each individual laminae [6].

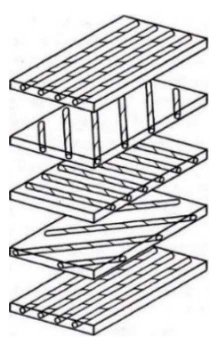


Figure 2: Non-bonded View of a composite laminate [6]

Each of the properties mentioned in the previous sentence can be seen above in figure two. In this case, the laminate has five plies, as well as four different ply orientations. The ply orientations from top to bottom are: 0°, 315°, 90°, 45, and 0°. Finally, the fabric type is unidirectional, as the fibers point one direction and are not interwoven between each other.

During the design phase, the material properties of the final part can be determined by changing the ply type, orientation and thickness of each lamina in the bulk lamina to fit a specific application [1]. However, any variation that occurs during the design phase can have significant effects on the final processed part. It is because of these variations that the final manufactured part is rarely a perfect match of the designed part. For example, during the manufacturing process, plies may slip or rotate within the part. Furthermore, there may also be air bubbles or parts of carbon fiber that were not coated in resin that would also contribute to the final processed part being different from the designed one [1].

Additionally, each individual lamina and fabric type affect the overall properties of the final fiber reinforced composite. An example of this is a laminate made of a unidirectional ply will have extraordinary strength along the direction of the fibers, but are much weaker in the direction perpendicular to fiber direction compared to the direction of the fibers [6]. Unidirectional fibers are often utilized for these longitudinal properties, as discussed in Tucker and Liang [7]. Consequently, a weave pattern may be used if loading conditions are anticipated in multiple directions or to ease the manufacturing process [1]. Once a laminate ply type and orientation are identified, laminate theory [6] can be used to determine material properties of the overall part.

Specific properties that are of interest are the bulk modulus or the failure envelope. Either of these can be found using any of the failure techniques described in paper of *Hinton* et al. [9]. There are multiple destructive techniques to determine ply type and orientation, but each involves the separation of fibers from the polymer matrix, which ultimately renders the part useless for its intended application [1]. Since this is the case, non-destructive techniques to identify part functionality and quality are not only necessary but becoming more widely used [10, 11].

Throughout the manufacture of these materials, the formation of defects and voids within the part are a common occurrence [11]. Traditional non-destructive ultrasound methods have been applied to locate these defects, as the ultrasound wave travels at a different velocity through a void than it does the rest of the composite part [1]. Ray *et al.* [12] applied this methodology to various types of defects within carbon fiber-reinforced composites and was able to detect the defects because the ultrasound wave travels at a different velocity through different materials. Ultrasonic techniques have been applied to various industries, including the aerospace, automotive and medical industries [1]. In Chapter Three of this thesis, an ultrasonic scanning methodology for curved carbon fiber laminates will be introduced, with the final goal of being able to see individual carbon fiber tows. The results from using this proposed methodology as well as its potential applications and limitations will be presented in chapter five.

2.2 Laminate Manufacturing Techniques

There are many different types of manufacturing for fiber reinforced composites including wet lay-up, injection molding, extrusion, blown film, prepreg laminates and Vacuum Assisted Resin Transfer Molding Method (VARTM). Due to their prevalent use in the author's research lab, the main methods of focus will be wet lay-up, prepreg laminates and vacuum assisted resin transfer molding methods. For this research vacuum assisted resin transfer molding method was used to create curved carbon fiber laminates, so it will be the main focus.

The wet lay- up method is one of the simplest and least expensive manufacturing methods [1]. Fiber layers are cut from a roll of fabric and coated in a resin of some kind. The resin usually hardens from some sort of chemical catalyst and may also have to be exposed to a thermal cycle to complete the process. These processes can last from several hours to several days [11]. The long layover time prevents these processes from being used for mass scale production, which is the production of large amounts of standardized products.

The prepreg method is one of the more expensive methods and offers the least amount of customability from the resin/catalyst point of view [1]. A prepreg material is fabric that has been infused with resin [13]. To manufacture the part, plies are cut according to desired size and orientation and placed on the necessary tooling and cured to the manufacturer's specifications [1]. Pressure is then added to the laminate during the cure cycle. It is this applied pressure that spreads the resin across the laminate to fill voids and create a smooth finish on the final part [14]. If no pressure is applied the laminate will not be manufactured correctly and will come out with noticeable voids.

2.2.1 Vacuum Assisted Resin Transfer Molding Method

The third and final laminate manufacturing method is vacuum assisted resin transfer molding method (VARTM) and is used to manufacture the parts used this thesis. VARTM is similar to the wet lay-up method in that the part must be held under pressure throughout the curing process. However, the methodology by which the resin is applied is quite different [1].

This method requires the dry carbon fiber fabric to be placed on top of the necessary tooling, in the desired ply stack sequence. A layer of peel ply and infusion mesh is then placed on top of the stack of laminate layers [1]. A hose is then attached on one side of the laminate and another hose is attached opposite of the first one. The set-up for this manufacturing method is seen below in figure three.

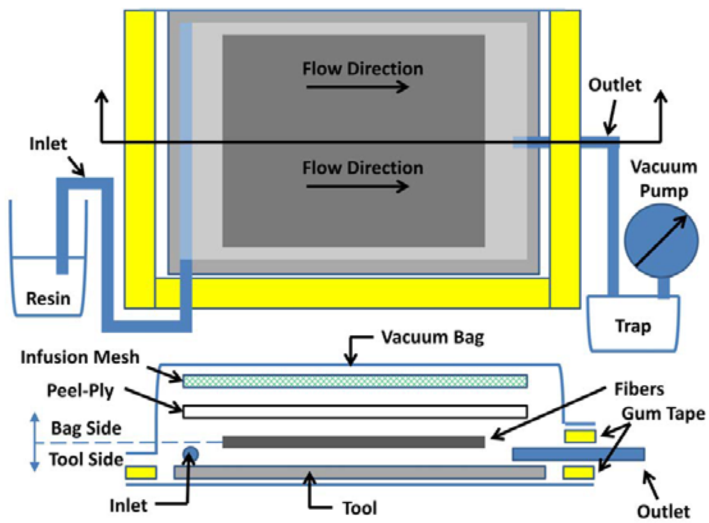


Figure 3: Schematic of Vacuum Assisted Resin Transfer Molding Manufacturing Method. Image Provided by Mailen [15].

The inlet hose is connected to the resin reservoir and the outlet hose is attached to the resin sink, which catches all excess resin [1]. The vacuum pump is attached to the top of the resin sink, allowing a vacuum to be pulled across the laminate [1]. This vacuum is what pulls the resin across the laminate, soaking the dry carbon fibers in resin [15]. For this process to be most effective, air bubbles cannot be allowed into the laminate. Air bubbles are a major issue because they are unable to transfer loads effectively, and thus weaken the overall laminate.

Manufacturing high quality parts using this method requires a great deal of skill as it takes multiple repetitions to be able to consistently get most of the air bubbles out, in order to create a near vacuum. This particular method is best for woven and twill fabrics. These fabrics have fiber tows which are interwoven and thus assist in effectively moving the resin throughout the entire laminate [1]. These types of fabrics were used in the ultrasound study introduced in Chapter Four. More details will be provided on the specifics of this, relevant to this thesis in Chapter Four.

2.3 Fundamentals of Ultrasound Analysis

In recent years, ultrasound systems have become more popular as they are much cheaper and easier to use than other more traditional non-destructive testing systems [16, 17]. Typical ultrasonic NDT systems use a flat front transducer that has its pulsar controlled by a computer [1]. The transducer can be configured so that it both emits and receives the signal or it can be configured to simply emit the signal and a second transducer can be placed elsewhere to receive the signal for processing. When the transducer both emits and receives the signal, it is called the pulse – echo mode, as shown in figure 4c [1]. When one transducer emits the signal and another receives it, this is called a pitch-catch set – up, as shown in figure 4b [1]. In the present research thesis, the author uses the pulse-echo technique.

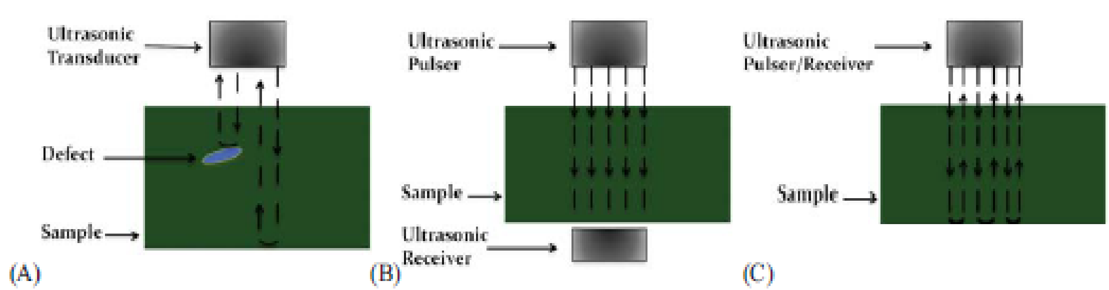


Figure 4: (A) Ultrasound being used to detect a defect/void, (B) diagram of the pitch-catch mode of a transducer, (C) diagram of a pulse – echo set – up. Image provided by Stair [1].

Furthermore, the transducers used in this research are spherically focused, instead of the widely used flat front transducers, such as shown in figure 5a. The resolution of a flat front transducer is dependent on the diameter of the transducer face [1]. The resolution of a flat front transducer is not refined enough to detect the individual weaves of a carbon fiber lamina, so a spherically focused transducer is used instead. Flat front transducers exist that are smaller than the tow, but they cannot be used as their frequency is often limited to 1-2 MHz and therefore they do not have sufficient vertical resolution due to the wavelength. A spherically focused transducer, as shown in figure 5b, focuses the acoustic wave to a single point, so the resolution is much greater, and therefore it is able to detect the individual weaves of a carbon fiber lamina.

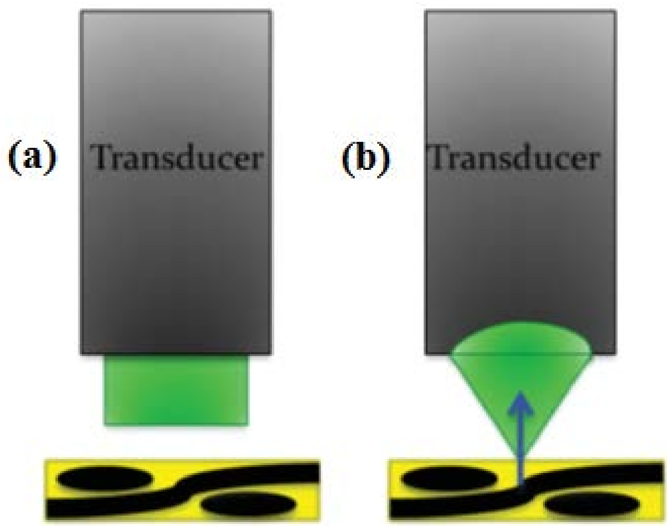


Figure 5a is a flat front transducer and Figure 5b is a spherically focused transducer. Image provided by Stair [1].

The increased resolution of the spherically focused transducer allows it to detect the carbon fiber tows from the resin. The carbon fiber is represented by the S-shape and the resin matrix by the yellow above, in figure 5 [1].

2.3.1 Mathematics behind Ultrasound Analysis

Within an elastic solid, the wave equation is governed by Navier's equations as (see e.g 14)

$$\frac{\partial^2 u}{\partial x^2} - \frac{\partial^2 u}{c_i \partial t^2} = 0 \qquad (2.1)$$

Where the Laplacian with respect to space x of the displacement u in one dimension is related to the acceleration of the displacement scaled by the speed of sound c_i within the ith acoustic medium [1]. The speed of the acoustic wave is dictated by the properties of the medium through which it is passing through and is most often a function of the stiffness and density [1]. Once the wave is transmitted between medium a reflection of this wave returns toward the transducer and a refraction wave is passed through the interface of the two mediums and continues to propagate through the part [1], as shown below in figure 6.

When the wave passes from one medium to another, the ratio of the reflective wave speed to the refractive wave speed is governed by Snell's law, seen below in equation 2.2.

$$c_1 \sin \theta_1 = c_2 \sin \theta_2 \qquad (2.2)$$

Where θ_1 is the angle of the incident wave with respect to the normal, θ_2 is the angle of the reflected wave with respect to the normal, c_2 is the speed of sound of the incident wave, and is the speed of sound of the reflected wave. A visual representation of Snell's law is shown below in figure 6.

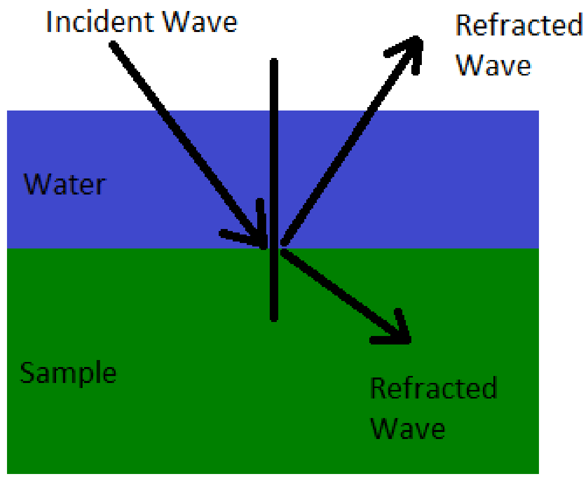


Figure 6: Visual representation of Snell's Law.

In a composite laminate these two separate waves are generated anytime there is a change between the resin and a fiber or vice-versa. The more layers within any given laminate the more reflection and refraction waves will be created. As the acoustic wave goes deeper into the part acoustical attenuation becomes a significant factor [1]. If the part is too thick, the signal will degrade too much and the data collected may not be useable. Deschamps and Hosten [17] discussed the attenuation within a medium, similar to the epoxy matrix used in this research, and provided multiple equations for predicting the attenuation. Also, Lonne *et al* [18] investigated the attenuation of an acoustical signal in a carbon fiber laminate and found their results correspond to the exponential decay form presented by Schmerr [19] as

$$\left|\frac{p_1}{p_2}\right| = e^{(\alpha \Delta x)} \tag{2.3}$$

where the ratio between the pressures $\frac{p_1}{p_2}$ within a material, separated by a distance Δx can be attained after the attenuation constant α is a known quantity. This constant is a material property that has been shown to be functions of the material stiffness as well as the frequency of the incident wave [19]. For the weave type used in the study presented in Stair [1], a maximum of 20-30 layers of different orientations can be used before the signal attenuation becomes too great. However this number is strongly dependent on lamina thickness and volume fraction of fibers [1]. More information will be presented on this in Chapter Four.

2.4 Non-Destructive Testing Techniques and Applications

As mentioned earlier in earlier chapters the manufacturing process of composite fiber reinforced composites, is crucial to the final properties of the part. While these composites have higher strength to weight ratios of traditional engineering materials, their manufacturing processes are more complex, leading to increased engineering difficulties as well as the need for testing techniques that can test the integrity as well as provide feedback on the properties of the part. In order to do these things reliable non-destructive testing methods are required. As these non-destructive techniques become more and more popular, they are being applied to larger structures such as wind turbine blades and airplane wings [20].

One of these such methods is testing using infrared vision. Generally speaking it is fast, cost efficient, and has the advantage of not having to be in contact with the part [21]. This technique is based off the detection of reflected or transmitted through infrared radiation through the part [21]. In order for this type of technique to work properly, an illumination source must be chosen correctly to provide continuous and uniform illumination [21]. For example, incandescent lamps provide a wide electromagnetic spectrum, going from the ultraviolet (.01 to 35 μm), and all the way to the infrared (14 to 1000 μm). Most of this radiation is visible on the infrared bands and therefore incandescent lamps can be used as an illumination source [21]. When this method is done properly it can be used to collect real-time information about the presence of subsurface defects, as well as offer the possibility to digitally compare infrared and visible images. [21].

Another type of non-destructive and non-contact testing and are a number of optical techniques including but not limited to digital shearography and Electronic Speckle Pattern interferometry (ESPI) [22]. Digital shearography has been around as a non-destructive testing technique since the 1980s. In real time, this technique is able to detect voids and defects within the part [22]. The way it reveals these things is through a "localized disturbance in the fringe pattern depicting the gradient of out-of-plane surface displacements" of the part being tested [22]. These disturbances are then measured using thermal, mechanical or pressure methods. These subtle changes are detected and the part is illuminated with a laser which creates a speckled image [22]. This speckled image is subtracted from one that was captured earlier, which results in a fringe pattern. [22]. The anomalies in this fringe pattern predict the approximate size and location of defects and voids [22]. ESPI is different from digital shearography in that the fringe pattern is displayed on a computer screen in the form of a contour map of the surface displacement of the part, when it is agitated in some manner [22]. The displacement can be measured in several different directions including, the in plane or out-of-plane direction. The out-of-plane direction is more versatile because it takes advantage better of the light coming from the laser, as described above [22].

Ultrasound techniques are the focus of this thesis as they are non-contact and may provide insight within a layered part. Currently ultrasound A-scans and C- scans are being used to determine ply type, orientation and thickness of each layer within a laminate [23]. Below, figure 7 shows the raw data from an ultrasound A-scan of a 4 layer curved carbon fiber laminate.

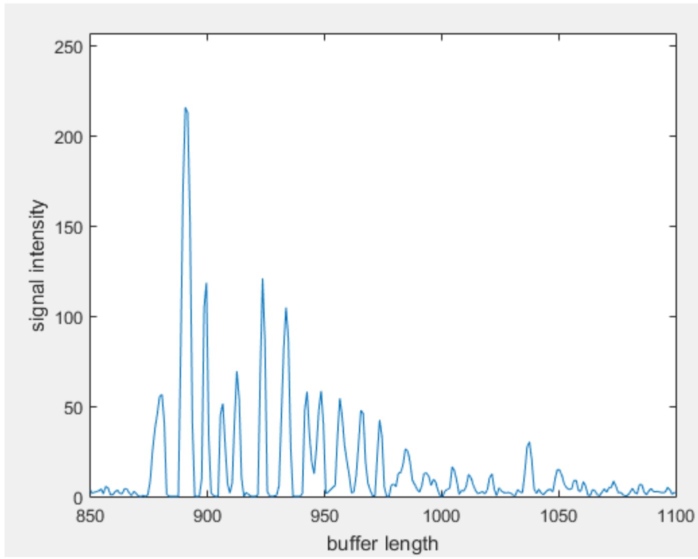


Figure 7: Raw A-Scan Data of a 4 layer curved carbon fiber laminate

This particular image was collected from a 4 layer curved carbon fiber laminate using a 15MHz transducer operating in pulse-echo mode.

The A-scan image is taken at an angle location within the part, and a group of A-scans can be gathered to form what is called a C-scan. The C-scan data can be used to generate planar images representative of different depths and layers within the laminate [1]. An early C-scan of a curved carbon fiber laminate can be seen in figure 8. The image is blurry due to the small nature of the overall scan which only had a total area of 25 mm^2. The study presented in chapter four attempts to create a clearer photo, so that the individual tows of the carbon fibers can be seen.

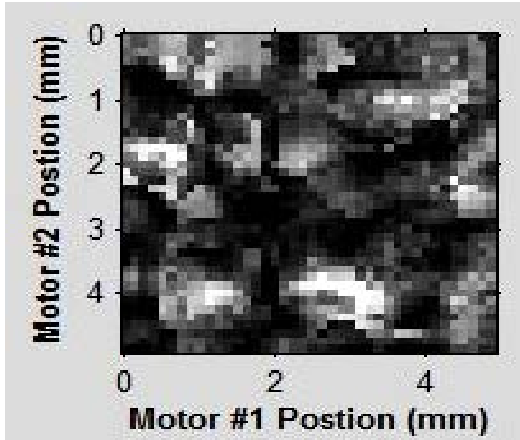


Figure 8: Early C-Scan of interior of curved carbon fiber laminate, .027 mm from the surface.

These images are pertinent because from them, the ply direction and orientation can be determined either visually or using patent – pending software. As formally mentioned, the ply direction and orientation are critical to determining material properties of a composite laminate.

The A-scans are collected using a x-y-z translation system that is controlled by a LabVIEW program with inputs including : pulse type, damping resistor value, pulse voltage, pulse width, wave type, gain, voltage DC offset, buffer length, low pass and high pass filter values, trigger delay, sample rate, frequency, trigger, number of pulses per signal, number of sample increments in each x and y direction and the number of steps taken between each increment in each direction [1]. The parameters mentioned in the previous sentence must be set prior to each scan, depending on how many layers and type of laminate. These parameters are fed into a custom Matlab subprogram which creates a 3D C-scan matrix, which is then created into a video that shows the varying depths of the laminate [1].

The ultrasound process mentioned in the previous paragraphs was developed for flat carbon fiber composites to detect ply orientation, ply type and thickness of each layer using a patent pending detection algorithm (PCT/US13/33187). This technique was modified by the author in order to be applied to curved carbon fiber laminates with the goal of being able to see a carbon fiber tow from a layer within the laminate. The experimental set –up of this procedure as well as the modified software behind it, will be discussed in detail in Chapter Three.

CHAPTER THREE

Ultrasound Scanning Methodology

This chapter includes a brief overview of the ultrasound scanning methodology used in this research project, including the front-end scanning, the mid-scan data processing and back-end data processing including the use of patent-pending algorithm constructed in the Matlab Software environment. More specifically this chapter will focus on the modifications that were done to the existing system in order to scan curved carbon fiber composites.

3.1 System Overview

At the beginning of this research two separate experimental versions of the ultrasound system existed within the laboratory. A prototype of an out of immersion tank that improved portability and the second was a full immersion system with planar motion capability. The full immersion system is not feasible for large parts, such as an airplane wing or fuselage as it would be impossible to submerge these types of parts in a tank. In this research, the conversion to scanning a curved structure were all done in the full immersion configuration to demonstrate a proof of concept.

3.1.1 Immersion Set-up without Curvature Modifications

This experimental system uses a US Ultratek PCIUT3100 ultrasonic pulser/receiver that is attached to a custom Velmex translation table, with degrees of freedom in the x-y-z as well the added ability to rotate about the y-axis. Initially, this system was only able to scan in the x and y directions, thus making it only able to scan perfectly flat carbon fiber composites. The previous set-up is shown in figure 9

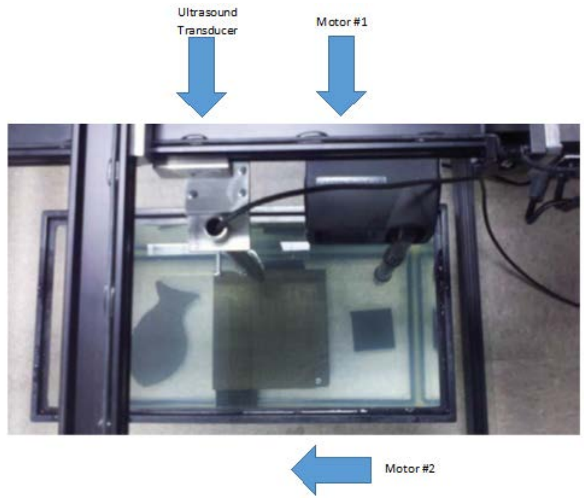


Figure 9: Initial Immersion set-up prior to curvature modifications. Image provided by Stair.

In both this experimental set-up and the curvature set-up, water was chosen as the medium between the ultrasonic transducer and the carbon fiber part. In the author's experience, distilled water works best to keep out impurities that could otherwise cause attenuation of the ultrasound signal. Water was chosen as the medium because it is cheap, readily available and does a great job at keeping the ultrasound signal from attenuating too quickly. Without water or some other medium, such as ultrasonic gel, the signal would attenuate very quickly, thus potentially making the data useless for further analysis.

There is a PCI board mounted in the computer that is based on the user's inputs, which creates an electric pulse that will be sent to the transducer and will be used to generate the ultrasonic acoustical signal [1]. The specific user points are: pulse type, damping resistor value, pulse voltage, pulse width, wave type, gain, voltage DC offset, buffer length, low pass and high pass filter values, trigger delay, sample rate, frequency, trigger, number of pulses per signal, number of sample increments in each x and y direction and the number of steps taken between each increment in each direction [1]. These user-defined quantities are shown below in figure 10.

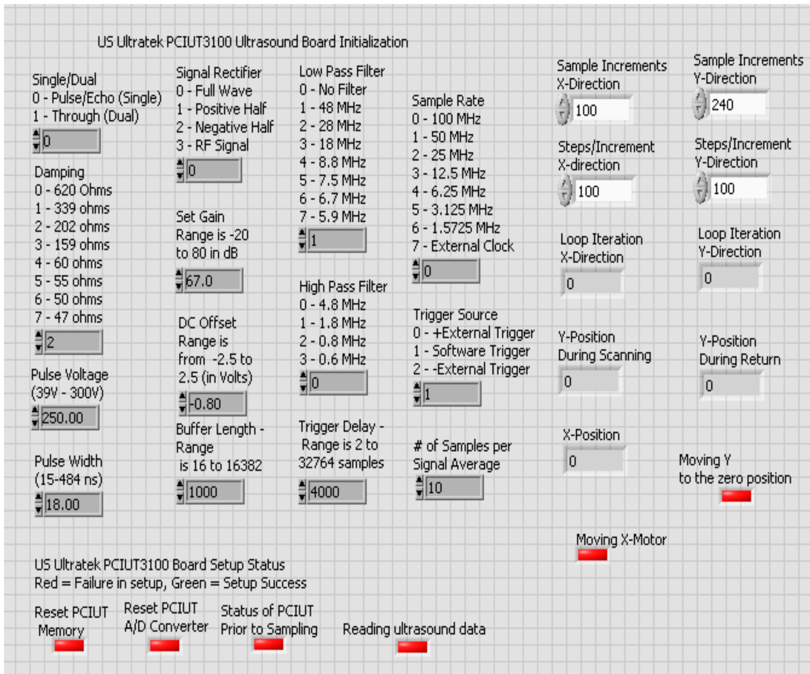


Figure 10: Screenshot of User-defined inputs for planar C-scan

Also in figure 10, the reader can see an example of often-used quantities for many of these inputs. For example the sample rate is always 100 MHz, the trigger source is always software, the low and high pass filters are always the same values, respectively and the buffer length is typically around a 1000. Furthermore, during this process, two separate considerations must be taken into account. These are the user – defined voltage must be large enough to reach through the entire part that is being scanned but not be too large to over saturate the response signal [1]. Through multiple trials by the author, a voltage of around 250 volts was found to be acceptable for most curved carbon fiber composites.

The x-y-z translation table has three stepper motors on each axis that is controlled by a specific LabVIEW program for flat carbon fiber composites. This LabVIEW program was modified extensively to accommodate curved carbon fiber laminates. Within this program, the user can define how large the scan will be, as shown above in figure 10. This is done by telling the stepper motor in both the x and y directions how many steps it is to take in total. Also, the user is able to define how detailed the scan is by defining the amount of steps between each scan point. The less steps in-between each point, the more detailed the scan and the longer the scan will take. In order to convert step sizes to physical distances, the user must know that each step that the stepper motor in any direction takes is 1/800th of a millimeter.

When using this set-up, the user first needs to focus the spherical transducer by using the US Ultratek oscilloscope software, which comes with the transducer. The focal length of the transducer is 1.5 inches, which means it must always be that length above the part during the scan. The sound emitted from the transducer must travel from the transducer and back in this experimental set – up, since there is only one transducer. This is a total of 3 inches. Given the speed of sound in water, as well as the distance, the amount of time it takes for the sound wave to travel back can be calculated using equation 2 shown below:

$$c = \frac{2h}{t} \tag{3.1}$$

In equation 2, c is the speed of sound in water, h is the focal distance of the transducer, t is the time required to travel the distance of the focal length. Thus for this focal length the total time through the water is around 51 microseconds [1]. Therefore, the first major spike on the oscilloscope should be seen at this time [1], as shown below in figure 11.

This is caused by a change in velocity by the sound wave as it comes into contact with the part.

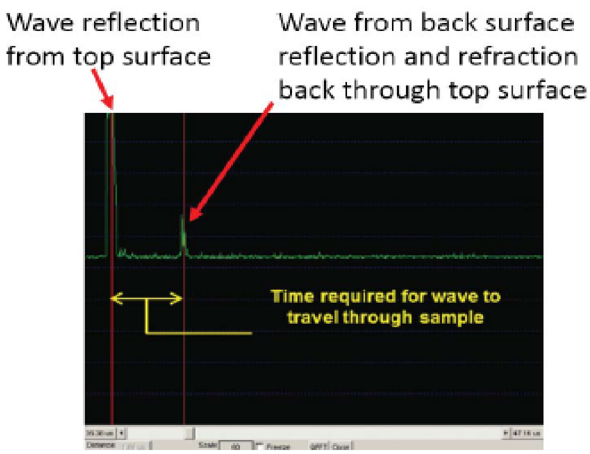


Figure 11: Oscilloscope view of a flat carbon fiber composite.
Photo provided by Stair [1].

The second major spike, seen above in figure 11, is from the ultrasound wave reflecting as well as refracting from the back surface of the part.

3.1.2 Immersion Setup with Curvature Modifications

Since most industry applications are not for simple flat carbon fiber composites, the system discussed in the previous section was modified, both in terms of hardware and software so that it can scan carbon fiber composites with one degree of curvature. Before the code was modified the system was fit with both a mount and a rotational motor. The system with these modifications can be scene below in figure 12.

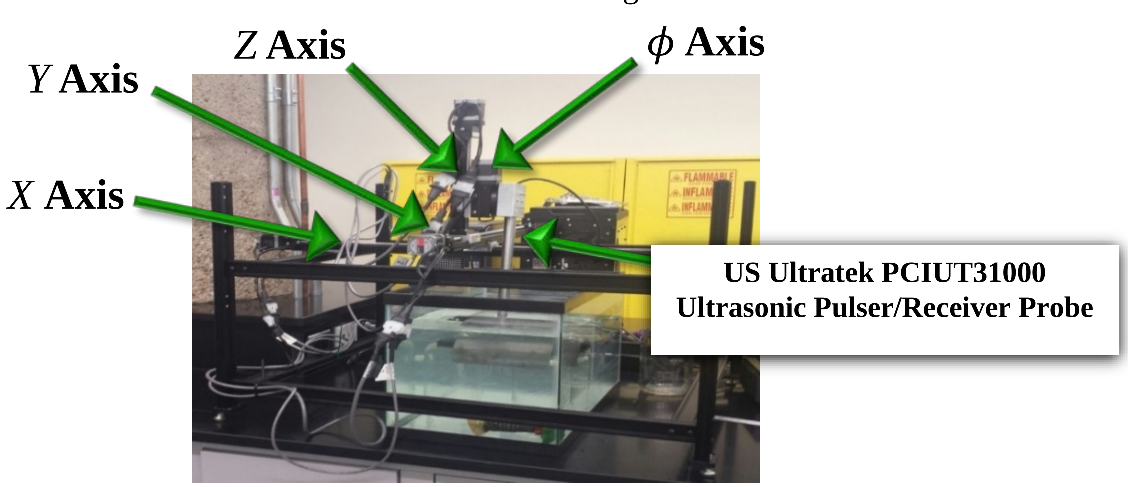


Figure 12: Modified System with curvature modifications

After the system hardware was modified, the LabVIEW software that controls the motors was modified.

3.1.3 Curvature System Theory

In order to be able to scan a curved carbon fiber part the LabVIEW software had to be modified to include controls for a fourth motor as well as a new procedure stage that will be called the Pre-Scan Stage. The mathematics, as well as the overall details of this modified procedure are discussed in this section.

To set-up the procedure background information, the mathematics as well as the theory behind it must be presented. As mentioned in the previous section, the transducer must be 1.5 inches above the part at all times. This is because the transducer has to be at the focal length in order to collect the most data from the return ultrasound signal. Furthermore, to prevent the creation of shear waves and thus the degradation of signal intensity, the transducer must be placed normal to each individual scanning point, as shown below in figure 13.

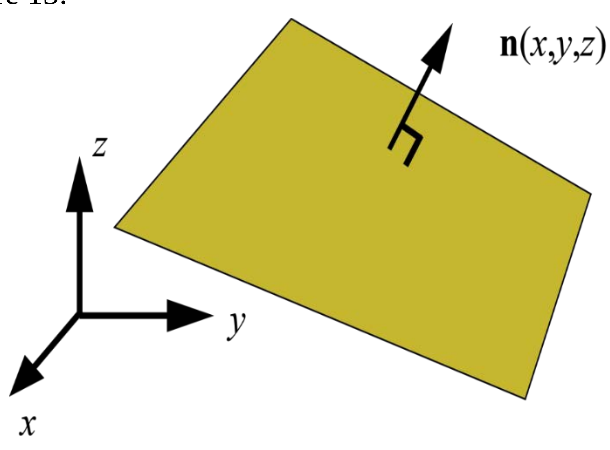


Figure 13: Graphical representation of a normal vector

In order to keep the transducer normal to the surface, the gradient of the known surface polynomial was taken using the gradient of the polynomial produced during the pre-scan.

The pre –scan will be discussed in more detail later on in this section. After the gradient is calculated, the coordinates (x,y,z) and the angle of the ultrasound transducer is determined using the equations below.

$$N_x = f_x(x_0, y_0) \tag{3.2}$$

$$N_y = f_y(x_0, y_0) \tag{3.3}$$

$$N_z = -1 \tag{3.4}$$

N_x,N_y and N_z are the different components of the Normal vector, as shown earlier in figure 13. N_x and N_y are gradients of the surface function that is developed during the pre-scan.

$$x = x_0 + N_x(d + t) \tag{3.5}$$

$$y = y_0 + N_y(d + t) \tag{3.6}$$

$$z = z_0 + N_z(d + t) \tag{3.7}$$

$$\phi = sin^{-1} N_y \ \ (degrees) \tag{3.8}$$

Where x_0,y_0,z_0, are points on the surface of the part. d is the distance in inches, from the transducer tip, to the center of the rotational stage. t is 1.5 inches or the focal length of the transducer. ϕ is the angle the transducer makes with respect to the surface normal component N_y.

3.1.4 Curvature System Procedure

When the user opens the curvature LabVIEW program, a screen that is very similar to figure 10, with a few subtle changes, will appear as seen in figure 14.

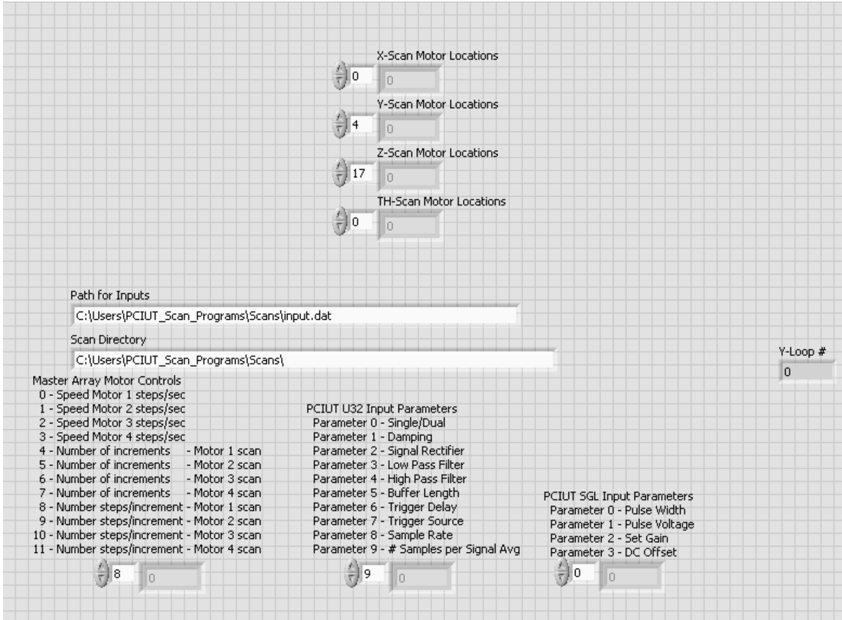


Figure 14: Screenshot of user-defined inputs for curvature scan

The user-defined inputs are the same as for flat laminate, but instead are inputted into a text file, which is then read into LabVIEW. To see which value in the text file refers to which input value, the user can simply look at the row number, the value is in and read it from the corresponding number, next to the name of the input, as seen in figure 14.

The first step of the curvature system procedure is called the pre-scan and uses A-scan techniques to collect data from a predetermined set of grid locations, with the objective being to capture the front surface of the part as a function of space. For best results, the entire surface of the part needs to be scanned to ensure the polynomial fit in the next step is a tight fit to the data. An example of an A-scan from a curved carbon fiber laminate can be seen in figure 15.

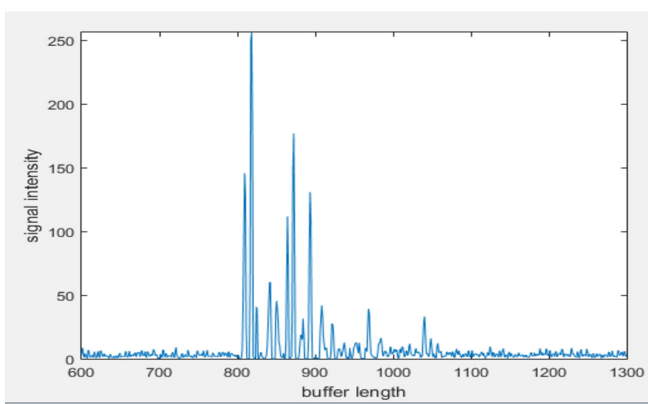


Figure 15: A-scan of a curved Carbon Fiber Laminate

The sudden peak in the middle of the A-scan represents the carbon fiber part. Everything else is simply the water that the part is submerged in. During the pre-scan, the transducer is always vertical and only scans in one direct line across the part, as shown in figure 16.

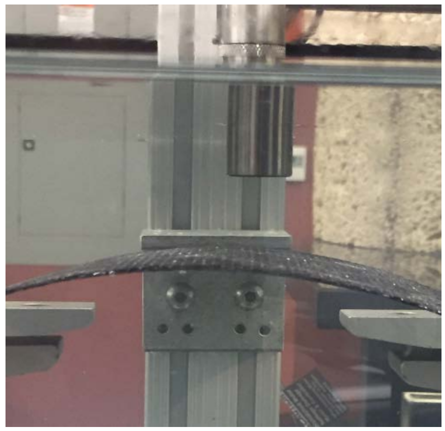


Figure 16: Transducer position during pre-scan

The pre-scan is meant to be quick and simply capture the general curve of the part. If the part has multiple curves, the distance between pre-scan points will have to be less, as more detail is necessary to capture all the different curves. Since there is only one rotation axis, only one dimensional curves can be recorded using this method.

The next step of this procedure uses Matlab and the data collected from the pre-scan to determine the distance the transducer was above the part at each scan point. It sorts through each individual A-scan from each pre-scan data point, using the predetermined buffer length, and finds the moment when the signal impacted the surface and returned to the transducer. This is possible because, when the signal comes into contact with the part, the incident wave reflects back to the transmitter and refracts into the part, as discussed earlier in chapter two.

In step three of this procedure, this signal intensity is recorded by marking the first point that is above a certain user-entered threshold, as shown by the red "x" in figure 17. This user-entered threshold refers to the peak in signal intensity above the threshold that is in each A-scan. Typically, a threshold above 50 for the signal intensity is sufficient to capture when the signal first comes into contact with the part.

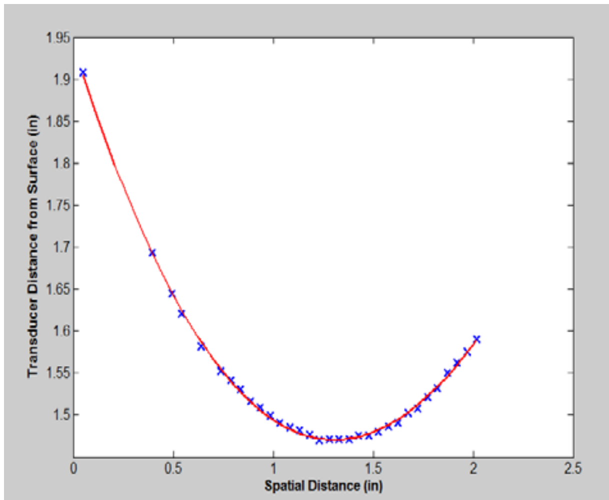


Figure 17: Graphical representation of a curved carbon fiber part

Utilizing the fact that the recorded point corresponds to a time value, and that the speed of sound in water is known, the distance is calculated using equation 3.1 and each contact point is plotted, as shown in figure 17.

In step four coordinates for the location of the transducer are calculated using the aforementioned equations 3.2-3.8 and put into a matrix using custom in-house Matlab software. This matrix has four separate columns, with each column referring to x,y,z and angle coordinates to ensure that the transducer is always 1.5 inches above the part and perpendicular at each C-scan point, as shown in figure 18. This matrix is then sent to the stepper motors, one set of coordinates at a time, to read using LabVIEW software and to execute the C-scan based on the user-defined inputs.

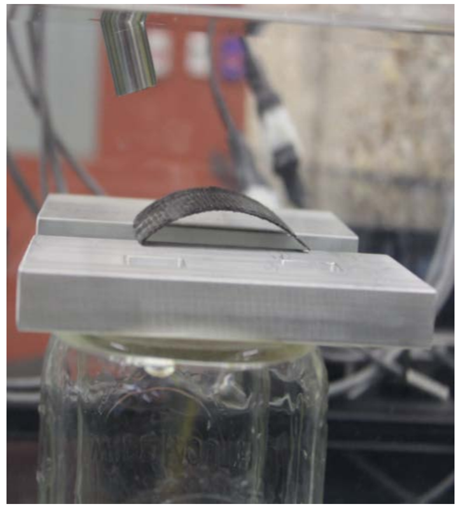


Figure 18: Transducer location during C-scan

During each scan point in this final step a C-scan is being performed, which can then be used to see the individual carbon fiber tows within curved carbon fiber structure. In the following chapter, an ultrasound study was performed in order to determine the feasibility of this new procedure.

CHAPTER FOUR

Ultrasound Study and Carbon Fiber Part Fabrication

4.1 Prior Relevant Ultrasound Study

As mentioned in Chapter Two, fiber-reinforced composites are gaining popularity and being incorporated into a variety of industries, such as automotive and aerospace due to their high strength-to-weight ratios. While the reduced weight makes these parts more applicable, the manufacturing process associated with them leads to increased part variability and causes the need for low-cost, dependable, non-destructive testing methods for the final part to increase [1]. Since non-destructive ultrasound testing has these qualities, they will be the focus of this chapter along with the manufacturing techniques used within this research for fabricating curved carbon fiber laminates.

As the automotive and aerospace industries incorporate substantially more fiber-reinforced composites into products, the maintenance and repair of these parts starts to become a concern [1]. The typical mechanic will not have proper training regarding composite materials and therefore will be unqualified to make decisions regarding the structural integrity of a part, should they arise [23]. Within the aerospace industry, key composite components of aircraft that have been repaired must be certified to nearly the same criteria as those as the original part, before the repair [1]. A three module approach to performing repairs on composite portions of airplanes is presented in Lin and Duong [24] and includes locating bondline defects and increasing the speed that the composite repair is analyzed.A recent study was performed by Stair [1] to apply an ultrasonic C-scanning technique to determine the ply type, orientation and thickness of each ply within the bulk laminate. In this study the C-scan followed a grid-like pattern across the top surface of the laminate, and the collected data was analyzed using a patent-pending ply detection algorithm [16, 25]. The uniqueness of this method is in its ability to capture carbon fiber tows within a single ply, thus allowing for the ply type and orientation to be determined for each lamina [1]. The ply orientations calculated from the C-scan data offer a way to validate the quality and correctness of manufacturing, which is incredibly important [1]. Using a combination of the previously mentioned properties and the constitutive properties of the carbon fibers and resin matrix, the failure envelope of the as-manufactured part can be compared with that of the as-designed part, since the two are not usually a perfect match [25].

The study presented in the previous paragraph focused on flat carbon fiber composites as well as the broader goal of developing a parts failure envelope. The research presented in this chapter focuses on the author's contributions to that study's broader goal, with specific interest in being able to see an individual carbon fiber tow of a curved carbon fiber laminate. In this research, carbon fiber-reinforced were manufactured using two separate variations of the vacuum assisted resin transfer molding method (VARTM), which will be described in detail in the next section. Once the parts were manufactured, they were placed one at a time inside the immersion tank and the process described in chapter three was performed on them. Once the final C-scan was performed, the collected C-scan data was read into a custom in-house Matlab program which analyzed the results and displayed scan images for various depths in the part [1]. This software will be discussed later but for the most detail, the author recommends reading chapter four of Sarah Stair's master thesis [1]. If the methodology, presented in chapter three was successful individual carbon fiber tows of a curved carbon fiber part would be visible in these images.

4.2 Manufacturing the Samples

Chapter Two provides descriptions of common laminate manufacturing methods including the wet lay-up technique, vacuum assisted resin transfer molding method (VARTM), and prepreg materials. An ultrasonic scan was performed on a laminate using two different variations of the VARTM method. The first involved a combination of 3D printing and mold manufacturing. The second involved the use of VARTM and an improvised curved surface. Each of these methods will be described in detail in the next sections.

4.2.1 3-D Printing VARTM

The first method combined computer-assisted design (CAD), 3-D printing technology and mold manufacturing techniques. In order to ensure the surface, did not change its orientation by greater than 4 degrees, as measured from the vertical a CAD model of the proposed curvature was designed, shown below in figure 19. Recall, this 4 degree limitation is based solely upon the experimental fixture limitations and the dimensions of the C-scan area desired, and is not a limitation of the method itself.

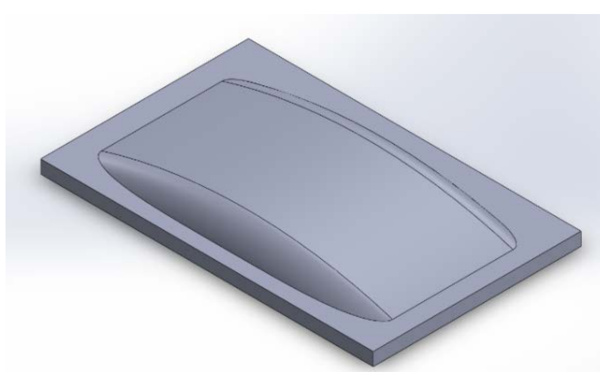


Figure 19: CAD Model for Curved Composite Mold

After the model was designed, it was converted to an STL file format and printed on a Makerbot 3D printer, similar to the one shown in figure 20.

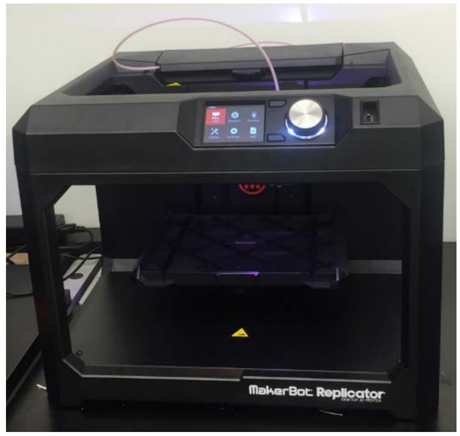


Figure 20: Makerbot 3D printer.

In order to reduce the ridges that are left behind by the 3D printer, it was printed with the highest resolution available. To reduce the amount of time necessary for the CAD file to print, a 10 percent infill was selected, which means that only 10% of the actual structure is plastic. It took on average 8 hours for the CAD file to be printed to completion, which is shown in figure 21.

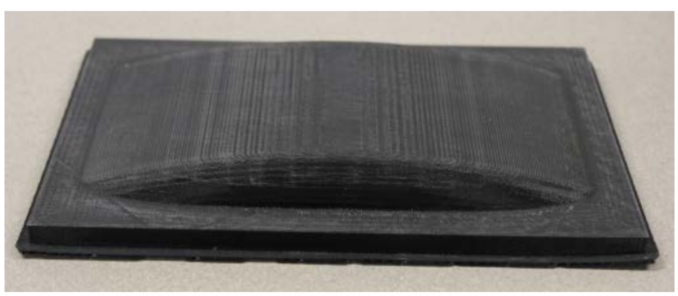


Figure 21: Completed 3D printed Mold Plug.

Once, the mold plug was printed, it was sanded to reduce the ridges created by the 3D printer. These sanding marks can be seen in figure 21 as the patches of white. In the author’s experience, the mold does not sand particularly well, and therefore it is impossible to fully eliminate them in this manner.

At this point, the mold plug is ready to be prepared for the mold manufacturing process. Firstly, three layers of mold release wax are applied, buffed and removed from the mold plug. This is to help with the releasing of the mold from the mold plug after completion. After this step, three layers of an orange gel coat were applied to the mold plug, as shown in figure 22.

Figure 22: Mold Plug with gel coat applied.

The gel coat acts as the final interior surface of the mold, so it is crucial that it is as smooth as possible, as well as not punctured in any manner. In order to prevent both of these things, the author recommends applying 2-3 layers of gel coat to the mold plug.

After the gel coats are applied and dry, the fiberglass can be added to reinforce the mold, so it can be used multiple times. Before applying the fiberglass, cut small pieces out from the roll of fabric, approximately 1 in^2 in size and ensuring there is enough for all layers to be applied. Once this is accomplished, tear the small square in half, as shown in figure 23.

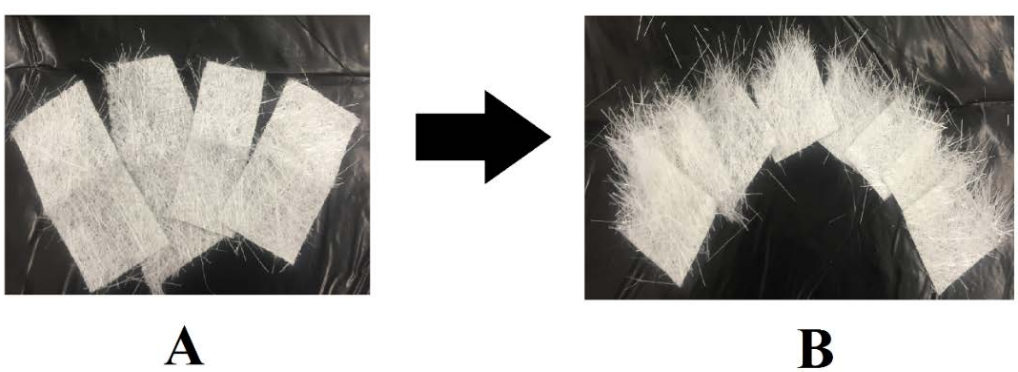


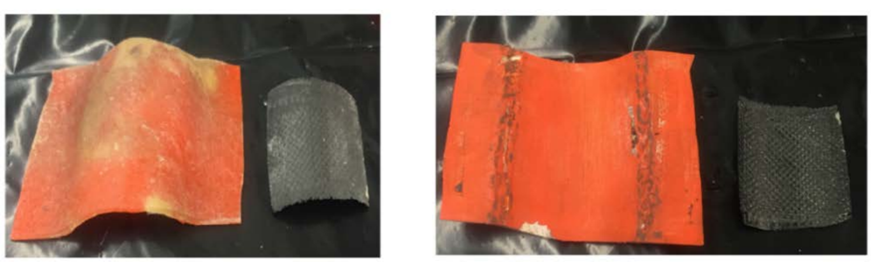
Figure 23: A) Cut individual plies of fiber glass B) Torn individual plies of fiber glass

This will expose individual fibers, which will make it conform much easier to the overall curved surface of the mold plug when the resin is added. Next, pour and mix the appropriate amount of Ashland AME-5001 resin and MEKP catalyst. The author recommends about 100 grams of resin per layer of fiberglass. It is important that all the individual fibers are coated with resin, as shown in figure 24, to ensure that no spare fibers are sticking loose at the end, as that poses a safety hazard.

Figure 24: Mold Plug coated in layers of fiber glass.

The author recommends 2-3 layers of fiberglass to ensure durable mold that is capable of multiple uses.

Once the fiberglass has cured, which takes 8 hours according to the manufacturer's recommended cure cycle, the mold is ready to be released from the plastic mold plug. This is the most difficult part of the process, and can often take an hour or more. A hammer and screwdriver combination works well for getting at the crease between the mold and mold plug, as well as creating the necessary leverage and torque to separate the two. Once they are separated viable mold will have been created, as shown in figure 25.



A B

Figure 25: A) top view of laminate and mold B) bottom view of laminate and mold

The mold developed using this method was then combined with the VARTM method to create a curved carbon fiber laminate with four layers that all had a ply orientation of 0°, as shown in figure 25.

While this method was successful in creating a mold and a part, the author does not recommend it for future part fabrication. The process as a whole takes approximately 5 days to complete, due to all the time required to let all the various layers cure properly. Furthermore, releasing the mold from the mold plug is also a very time intensive and arduous process.

4.2.2 Pre-Made Curved Surface VARTM

The second method that was used to create curved carbon fiber parts for this study was the VARTM using a pre-made curved surface. Any object with a surface that is smooth, and has an overall area larger than the desired parts with suffice. For this study, two 5 gallon buckets were used as the curved surface.

The first step in this method is to clean the surface using acetone. Acetone should be applied to entire surface, where the part will or VARTM materials will come into contact with the surface. Acetone will remove any impurities from the surface that would otherwise interfere with the process.

Figure 26: Five gallon bucket with Acetone

Upon cleaning the surface with acetone, wax is then applied to the whole surface that was cleaned with acetone. This should be done 2-3 times, with the wax being buffed and removed after each coat. This will help with the carbon fiber parts being released from the surface of the bucket.

After this, cut out the necessary individual plies of carbon fiber, at the necessary ply orientations. For this study, laminates were made with 5 plies, with ply orientations of: 0°, 45°, 0°, 45°, and 0° for plies 1-5 respectively.

Figure 27: Individual cut carbon fiber weave plies

Each ply was 4x6 in, and comes from a carbon fabric weave of 1,000 tow.

At this point, the carbon fiber plies were put in the ply orientation mentioned in the prior paragraph, and gum tape is placed on the bucket around where the carbon fiber plies will be placed, as shown in figure 28a. During this step, it is crucial that there is no wax, where gum tap is placed. If there is, it will cause leaks later on, when a vacuum is formed. After this, mesh tubing is added along the sides of the gum tape and vacuum tubing is connected to the mesh tubing, as seen in figure 28b. Next, the carbon fiber plies are placed on the curved surface and white mesh ply is placed on top, followed by green vacuum bagging, as seen in figure 28c.

Applying the green vacuum bagging is the most critical step during this entire process. If it is not done correctly, air will get into the part during the resin infusion. Therefore it is critical, that it is done slowly, and meticulously to ensure a proper vacuum is formed.

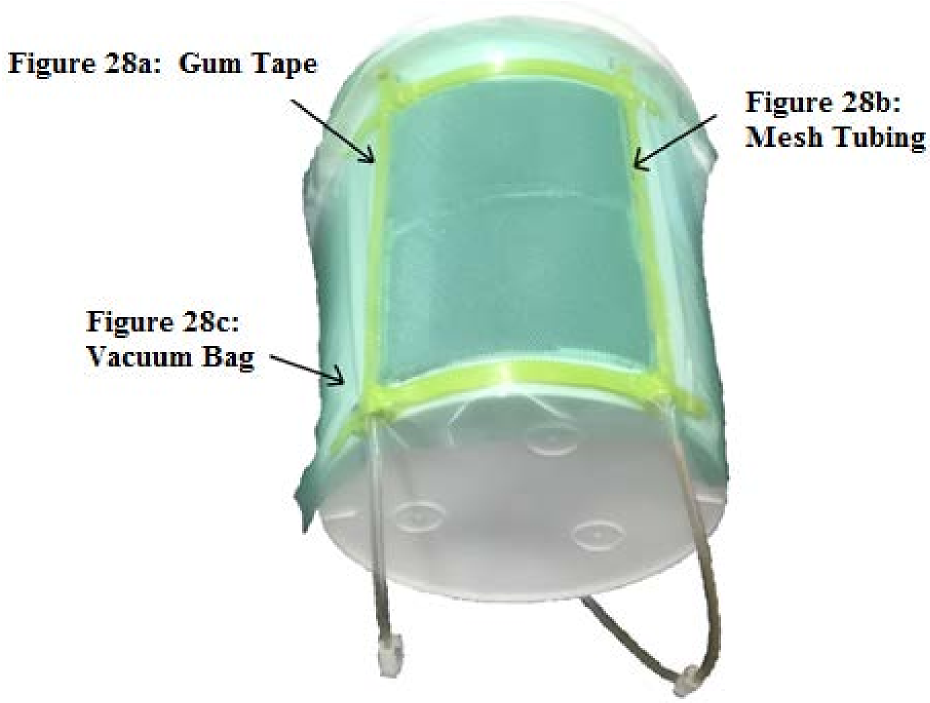


Figure 28: a) Gum tape placed around carbon fiber laminates b) Mesh Tubing c) Vacuum Bagging

Once the laminates are prepared as shown in figure 28, the tubes are attached to a vacuum motor and a vacuum is formed when the green vacuum bag is sucked tight to the laminates. At this point it is critical to listen for any leaks that may occur around the gum tape and to seal them. If the laminates are infused with resin, and there are leaks, air bubbles will get into the part, which will cause defects. Once there are no leaks, place one of the tubes in a cup of Ashland AME-5001 resin that has been mixed with MEKP catalyst. For these parts, a 100 grams of Ashland AME-5001 resin was used and mixed with 2 grams of MEKP catalyst. The created vacuum pulls the resin out of the cup and into the vacuum bag, effectively fusing with the carbon fiber fabric. Once the resin has soaked into all the carbon fiber plies, keep the motor running until the left over resin in the cup has hardened. Once this has happened, the final step is to put the carbon fiber laminates in a furnace at 60 °C for 8 hours. This will complete the curing cycle for the resin that was used in this study.

Figure 29: Completed curved carbon fiber laminates

The bottom two laminates in figure 29 fused together during the manufacturing process, which suggests there was not enough space between them when placed on the curved surface. To prevent this from happening next time, more space should be allowed between the laminates, by cutting them to smaller sizes than 4x6 in. Afterwards, the laminates can be released from the bagging material and the final part, as shown in figure 29, is ready to be scanned.

4.3 Ultrasound Study Specifics

One curved carbon fiber laminate using each of the previously discussed manufacturing techniques was chosen and placed individually in the ultrasound immersion tank. The methodology discussed in chapter three was then performed on each laminate, with each C-scan being 15x15 mm in size on the outer surface of the curved laminate. Once the final data was collected, it was processed using the in-house Matlab software discussed in detail in Sarah Stair's master thesis [1].

4.3.1 Ultrasound C-Scan Data Processing

This section will briefly describe the custom in-house Matlab software that was used to process the ultrasound data after the C-Scan data was collected. The purpose of this software is to present a preliminary investigation into the ply microstructure within a laminated composite [1]. When using this software, the scan resolution is of most importance. For this study, the C-scan was 15mm x 15mm with a spatial resolution of .1mm x .1mm for 150 total points in the X and Y axis directions as shown in figure 12. At each scan point, the transducer is fired to generate an individual A-scan similar to the one in figure 15.

As the LabVIEW program performs the ultrasonic C-scan, each B-scan (a set of A-scans along one trip down the X axis) is compiled from the individual A-scans and stored as a text file [1]. The summation of these B-scans is called a C-scan [1]. All the B-scans are stored in a folder along with the individual user-defined inputs mentioned in chapter two [1]. These user-defined inputs are read into a custom Matlab subprogram which opens and reads the text file and stores each of the values as a variable [1]. Using the C-scan data files, a three dimensional C-scan matrix is formed within Matlab where the A-scan associated with each scan point (x, y) is stored as the corresponding location in the C-scan matrix [1].

Within the main Matlab program, the point at which each A-scan first reaches the part is determined by locating the first point in time at which the amplitude is at least

20% of the value of the maximum A-scan amplitude at that location [1], as shown in figure 30 by the red “x”.

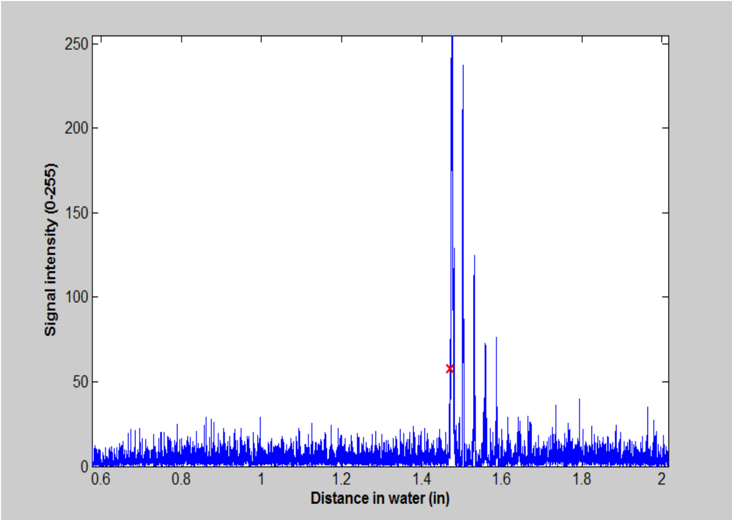


Figure 30: A-scan showing user-defined input

After this location is discovered a new C-scan variable is defined that removes the time from each A-scan that represents the ultrasound wave travelling through the water before it reaches the part [1]. Once each A-scan has been shifted, this new three dimensional C-scan matrix can be thought of representing the physical dimensions of the scan area in the x and y directions, with the thickness of the matrix corresponding to the A-scan signal remaining after the wave’s water path has been removed [1].

With this revised A-scan data a plot of the top surface of the laminate is generated. From this image, the user can observe if the transducer was normal to the part surface at each scan point and if there are any surface features, such as areas where the resin does not form a smooth surface [1].

The C-scan data is then used to generate images representative of different depths throughout the laminate [1]. These images will be presented and discussed in further detail in the next chapter. The number of figures depicting the results throughout the thickness of the part is a user input [1]. Thus, if the user chooses a number larger than the number of plies within the laminate, multiple images for depths within a single lamina may be generated [1].

These figures are gray scale plots of the signal intensity associated with the ultrasound signal normalized with respect to the largest intensity value for each different depth analyzed [1]. There are several ways to define the intensity including an integral average, using the first A-scan value, using the largest A-scan value and using the average A-scan value [1]. For a detailed description of these different methods the reader is encouraged to read chapter four of Sarah Stair's master thesis [1].

For each frame, the intensity at each (x, y) location is stored in a matrix that is the size of the number of number of scan points in the x and y direction [1]. Next, the power at a given depth is normalized by the maximum intensity within the array and therefore have a value from 0 to 1 [1]. Once the intensity matrices have been normalized, each solution is plotted as a subplot as a single Matlab figure [1]. As previously mentioned, these attempted images will be presented in greater detail in chapter five. The process for calculating the intensity for each scan point of the laminate, using the previously mentioned methods is repeated for each frame [1]. Once all the frames have been completed, the file will be closed by Matlab and the user can play back the results as a video [1]. This code is beneficial as it allows the user to step through the thickness of a laminate starting with the top surface and going to the bottom surface while observing the ply structure [1].

As previously stated, the goal of this study was to see if the methodology discussed in chapter three is capable of clearly seeing individual carbon fiber tows within a curved carbon fiber laminate utilizing the Matlab code discussed in the previous paragraphs. The results of this study and the specific difficulties that were encountered throughout the entire process, from developing the methodology, to manufacturing curved carbon fiber laminates, will be discussed in detail in the next section.

4.4 Discussion of Ultrasound Study Results

Curved carbon fiber-reinforced laminates are becoming increasingly prevalent in the automotive and aerospace industries. As this continues to happen, the need for non-destructive testing methods to compare the as-manufactured part with the as-designed part. This section presents the results of the ultrasound study described in the previous section, using the methodology presented in chapter three. The parts used in this study were created using pre-made curved surface VARTM.

The 15x15 mm C-scan for this study took approximately 11 hours to complete. The resolution of the scan was .1 mm in both the X and Y directions. After the C-scan was completed the data was loaded into the Matlab software discussed in section 4.3.1. This software then creates a video that allows the user to step through the various depths of the part. In Figure 31 three frames from the generated video are shown.

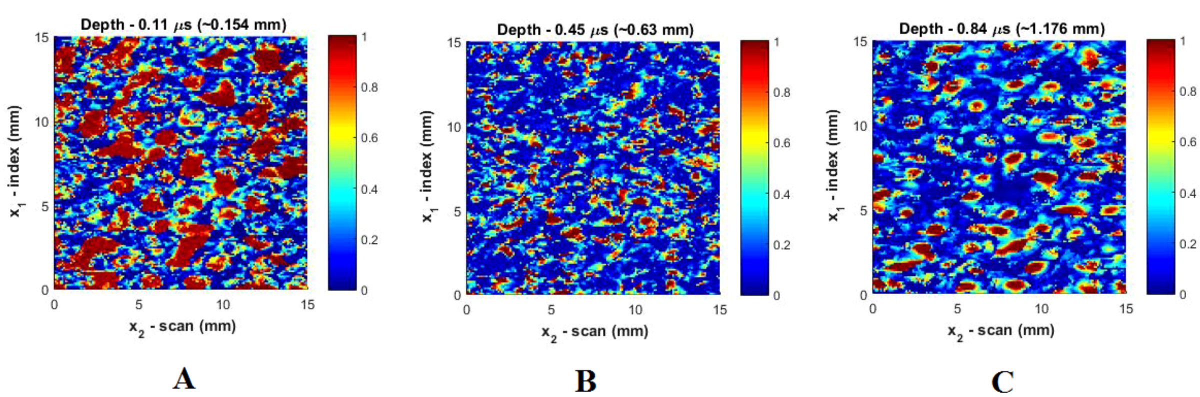


Figure 31 A) View of curved laminate at .154 mm depth B) View of curved laminate at .63 mm depth C) View of curved laminate at 1.176 mm depth

Figure 31a shows the view of the laminate when the ultrasound signal was approximately .11 µs into the part, which corresponds to a depth of approximately .63 mm. Furthermore, figures 31b and 31c show time stamps of .45 µs and .84 µs which correspond to depths of .63 mm and 1.176 mm respectively. The red spots highlighted in figure 32 are locations of transitions between carbon fiber tows and resin, and the regions in blue indicate that at the selected depth there is no material boundary between the tows or the resin.

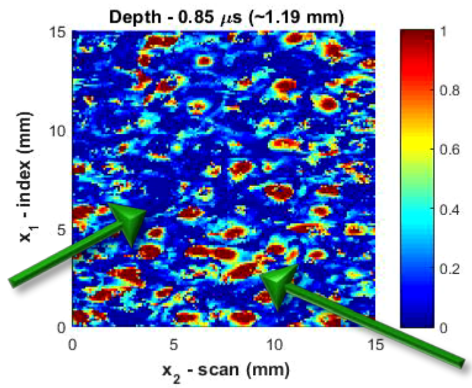


Figure 32: Image of laminate at depth of 1.19 mm

These results show that this methodology is able to detect the transition between the resin and the carbon fiber tow within a curved carbon fiber laminate. However, a closer analysis shows that the red spots are likely carbon fiber tows as the measured distance from the center of one spot to another is 3 mm, which corresponds to the physical distance between carbon fiber tows on the actual part. This is shown in figure 33.

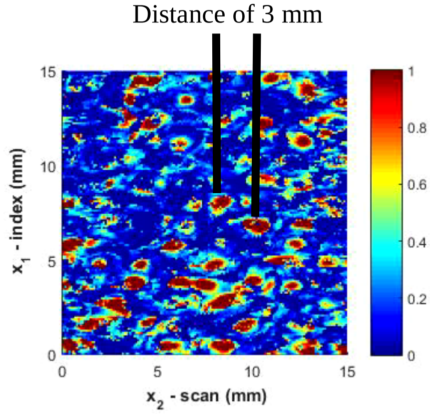


Figure 33: Image of laminate showing physical distances between carbon fiber tows

However the images are not good enough to detect ply orientation within the laminate. This is mainly due to the size constraints of the scan due to the current set-up. This limitation and others will be discussed in the following chapter.

CHAPTER FIVE

Conclusion

5.1 Discussion of Results

Carbon fiber composites have continued to become more frequent in major industries such as Aerospace and Automotive, due to their high strength-to-weight ratios. While these composites have higher strength-to-weight ratios than traditional metals, they also have a more complex manufacturing processes that makes achieving the final designed product very difficult [1]. Furthermore, traditional destructive testing is not always applicable as it renders the part useless for its intended purpose. Therefore, non-destructive testing is necessary to keep the part in place for its intended application. Up to this point, non-destructive testing with high-frequency ultrasound has only occurred on flat composites. Due to the prevalence of curved composites in industry, this thesis presents a scientifically impactful contribution using high-frequency ultrasound A-scan and C-scan techniques to see individual carbon fiber tows within a curved carbon fiber composite.

The non-destructive evaluation method described in this thesis incorporates ultrasonic A-scan and C-scan techniques to see a carbon fiber tow within a curved carbon fiber laminate. A background on the fundamentals of ultrasonic technology are provided in Chapter Two. In the current study, a spherically focused, high frequency transducer is attached to an x-y-z translation table along with a rotational axis attached to the z-axis. Both the transducer and translation table are controlled by the same custom LabVIEW program. For this experimental set-up, the transducer and part are kept in an immersion tank in order to provide water as the necessary medium for the acoustic wave. In the future this immersion tank will have to be removed in order to allow for larger parts, such as airplane wing, to be analyzed. The data obtained from the C-scan is input into an in-house Matlab program which analyzes the data and creates a video that allows the user to see through the entire thickness of the part.

Since this proposed methodology allows the user to see within a curved carbon fiber composite, it could potentially be useful for seeing more detailed structures within a curved carbon fiber laminate. Some of these structures could be defects, individual lamina or individual fibers, however more research would be required to see if this is the case or not.

5.1.2 Difficulties and Limitations of Proposed Methodology

The proposed methodology introduced in chapter three of this thesis, while successful did not come without its limitations or difficulties. These will be discussed in this section.

The first main difficulty that arose during this project was controlling the motors in the proper order, while making the initial software modifications, as well as during the ultrasound study performed in chapter four. This included the motors moving in the incorrect order, or simply not moving at all. This is a huge issue, because if the motors do not move in the correct order, to the correct location the ultrasound C-scan data collected will not be useful when processed by the in-house Matlab software.

The second main difficulty that arose was creating the necessary curved carbon fiber laminates to perform the methodology on. The 3D printing VARTM mentioned in chapter four, had issue of not releasing properly from the 3D printed mold as shown in figure 31 and 32b.

Figure 34: Bottom view of improperly released mold

Often, the mold would not release properly, as the mold gel would bind and get attached to the 3D printed mold plug. In order to counteract this the author tried various strategies such as cutting the sides off the mold, in order to gain better access to the 3D printed plug or layering various substances on top of the plug, such as calk shown in figure 32a.

Figure 35: A) Curved Mold plug with calk B) Improperly released mold

Cutting the sides off the finished mold as shown in figure 32b, helped provide more leverage with better access to the 3D printed mold inside and layering calk on top of the mold was meant to lessen the bonding between the mold and the 3D printed plug. Cutting the sides off the mold was effective in eventually releasing the mold, but the calk proved to be ineffective in helping release the mold.

While the proposed methodology was successful, it does not come without its limitations. These limitations will restrict the methodology proposed in chapter three from undergoing full – scale implementation.

The first limitation of this methodology is it can only scan curved carbon fiber laminates with curvature with one degree of freedom, meaning there can only be curvature in one direction. This is simply because the rotational motor that was added to the system can only rotate in one-direction. To be able to scan in multiple degrees of freedom, additional rotational motors would simply have to be added to the existing system.

The second main limitation of this methodology, using the existing experimental fixtures, is the rotation of the motor cannot exceed 4 degrees relative to the direction vector along the transducer in any direction, otherwise the transducer can't remain perpendicular to its surface. However, this is dependent on the size of the scan region and a smaller scan region could allow for a higher degree of curvature. This limitation can be alleviated by using a larger immersion tank or simply eliminating the tank altogether. Using a larger tank would allow the transducer more mobility while scanning the laminate and thus allowing for a larger radius of curvature. Furthermore, eliminating the tank altogether would also allow this because the user would no longer have to worry about the transducer remaining in the water or not. Currently, there are two main methods that this could be achieved. The first is substituting an acoustic gel as the medium, instead of water. This method would allow for the tank to be eliminated and would be effective as long as the transducer remained in contact with the gel. The second method involves shooting a stream of water through where the transducer is emitting sound. The stream of water acts as the necessary medium and allows the soundwave to remain focused. Since the speed of the stream is on the magnitude of 10 ft. /s it does not interfere with the sound wave as the speed of sound in water is on the magnitude of 4900 ft. /s.

5.1.2 Potential Future Work

An important topic which arose in this study was the importance of manufacturing a quality curved carbon fiber laminate. In the future, the author thinks it would be helpful to learn new manufacturing techniques and to broaden the type of surfaces used to achieve the desired curved part. In the author's experience, too much time was spent on attempting to create a proper curved mold. As previously mentioned, that methodology proved difficult because releasing the mold from the 3D printed mold plug was often impossible or very difficult. In the future, an autoclave could offer higher pressure capabilities than what is currently available in the laboratory [1]. Unlike the vacuum bagging technique used in this study an autoclave maintains constant pressure throughout the cure cycle [1]. This could lead to improved part quality, by removing surface defects and improved part-to-part repeatability [1].

While the current setup has the capability to scan curved surfaces with one degree of freedom it would benefit greatly if it could scan curved surfaces with two degrees of freedom, such as s sphere. Thus, a suggestion for future work would be to incorporate an additional rotational axis into the current x-y-z translation table. The main difficulty in this would be the additional weight added to the already current system. If the current rotational axis is left on the x-y-z translation system for too long it will bend z-axis as a result of the moment caused by the rotational motor. Adding a second rotational motor would only exaggerate this. Therefore, for potential future work the author suggests finding a compatible rotational motor that weighs less than the current motor.

Finally, to improve the marketability of this system and methodology improvements to how long it takes to complete a C-scan must be made. Currently, it takes approximately two hours for a 5x5 mm scan and six hours for a 10x10 mm scan. The simplest way to improve this would be to redefine how the transducer travels during the C-scan. Currently, the transducer begins at one end of the laminate, travels across the x axis, while the z and rotational axis shift to the necessary locations at each scan point. When it reaches the end of the x direction, it shifts forward in the y direction before returning to starting point in the x direction and then begins travelling across in the x direction again. The time to complete the C-scan would be greatly reduced if the transducer traveled down the x axis collecting data and then once complete did not always return to its original position and instead simply moved forward in the y direction to continue collecting data. These changes are able to be made in the block diagram portion of the LabVIEW program, within the overall process.

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