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Feasibility Study For The Detection Of Damage To Composite Overwrapped Pressure Vessels With Phase Array Ultrasonic Testing

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FEASIBILITY STUDY FOR THE DETECTION OF DAMAGE TO COMPOSITE OVERWRAPPED PRESSURE VESSELS WITH PHASE ARRAY ULTRASONIC TESTING

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Dedication

I would like to dedicate this work to my grandparents, parents, and sister. Thank you for taking this journey with me and providing your unwavering support. I would not be the person I am today without your love and guidance. This work is also for those who could not be here with me today, Papa Ed, Grandma Alice, and Grandma who I know have always been looking over me from above. This is for my Grandpa, the man who introduced me to the game of golf, called me on weekends to tell me jokes and talk about the comics, and has consistently provided encouragement and positivity in everything I do. This is for my parents who were pivotal in making me the person I am today. You two never doubted me and always gave me the strength to move forward. This is for Kenna, my older sister, role model, and best friend. I would not be here today without your positivity, love, encouragement, and advice.

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by

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THESIS

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Abstract

When discussing the field of Nondestructive Examination, there are various techniques and instrumentation that can be utilized for analysis of components. However, with newer technology and the development of newer forms of technique, it is critical to explore exactly how these can be applied. This work will aim to explore one newer technique, Phased Array Ultrasonic Testing, and determine the viability of its use for examining Composite Overwrapped Pressure Vessels (COPVs). Currently, the types of vessels have been used in a variety of ways such as in transportation vehicles. More notably, these vessels are used in aerospace applications hence the importance of inspecting these components before use. A development of a test plan was utilized to provide a guide to obtain results that could be comparable to those already collected by established techniques such as ultrasonic testing, shearography, acoustic emission, etc. The test plan was created to be able to be system independent and identifies key test parameters such as probes, frequency, imaging modes, and suggestions for future work.

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1. Introduction

In the field of aerospace today, there are multiple nondestructive examination techniques being used to inspect composite overwrapped pressure vessels, COPVs. The National Aeronautics and Space Administration (NASA) is looking towards other options to help with nondestructive examination of their COPVs. Although they have some methods currently that do provide results, they are interested in Phased Array Ultrasonic Testing (PAUT). The interest comes from PAUT being able to generate the ultrasonic energy necessary to characterize changes in response to damages and flaws, as well as the ability to steer the sound waves [1]. Currently, there has been some work with PAUT regarding health monitoring systems. However, there have not been substantial testing as to the results PAUT can provide when examining COPVs manufactured through filament winding. Metallic material, as well as polymers, have been studied and the behavior of ultrasonic waves has been documented. In COPVs, having the composite along with the metallic liner makes the reading difficult. The interface between the metallic liner and the composite acts as almost a third material system making it difficult to read or obtain results.

The objective is to create a test plan to create a uniform test procedure that can be used regardless of the type of phased array system. The procedure will focus on keying in on a way to initially test a COPV that has been filament wound and has an aluminum liner. Regarding type of transducer, frequency used, and the number / size of elements, the best combination predicted to give the best results will be recommended for the plan.

2. Background

2.1 Acronyms and Definitions

CFC	Carbon Fiber Composite
CFRP	Carbon Fiber Reinforced Plate
COPV	Composite Overwrapped Pressure Vessel
dB	decibels
FW	Filament Wound
kHz	Kila-hertz
MHz	Mega-hertz
PA	Phased Array
PAUT	Phased Array Ultrasonic Testing
SNR	Signal to Noise Ratio
UT	Ultrasonic Testing
Z	Referring to depth of penetration
ZRE	Referring to energy reflected at interface
“	Inches
°	Degrees
6061	6061 Aluminum Liner

2.2 Composite Overwrapped Pressure Vessels (COPVs)

Composite Overwrapped Pressure Vessels or COPVs are vessels composed of two components. The first is a fluid retention barrier which can be plastic, rubber, or in most cases a metallic liner. The main purpose of these liners is to minimalize any leakage of the fluids to the composite jacket. This is vital to assure the composite does not become affected by the fluids but also assure the composite itself does not affect the quality of the fuel being carried [1]. The second is a composite material which can be defined as structural fibers and a resin that is wrapped around the composite. The design of the composite assures that the tensile strength comes from the fibers, with relatively 80% of the load being supported by the fibers in some cases. The matrix or resin helps to keep fibers in place and takes some of the shear loads that may be present. Typical composites used include graphite, carbon fiber, fiberglass, and Kevlar™ [1, 2]. COPVs were first developed around the 1970s when NASA along with other fire services departments around the United States were working to improve respiratory equipment for firefighters. The major focus of the project was to help reduce the weight and bulk of the metal respiratory tanks used at the time. Since their development, COPVs have found various uses apart from their original use as respirator tanks for firefighters. They are being used to store natural gas for uses in buses and utility vehicles, as well as oxygen storage for commercial airplanes [3]. However, the main use has come from the aerospace industry, more specifically space travel. COPVs have been used as storage tanks on launch vehicles as well as thrusters for satellites due to the strength to weight ratio of these vessels. A COPV can perform the same as prior metal tanks that were used, but only account for 50-70 % of the weight penalty that would be associated with the old metal tanks [2].

When it comes to the manufacturing of these vessels, there are five different types of COPVs. Type 1 is a fully metallic tank along with a metallic liner. Type 2 is made from a composite that is hoop wrapped around a metal liner. Type 3 is a composite that is wrapped both helically and hoop around the metallic liner. For Types 1-3, the metallic liners consist of either aluminum or steel (alloys included). Type 4 is also a composite that is wrapped both hoop and helically around a liner. However, in the case of Type 4 the liner is polymeric. The polymeric liner could consist of either high density polyethylene (HDPE) or polyamide. Type 5 consists of the tank being just a composite that is wrapped both hoop and helically with no liner present. All five types of

COPVs overwrap material, overwrap method, and liner material used can be seen in Table 2.1. When comparing the COPVs to one another, Types 3 and 4 can reduce the weight of the vessel by around 70 to 80%. This not only is desirable for strength to weight ratio, but it is also beneficial in terms of consumption of fuel, the amount of fuel that can be stored on a launch vehicle, and even the distance travelled by the spacecraft [4,5].

Table 2.1 Composite Overwrapped Pressure Vessel Types & Manufacturing Method adapted from [5]

Composite Overwrapped Pressure Vessel Types					
Type	**Overwrap Material**	**Method of Overwrap**	**Liner Material**	**Typical Load of Liner (%)**	**Typical Load of Composite (%)**
1	Metal	Preferably Seamless Tanks	Metal (Steel or Aluminum alloys)	100	N/A
2	Composite	Hoop Wrapped	Metal (Steel or Aluminum alloys)	50	50
3	Composite	Hoop wrapped and helically wrapped	Metal (Steel or Aluminum alloys)	10	90
4	Composite	Hoop wrapped and helically wrapped	Polymeric	N/A	100
5	Composite	Hoop wrapped and helically wrapped	No Liner Material	N/A	100

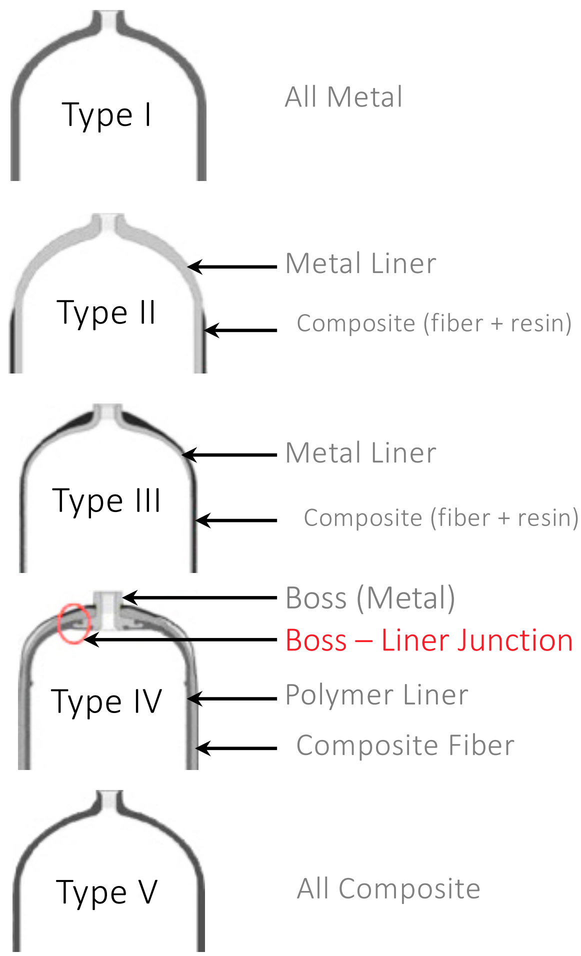

Figure 2.1 a) COPV types showing makeup of liner and overwrap correlating to Table 2.1[5]

2.3 MANUFACTURING OF COPVS THROUGH FILAMENT WINDING

The most common method used for cylindrical and spherical tanks, especially Type 3 tanks is filament winding. When analyzing different methods in which COPVs may be produced, filament winding is well known and inexpensive. Since this method allows for mass production it further reduces cost for manufacturing. Filament winding is reported to have been practiced and used around the 1940s when plastic hoops were used for reinforcement during the Manhattan project [4]. Filament winding can be performed in 2 methods. The first is through wet winding. In this process, a dry fiber is run through a resin bath and becomes wetted or impregnated. The now wet fiber is then applied to create the vessel. The second method is known as towpreg winding where a pre-impregnated fiber is used directly for manufacturing. The application of the filament winding is done mechanically through an automated mandrel. The two main patterns of interest include vessels with both hoop and helical layers as seen in Figure 2.1. By being filament wound, everything except the vases of the vessel are going to be load supported by the composite. With that in mind, it’s important to note that manufacturing methods between suppliers can be inconsistent leading to vessels with different properties. Factors such as void levels within the composite as well as fiber volume distribution all have impacts into what type of strength a COPV will have. Common factors that are recorded and analyzed include winding tension, winding time, and the winding tension gradient. It was determined that the vessels that saw increase of strength did not have a winding gradient, were wound for a short amount of time, had a high winding tension, and had multiple hoop plies in each layer [6].

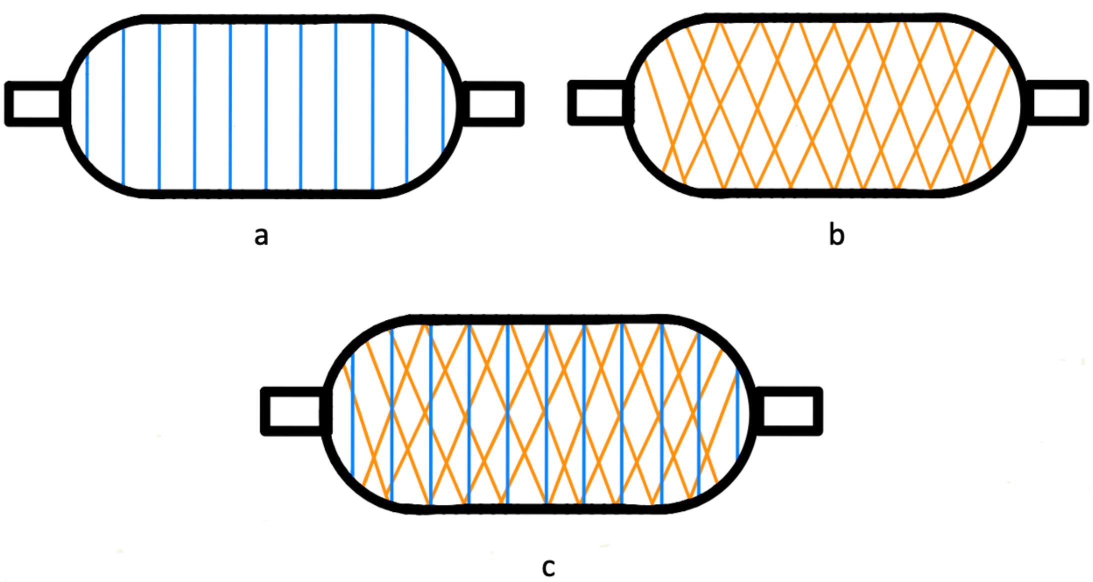

Figure 2.2 a) COPV manufactured by hoop winding b) COPV manufactured by helical winding c) COPV manufactured by both hoop and helical winding

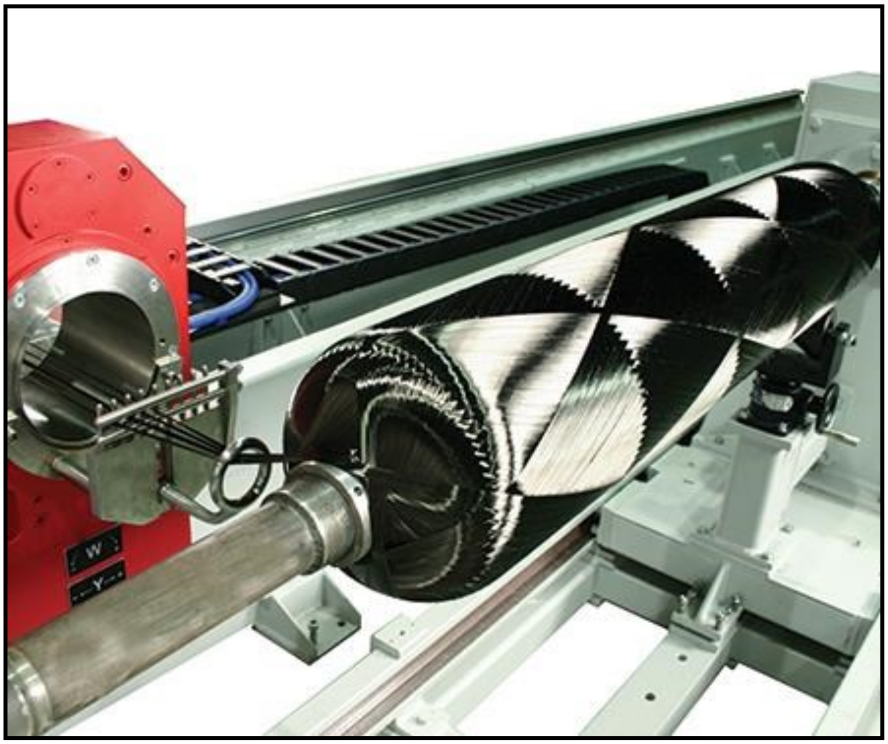

Figure 2.3 COPV manufactured by FW [5]

Figure 2.4 COPV manufactured by FW shown in different configurations [5]

2.4 CURRENT WORK WITH NONDESTRUCTIVE EXAMINATION OF COPVS

Since COPVs can have a variety of failure modes such as fatigue, stress rupture, and bursts from over pressurization/damage, it's important to try to inspect them using nondestructive examination (NDE) techniques. NDE methods are vital due not only to the modes of failure, but because of the behavior of COPVs themselves. If a vessel is dented at any time, the vessel can repressurize and remove any evidence of the dent. Currently, some of the techniques used and proven to provide results include thermography, shearography, radiography, and acoustic emission testing [7 , 8]. Although these methods have a proven track record of obtaining results, there has been a question related to ultrasonic testing (UT) and whether it could be another test that could be used. Past testing within NASA has shown some promise of obtaining results, although they were not as strong as the other methods listed prior. However, ultrasonic signals are not only sensitive to the damage present on the surface, but also to damage within the composite which also makes it attractive to investigate [2]. An example of damage within a composite is delamination, which is separation between the layers of composite. Delamination can occur in a variety of ways including during manufacturing or even due to object damage through transportation or installation. This defect can lead to many issues as areas with a delamination can drastically affect the load capacity as mechanical properties are commonly decreased [9].

With the advancement of technology, there is now a form of UT testing called Phased Array Ultrasonic Testing (PAUT) in which the waves can be guided. Being that interest in UT has risen, there has been some recent research done to try to obtain results from this method along with studies on guided waves. Structural health monitoring (SHM) systems have been developed to help monitor the integrity of COPVs. These systems are run through piezoelectric transducers that are attached to the vessels permanently. The main goal of SHM systems is to monitor any changes that would indicate flaws or local damage to the structure overtime using guided ultrasonic waves. Many of the experiments run with these systems use composite laminated plates as opposed to filament wound plates [10-12]. Although these systems do use guided waves to detect damage, the resulting waves propagated tend to be multi-modal, dispersive, and attenuating waves. This differs from traditional UT, as bulk wave propagation is typically observed [13]. Aside from structural health monitoring, there has been a handful of other research looking at the effectiveness of both UT and PAUT. A study was conducted to observe different damages when comparing a filament wound COPV, a filament wound plate, and a laminate plate. Each of the three models were made using carbon fiber composites and were analyzed using various techniques that included UT testing

[14]. The results found supported another study which stated that damage commonly seen with filament wound vessels such as fiber breakage, matrix breakage, and delamination were able to be detected [14,15]. In the aspect of PAUT, a study was performed comparing traditional UT and PAUT. Glass fiber reinforced composite plates were used that had flaws differing in depth. The study showed that it was possible to detect flaws of various sizes, the smallest being 0.8 mm with a depth of 25 mm, using guided waves. When compared to traditional UT, PAUT performed better when looking at the result signals and capabilities of flaw detection [16]. Another study decided to compare and analyze the results of using ultrasonic testing, optical thermography, and sonic infrared to analyze low impact of carbon fiber composite laminate plates. They found that by using PAUT, this method was able to detect more delamination areas in the composite than the other methods [17].

2.5 Current PAUT Equipment and Flaw Capability

When discussing the current equipment on the market for PAUT testing, there is a variety of different systems and probes to choose from. Earlier it was mentioned how 0°, delay line, and angle wedges were the most common probes. However, since this study will focus on angle wedges, the different types available will be discussed. As we can see below in Table 2.2, the degree of angle wedge, the sweep angle of the probe, elements present, and probe dimensions can be seen. The typical ranges seen for these probes are the values listed in the table. The typical configurations of these probes can also be seen in Figure 2.5.

Table 2.2 PAUT Angle Wedge Type with corresponding Sweep Angles, Probe Dimensions, and Elements adapted from [18,19]

	Transducer Type	Inspection / Sweep angles (Degrees◦)	Probe Dimension (Range)			Elements
			Length (mm)	Width (mm)	Height (mm)	
Angle wedge	0°	-30° - 30°	16 - 157	12 - 47	11 - 40	8 - 128
	45°	30° - 60°	55 - 90	37 - 47	30 - 85	
	55°	40° - 70°	23- 87	23 - 31	14 - 49	
	60°	40° - 70°	18 - 86	14 - 50	13 - 53	

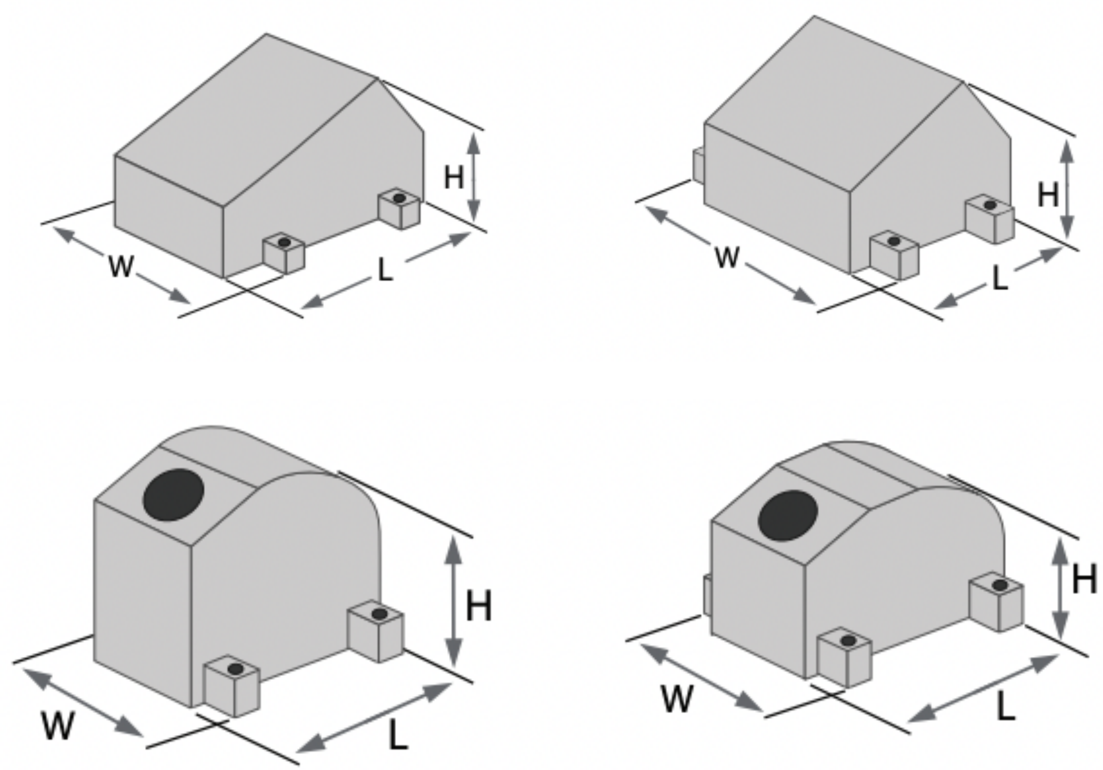

Figure 2.5 Common configurations for PAUT Angle Wedge Probes [19]

With NDE, its important to know what the flaw detection capabilities are for a given technique. With classic UT testing, it is documented in literature that the smallest defect that can be detected is 0.1mm in diameter in metals. In the case of PAUT, since it is a newer method we cannot establish a sure minimum size for defects. However, with recent studies, in the case of metals the smallest size that they detected was porosity with the size of 0.6mm [20]. In the case of composites the smallest defects detected were mentioned before being 0.8mm with a depth of 25mm [16].

2.6 Ultrasonic Testing Vs Phased array ultrasonic testing

2.6.1 History and Basis of Ultrasonic Testing

As more research is starting to be conducted on UT and PAUT, it is important to understand the history and background of both techniques, starting with classic ultrasonic testing. To detect any change in sound within the human hearing range, a very large defect would have to be present within the piece which is rarely the case. Work began around the 1870s in which Lord Rayleigh published his work regarding sound waves in the three states of matter. This work allowed future innovators a place to build off eventually leading to the techniques seen in present day NDE. As time progressed, work with frequencies above the human audible range developed, with a big focus coming around 1942 for the pulse echo detection of submarines during World War II. Since then, the technology has been implemented and seen in crystal microphones, gramophone pickups, and NDE transducers for ultrasonic testing [21].

Both methods are based on the propagation of waves and vibrations. The presence of vibrations means that an item is undergoing repetitive change in position with respect to time. To sustain vibrations, there are two key factors. The first is there must be something to move, and the second is there must be a second force that is trying to offset the displacement that is occurring. The vibrations in the case of UT are known as sound waves. The properties of sound waves are affected by a variety of factors with the biggest being the velocity of a sound wave. The density of a material as well as the elasticity of the material greatly influence the velocity. This is what makes using UT challenging for COPVs as there is multiple materials with varying densities and elasticities [21].

2.6.2 Similarities between Ultrasonic Testing and Phased Array Ultrasonic Testing

With traditional UT and PAUT, there are multiple waves that can be produced to examine a component. The first type is a compressive wave where the particle motion is in the same plane as the direction of propagation. The second type of a wave is a surface wave where the particle motion is elliptical with the major axis of the ellipse being perpendicular to the direction of propagation. The third is a lamb or plate wave where the particle motion is elliptical and the waves that are generated propagate parallel to the surface of the test. The last is shear waves in which the particle motion is perpendicular to the direction of propagation [21].

The main component of these two NDE techniques is centered around transducers and receivers. Transducers are used to change the sound waves produced during the test into electrical energies. These energies are then able to be seen as visual signals on screens for inspections. Whether it is UT or PAUT, there is two methods to receive the produced waveform to analyze your results. The first is known as reflection or pulse-echo. In this method, the transducer creates and send the pulsed waves while also acting as a receiver. The results are displayed on a screen where the amplitude of the signal displayed represents the intensity of the reflection and the distance represents the arrival time of the reflection. The second method is known as attenuation or through transmission. In this method a transducer is still used to generate and send waves on one surface. However, there is a separate receiver positioned on the opposite surface to detect the number of waves that travelled through the component and reached the other side [21]. An example of how waves from the PAUT are transmitted, received, then displayed on the graph. Traditional UT setup and scans are shown in Figure 2.6, with Figure 2.7 showing areas detected to have damage using a UT A scan, and Figure 2.8 showing a C- Scan resulting from UT.

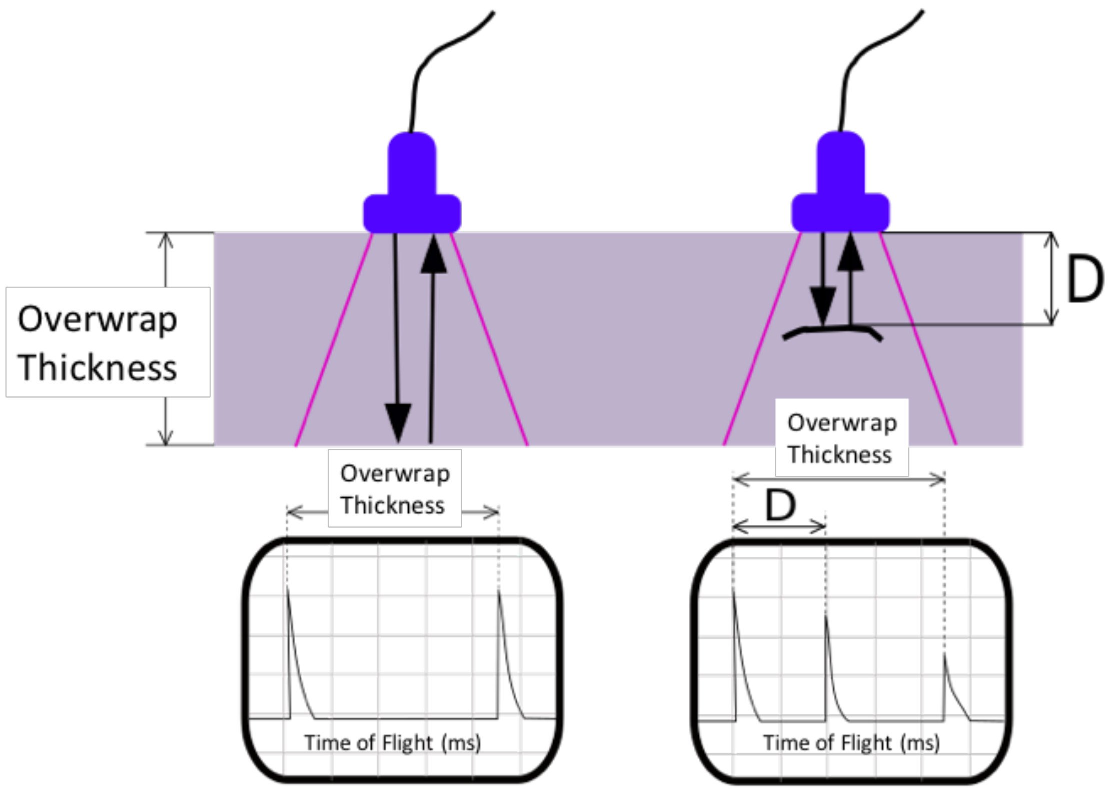

Figure 2.6 Fundamental Time-of-Flight Principles of Ultrasonic Inspection of Composite Overwrap [5]

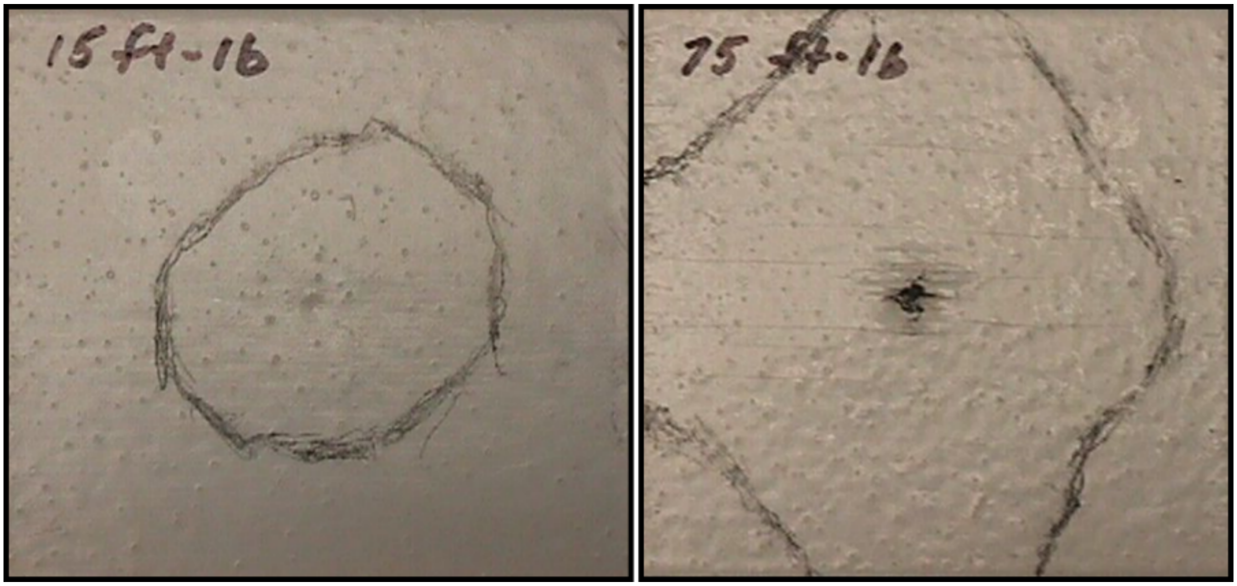

Figure 2.7 UT A-scan Revealing Delamination Areas Surrounding Impact Sites of Different Energy [5]

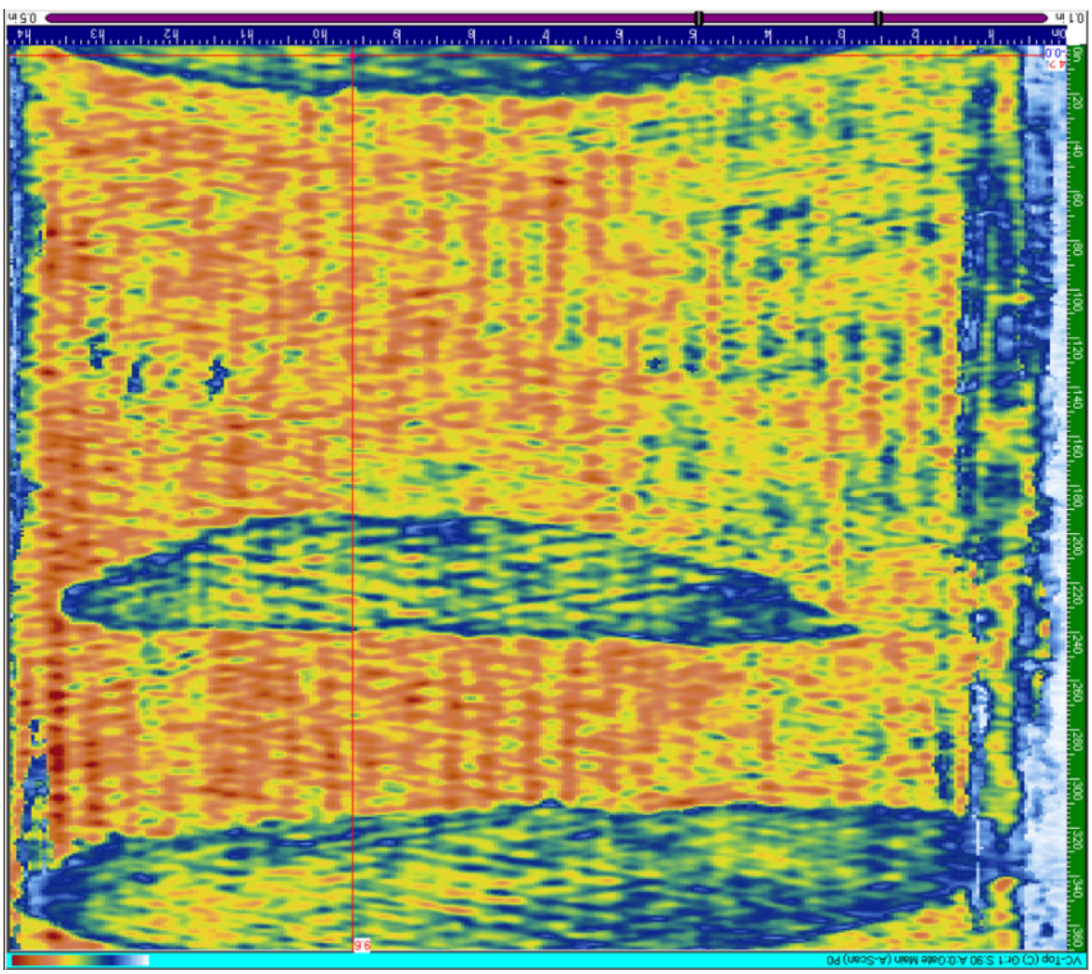

Figure 2.8 UT C-scan Results [5]

2.6.3 History of Phased Array Ultrasonics

Although work with classic ultrasonics has been practiced for longer period, the idea of phased array was briefly introduced in 1801 where interference patterns were observed in an experiment by Thomas Young. Unlike classic UT, which began being developed in the 1870s, experimental work did not begin for phased array until around 1905 through the steering of radio waves. Even after being developed for a while, phased array was confined to being used in the medical field since analyzing the image was direct as the human body and its structure was well known. Eventually around the 1980s, phased array began to start being used in commercial settings and is now used for NDE methods more frequently [22].

2.6.4 Difference between Phased Array and Conventional Ultrasonics

The main differentiation between the two techniques comes from the ability for phased array ultrasonics testing to steer waves. The ability to steer the waves comes from the principle of PAUT which is based off the constructive and destructive interference of the waves. These interferences are created when waves are generated from two or more sources and meet creating a point of combination. At this point, the energies will either increase or decrease. Constructive interference is when waves can combine and reinforce one another due to them being in phase. An example of this occurs for 0° phase angles as the waves will add together creating a larger wave with a larger amplitude. Deconstructive interference occurs when waves are not in phase leading to them to eventually cancel one another out. An example of this occurs with 180 ° out of phase angles where the displacements will be opposite one another cancelling each other out. In the case that there are phase angles between 0° and 180°, there is an intermediate condition. The waves will act in stages of either full addition or full cancellation [22]. These examples can be seen in the Figure 2.9 below.

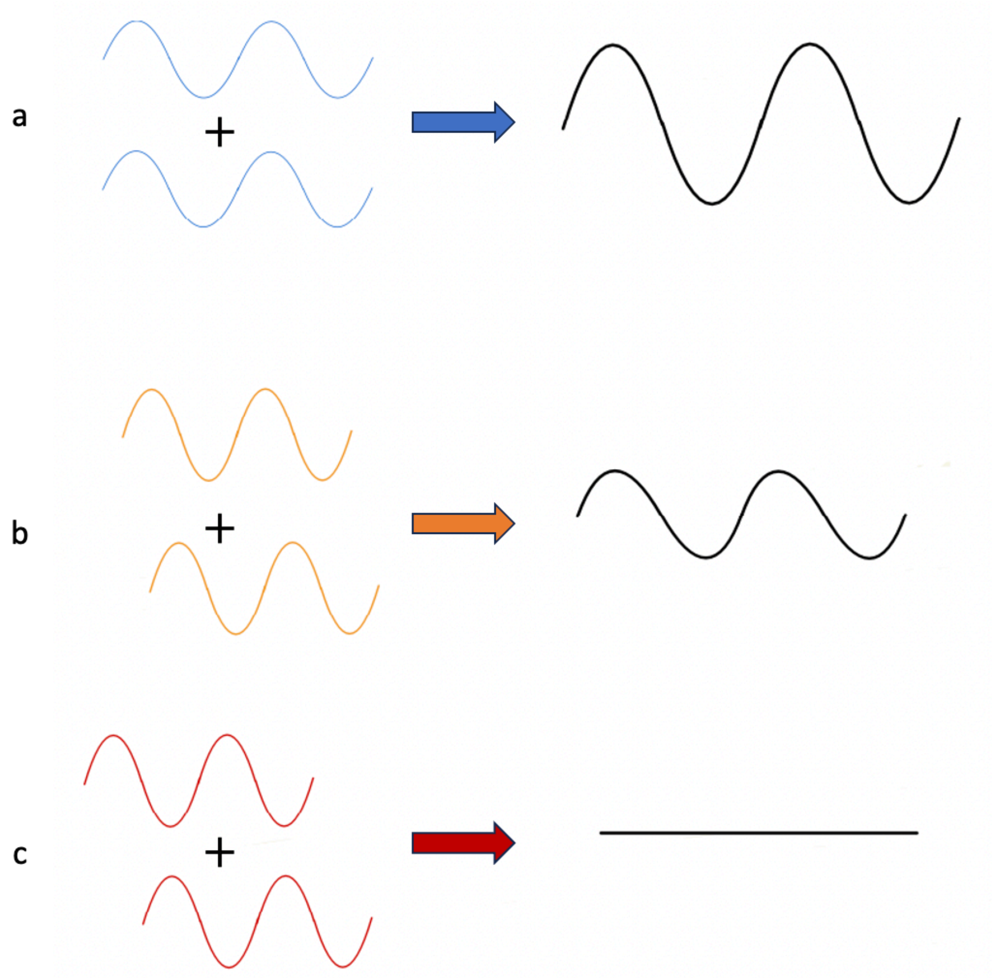

Figure 2.9 a) Two waves in phase, 0° phase angles, resulting in reinforcement wave b) Two waves, phase angles between 0° and 180°, resulting in intermediate condition c) Two waves out of phase, 180°, resulting in cancellation

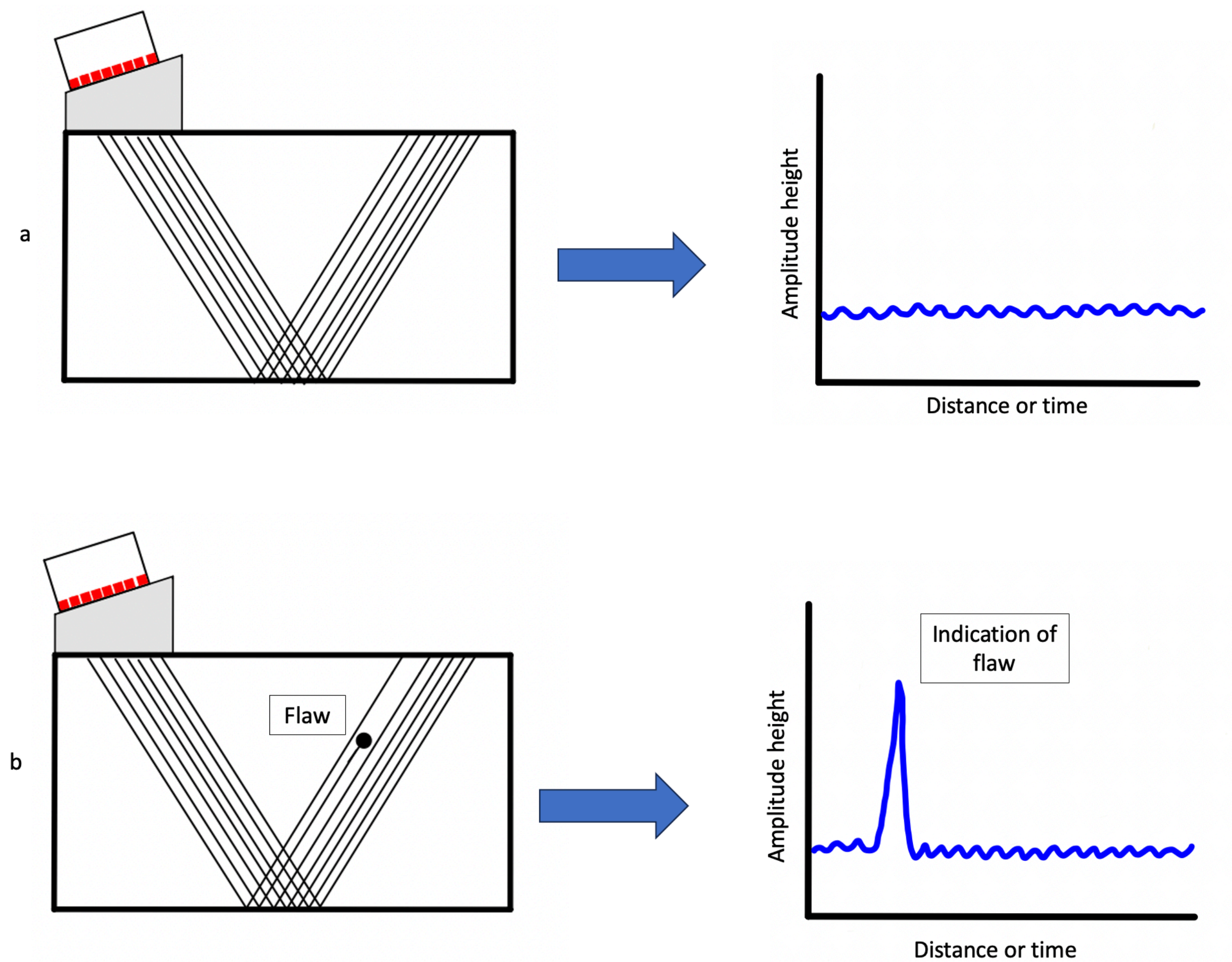

Figure 2.10 a) PAUT scan through material with no defect present and resulting produced signal and b) PAUT scan through a material with a defect present and the resulting produced signal

Although the basic principles are the same, the difference in PAUT comes from the transducers used and their ability to steer the waves. There are four main characteristics that are analyzed when looking at these transducers with the first being the type. The most common transducer used for applications are angle beam. These transducers consist of three variations which include an angle wedge, 0° wedge, and a delay line. After type is considered, the frequency that is used must be determined. In most cases a frequency of 2-10 Megahertz is used. After frequency is determined, as well as type, the number of elements as well as the size of the elements on the transducer are decided. Most transducers consist of 16-128 elements with the size depending on the coverage area you are looking at observing. Transducers for PAUT are one of two types, either a piezoceramic or a piezocomposite transducer. While piezocomposite transducers are harder to manufacture, they are often considered because they offer better sensitivity compared to piezoceramic transducers on the scale of around 10-30 decibels [22].

2.6.5 Advantages and Disadvantages of Phased Array Ultrasonic Testing

Since there is high interest in implementing the use of PAUT, it is important to note both the advantages and disadvantages to this NDE approach. The positives this technique presents are:

1. Allows for inspectors to conduct rapid screening for any service degradation that may have occurred
2. Allows for the ability to detect both internal and external metal loss
3. Allows for fully automated data collection to occur
4. Insulated lining is able to be inspected with only minimal removal of insulation

When summarizing all the advantages, it's easy to see that time is a big factor as to the appeal of PAUT. Even with all these advantages, some disadvantages do accompany PAUT such as:

1. Interpretation of data collected is highly dependent on the operator
2. PAUT is not as effective when examining areas close to part accessories
3. PAUT requires that a qualified and detailed procedure be established and followed

The main drawbacks for PAUT comes from the fact that not only highly skilled operators are required, but that detailed and qualified procedures must be created and executed to obtain results [23].

3. Test Plan

3.1 Scope

3.1.1 Development of Test Plan and approach

The development of this test plan has occurred over the course of two years. Background research was first conducted to learn more about UT, PAUT, and COPVs and what work is currently being done with these topics. Once a literature review was performed, assumptions and parameters began to be set to evaluate a feasible test plan for which COPVs can be analyzed and evaluated using PAUT methods.

3.1.2 Parameters and Assumptions

In the development of the test plan, a few key assumptions and parameters were first established to build off a starting point. The first few parameters that were decided included the type of COPV we wanted to replicate. The Type 3 COPV was decided on which then led to the discussion of the type of metal liner and composite that would be used. The metallic liner of 6061 along with the combination of CFC was chosen as this is a commonly used COPV in the aerospace industry. CFC has been very popular in being introduced and used in aerospace as it provides good corrosion and fatigue resistance while supplying high strength with a low density [24]. The liner and composite type used would stay consistent throughout the sample configurations as they are tested.

In addition to parameters, key assumptions were created. These assumptions were made to give a clearer scope of work for testing and as to what results should be obtained. The assumptions made are as follows:

1) The 6061 liner is acoustically isotropic

Allows for simplification of results and calculations needed to examine the data

2) Liner material stays constant between samples

Allows for consistency between test panels being evaluated

3) Fiber direction will stay the same throughout the T

Allows for simplification of results and calculations needed to examine the data

4) Composite configuration will be fixed

Allows for consistency between test panels being evaluated

5) Perfect coupling is achieved

Allows for pure examination of data collected without including varying factors such as improper coupling

6) Epoxy used for composite is isotropic phenolic epoxy

Allows for simplification of results and calculations needed to examine the data

3.2 Test Methodology

3.2.1 Test Panel Configurations

The composite panels used for this testing shall be formed through the process of filament winding (FW). Once the FW samples have been manufactured, it will be sectioned to produce the sample plates that will be examined. The dimensions of the plates shall be 5 x 5 in. The plates have the same configuration consisting of a 6061 liner and CFC. The panels will consist of two layers, the 6061 liner along with the CFC. The 6061 liner of 0.05” thickness will be standard throughout the samples. As for the CFC layer, the T will vary between panels. The CFC layer will have a T ranging between 0.05” – 0.25”. The overall configurations can be seen below in Figure 3.1.

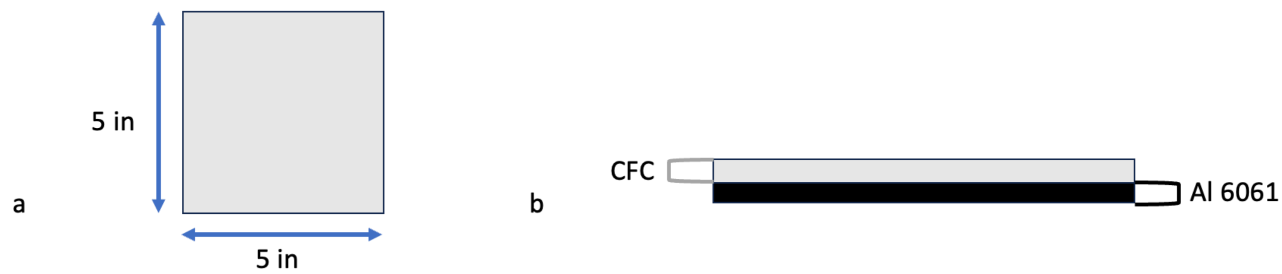

Figure 3.1. a) Dimension of test panels shown as 5x5in and b) Showing sample makeup consisting of CFC layer with 6061 liner

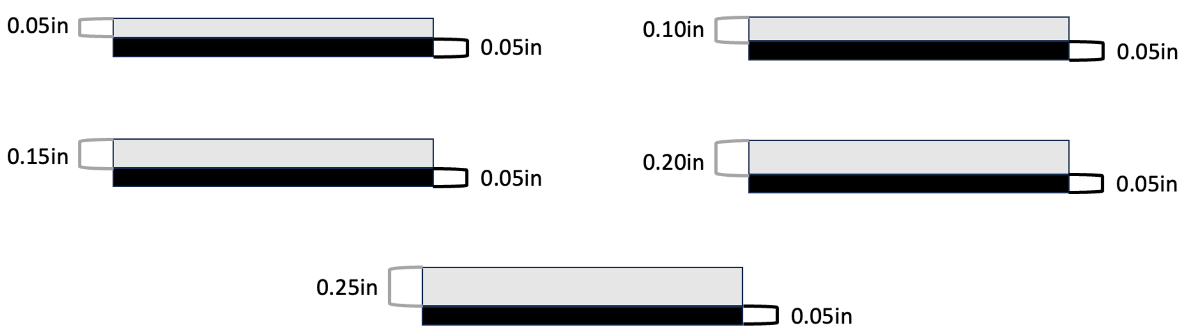

Figure 3.2. Side profile of test panels to show the varying Z height that will be examined along with the consistent thickness of the 6061 liner

While manufacturing is taking place, a planar defect will be added in a way that the defect is parallel to the ply orientation so that it can be observed whether PAUT will detect it. A planar defect was chosen rather than a volumetric defect. This is because the planar defect will serve as a reflection orthogonal to the surface, however it will not reflect at a wide variety of beam angles. The reason this planar defect was chosen is because volumetric defects are being looked at already, as well as the fact that planar defects are of main concern with these COPV Type 3 vessels. When COPVS are transported, there is possibility of damage through transportation and installation. One possibility of damage comes in the form of dents. Once these vessels are pressurized, it's possible for these dents to disappear and no longer be visible to the naked eye, however there is still damage there. The dents are representative of volumetric defects and as these dents repressurize, planar defects radiate off the edges of the volumetric defect and are subsurface. These situations are what is trying to be replicated through the introduction of planar defects in the test panels. Following practices that are currently used, a Teflon sheet will act as the planar defect. As the COPV is being filament wound, the Teflon sheet measuring 1x1” with a thickness of 0.025” will be laid between the layers of the composite as it is being wound at the calculated depths as shown in Table 3.1. It was decided to have defects at 25% thickness from the outside layer of the composite, 50% thickness of the composite, and then 75% thickness from the outside layer of the composite (also can be viewed as 25% thickness from metallic liner). The reason these depths were chosen is to simulate defects at varying depths of the composite, with one site being closer to the surface, one site being in the middle, and one site closer to the metallic liner. It was decided to only place defects in the composite material as defects in the liner or on the interface of the liner and composite are already being looked at.

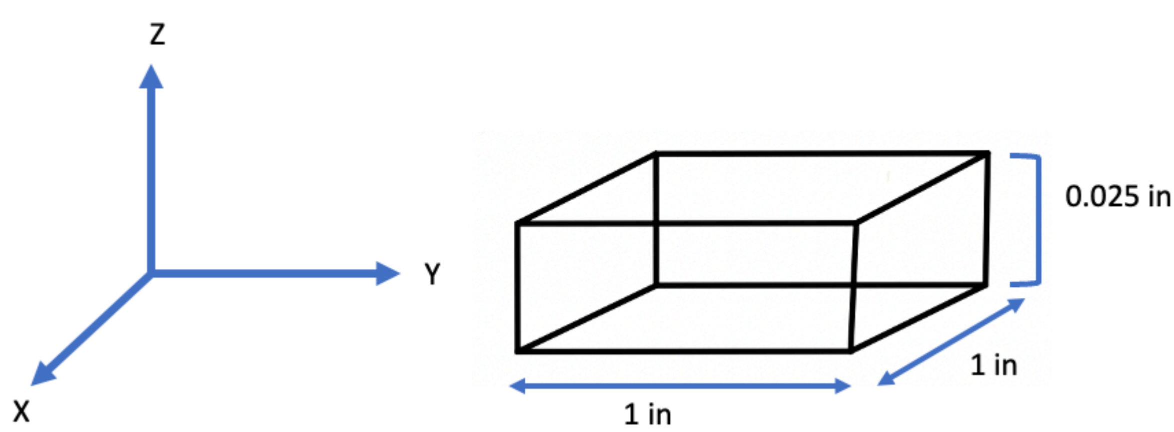

Figure 3.3. Depiction of the planar defect with length, width, and thickness of 1” x 1” x 0.025” respectively

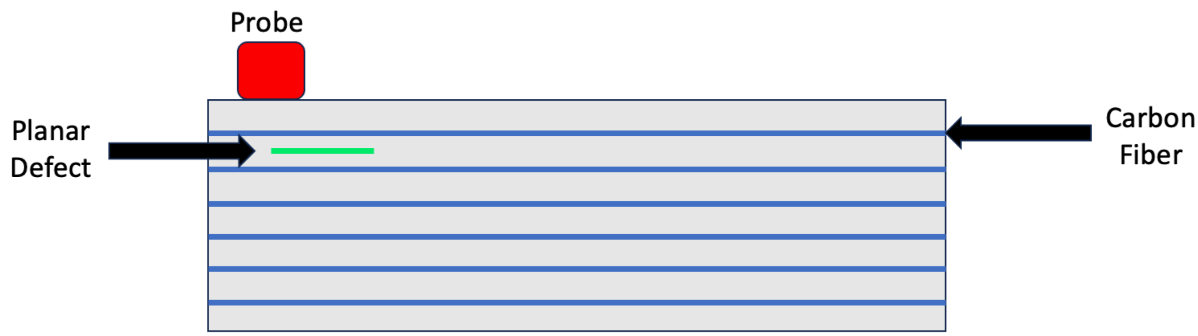

Figure 3.4. Depiction of the planar defect being parallel to the fiber orientation and orthogonal to the surface

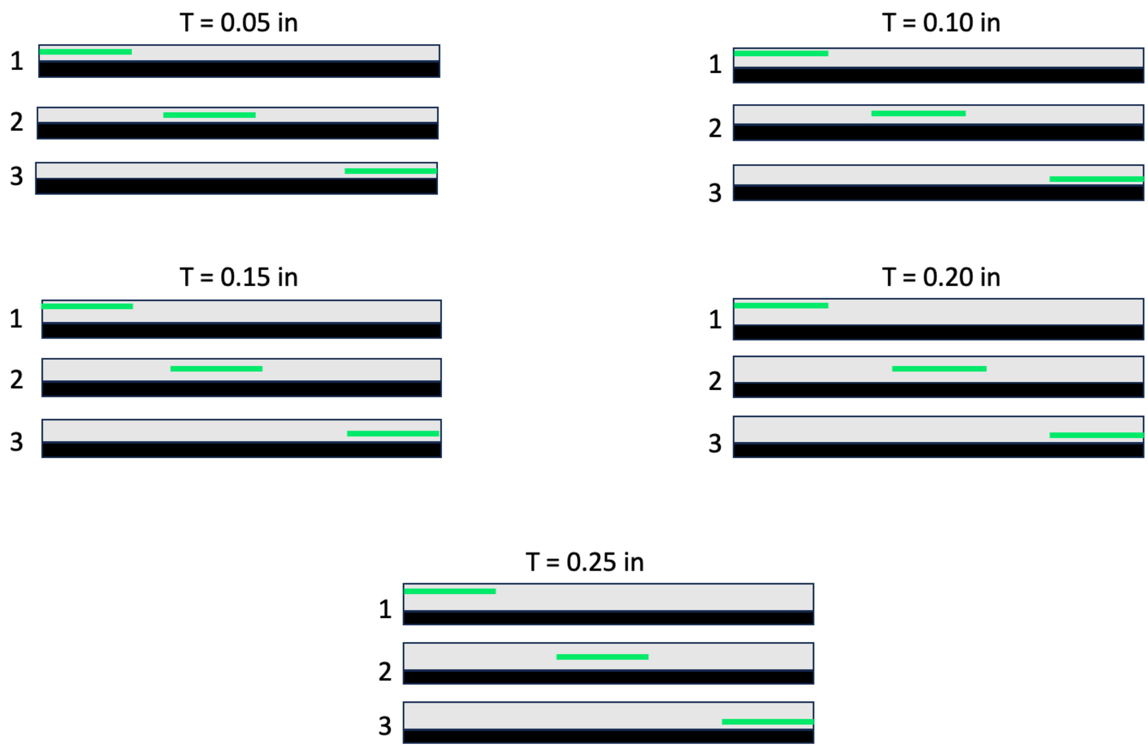

Figure 3.5. Depiction of defect at sites 1, 2, and 3 where the sites are at different depths of the thickness of the composite plates. Depth of defect is shown in Table 3.1

Table 3.1 Defect depths in each composite plate calculated based on differing thickness (T)

Defect Placement within the COPV Test Panels			
Composite Layer Thickness (T)	**Percentage of thickness defect Is at**	**Site of Defect (as represented in Figure 3.5)**	**Calculated Depth of Defect (in)**
T = 0.05	25%	1	0.0125
	50%	2	0.0250
	75%	3	0.0375
T = 0.10	25%	1	0.0250
	50%	2	0.0500
	75%	3	0.0750
T = 0.15	25%	1	0.0375
	50%	2	0.0750
	75%	3	0.1125
T = 0.20	25%	1	0.0500
	50%	2	0.1000
	75%	3	0.1500
T = 0.25	25%	1	0.0625
	50%	2	0.1250
	75%	3	0.1875

3.2.2 PAUT Parameter Determination

To properly examine the COPV test panels, several different parameters need to be established. The actual type of PAUT system will not be specified as the aim is to have the test plan be system independent. However, certain frequency, imaging modes, and transducer types will be outlined based off what was found from the literature study.

3.2.3 Probe Selection

As mentioned in section 2.5.4, there are three main factors to consider for a PAUT probe including type, size of elements, and number of elements. The types include wedge (0°), angle wedge, and delay line. The 0° wedge as well as the delay line wedges typically are used for smaller thinner samples and operate at lower evaluation or sweep angles, for example -30 - 30°. With angle wedges, these come in standard refracted beam angles of 45°, 55°, and 60° but can also be customized for different refraction angles. The benefit to using these comes from being able to perform higher sweep angles (30°-70°). Advantages with angle wedges allow for scanning of the component without having to laterally move the probe across the surface [25]. After type of probe is established, next the size of elements, but more importantly the number of elements is considered. Probes typically range from anywhere between 8-256 elements. With an increase in elements, the operator increases their ability for beam steering and focusing [22]. However, with more elements comes with increase in cost as well. In the case of this study, the probe shall be a 16 - element 60° wave wedge. Up to date, multiple studies have collected satisfactory results with this probe allowing it to be a viable option to examine the COPV [16].

3.2.4 FREQUENCY SELECTION

Typical PAUT frequency includes a range that falls between 2-10 MHz as stated in section 2.5.4. It has been demonstrated that at lower frequencies, the depth of penetration for the probe increases. However, when the frequency is increased, there is also an increase in focal sharpness as well as resolution. For this procedure, the PAUT system will be run at 1.5 MHz as other studies have used this frequency and been able to detect flaws of various sizes when dealing with composites and metal samples [16]. For future reference, if unsatisfactory results are collected at 1.5 MHz, increasing the frequency may prove beneficial.

3.2.5 IMAGING MODE SELECTION

One of two modes may be selected to evaluate the test panels.

A Scan: Scan in which the echo amplitude (vertical axis) and the transit time (horizontal axis) are plotted. Multiple A scans are stacked together to create the image.

Linear Scan: Electronic scan that runs the length of the linear array probe. By doing so a cross sectional profile is created without moving the transducer.

3.2.6 PROBE POSITIONING AND TEST PROCEDURE

When discussing probe positioning, it's important to remember the attraction for PAUT comes from the ability to steer inspection waves. In section 2.5.4, it mentions how the method of constructive and deconstructive waves are used for PAUT. Along with understanding this, we must also understand the concept of wave steering. The way this occurs is by a time delay. In other words, the elements present in the transducer are transmitting and receiving signals at different times. By doing this, the multiple waves are constructively produced at the desired angle that is established by the operator [26]. By this occurring, the beam can then be steered across the sample without having to move the probe as shown below in Figure 3.5.

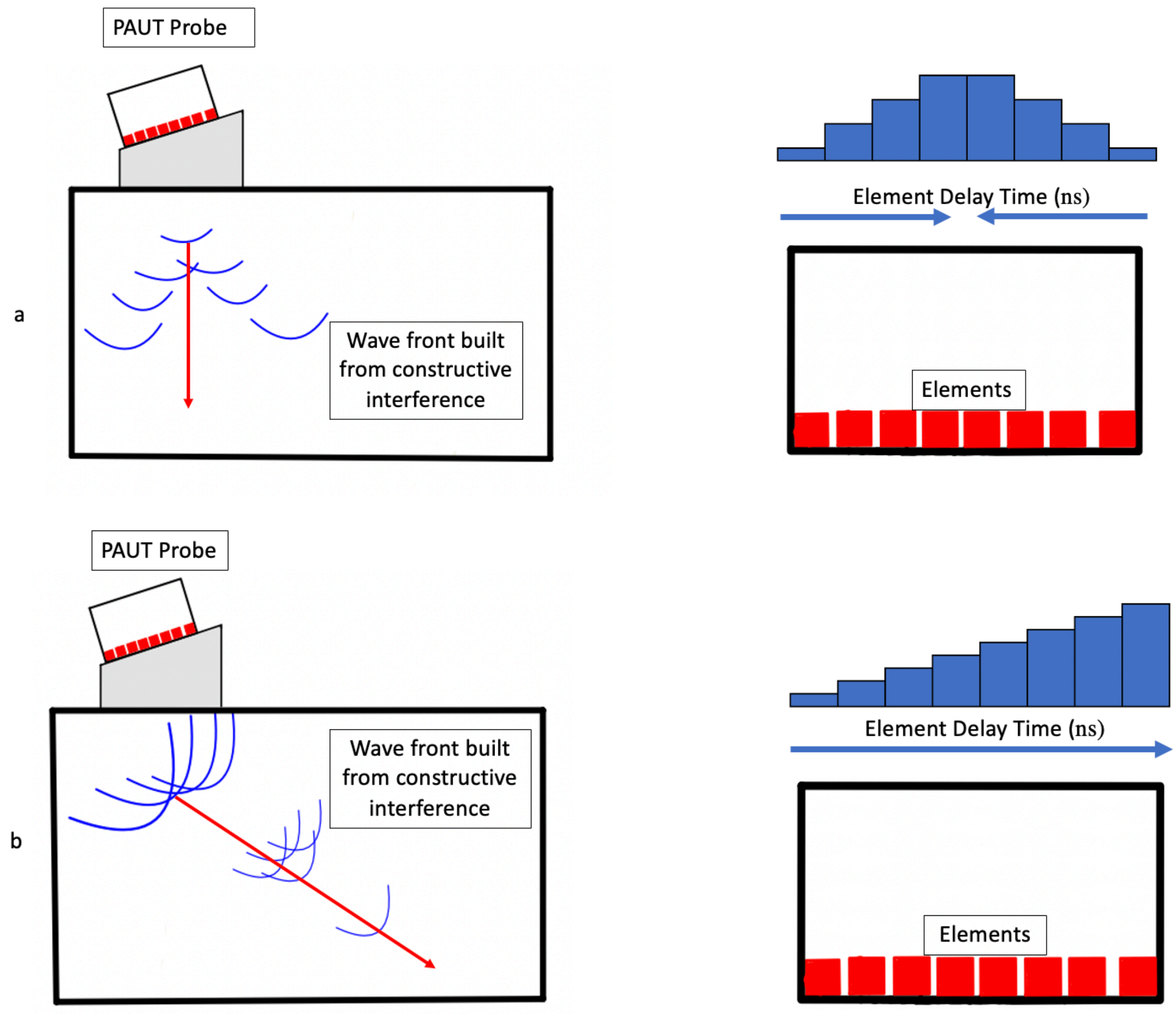

Figure 3.6. a) Depiction of time delay of elements used to achieve constructive interference for straight beam and b) depiction of time delay of elements used to achieve constructive interference for angled beam

In the case of analyzing the test panels, the probe will not be manually moved across the surface and will be stationary to allow for inspection to occur by wave sweeping. Only two probe positions will be of interest. The first orientation that will be examined will be with the probe positioned 0° to the fiber orientation as shown in Figure 3.6. When the probe is in this position, the only speed of sound that will be of interest is that of the fiber.

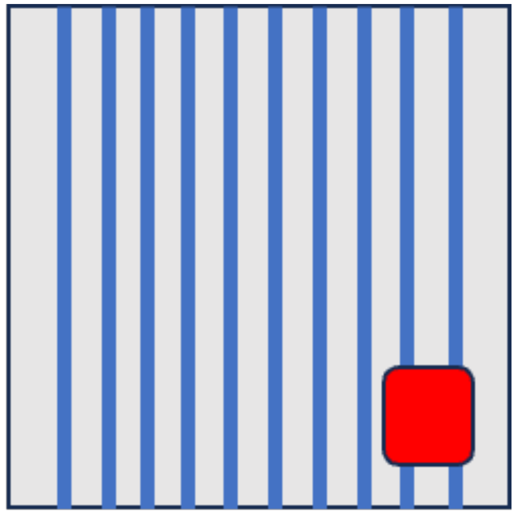

Figure 3.7. PAUT Probe positioned 0° to fiber orientation of test panel

Once data has been collected for the 0° positioning, either the probe or panel will be rotated so that the probe and fiber orientation of the panel are now 90° as shown below in Figure 3.7. In this case, the speed of sound that is important to note is that of the epoxy (matrix of composite).

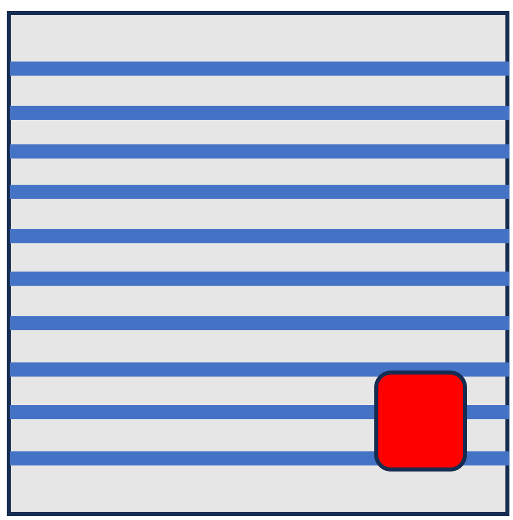

Figure 3.8. PAUT Probe positioned 90° to fiber orientation of test panel

It is important to note that the probe will not be moved across the surface but will rather be stationary. As mentioned in 2.5.4, the main interest in PAUT is the ability to steer waves. For that reason, the probe with remain stationary and the beam will sweep across the sample collecting the data.

3.3 DETERMINATION OF DATA QUALITY

3.3.1 SIGNAL TO NOISE RATIO

When looking at the results produced from PAUT, it must be determined whether the data collected is useful. A factor to determine this is the Signal to Noise Ratio or SNR. SNR has been a proven factor for being able to detect a flaw. SNR measures the signal from the defect and then compares it to the signal of background reflections which is often referred to as noise. When looking at different materials, there may be variation in SNR, however, a general rule of thumb is that the minimum SNR is 3 to 1 [27]. This recommendation was further justified in another study which showed that not only flaw detectability, but the accuracy of flaw size was highest when a SNR of 3.22 was achieved [16]. Due to the recommendations and results found in literature, for the results to be considered viable for this study the SNR must be a minimum of 3 to1.

3.3.2 ACOUSTIC IMPEDANCE

When dealing with PAUT, an important factor to consider when you have a boundary between two materials is acoustic impedance (Z). Z is a factor that is calculated by multiplying the material density by the material velocity to help explain the reflectivity that occurs at the interface of that material.

When looking at the interface between two materials as is the case between the 6061 liner and the CFC, the percentage of the energy reflected by the interface between the materials can be found using the Z of both materials using equation 1.

(1) Reflected Energy = $(\frac{Z_1 - Z_2}{Z_1 + Z_2})^2 \times 100$

Using equation 1, the percentage of the reflectivity of the interface was calculated using the Z of both 6061 and CFC as shown below in equation 2 and 3.

$Z_{Al6061} = 17$ $Z_{CFC} = 5.5 – 6.2$

(2) $(\frac{17-6.2}{17+6.2})^2 \times 100 = 21.67\%$

(3) $(\frac{17-5.5}{17+5.5})^2 \times 100 = 26.12\%$

Since the reported Z_{CFC} has a range reported to be 5.5 – 6.2, the minimum and maximum value were used to give the range of reflectivity that could be observed which was calculated to be between 21.67 – 26.12 %. This calculated value is not high by standards but is not too low to be considered worrisome.

Using equation 1, the percentage of reflectivity of the interface between the CFC and the Teflon planar defects were calculated using each materials respective Acoustic Impedance (Z) values as shown in equation 4 and 5.

$Z_{CFC} = 5.5 – 6.2$ $Z_{Teflon} = 3$

(4) $(\frac{5.5-3}{5.5+3})^2 \times 100 = 8.65\%$

(5) $(\frac{6.2-3}{6.2+3})^2 \times 100 = 12.10\%$

After calculations, we can see that the percent reflectivity between CFC and Teflon is lower compared to the percent reflectivity of CFC and 6061. Although it is lower, these values are not too low to be considered worrisome.

3.4 Notes, Recommendations, and Future Work

Once data has fully been collected, there are a few recommendations that can be added to the original scope of the test plans to either increase range of testing or better results collected.

Probe

With newer technology being developed, new probes can be examined in future studies. A new probe that is of note is a Flexible array transducer. This transducer allows for the inspection of curved metals and composites making it a viable option for inspection of COPVs.

Frequency

When performing the PAUT on the test panels, focal sharpness and resolution can be increased by increasing the frequency. If results are not satisfactory with the recommended 1.5 MHz, an increase in frequency between 2-10 MHz can be examined.

Elements

After performing initial testing, if results are satisfactory and further testing is wanted, an increase in the number of elements on the probe can be explored. This increase would in turn increase the capability of the operator when it comes to focusing and beam steering.

3.5 Conclusion

PAUT is a newer technique that is being explored. The interest comes from the ability to generate ultrasonic signals that can detect flaws/defects and well as giving the operator the ability to direct or steer waves. This ability comes from the principle of constructive and deconstructive interreference that is used in the transducers or probes. The ability to activate each element in these probes at different times is what essentially allows for waves to be directed through the inspection piece at different angles. Due to most work being done through Structural Health Monitoring, there is a need for studying the capabilities PAUT has with composite materials.

As mentioned previously, there are no established standards for operators to use when using PAUT and this test plan aims to establish a procedure that operators can follow regardless of PAUT system. The parameters selected included using a 16 element 60° wedge probe which be run at a frequency of 1.5 MHz. The test panels used will consist of a 6061 Aluminum liner that will have a thickness of 0.05 in and a CFC which will have varying thicknesses of 0.05 – 0.25 in. The test panels will have intentionally introduced planar defects that will be made from Teflon and have dimensions of 1 x 1 x 0.025 in. Once results are collected, the SNR used shall be a minimum of 3 : 1 to determine viability of what can be used. Acoustic impedance values were used to determine that there will be 21-26% reflectivity occurring at the CFC and 6061 interface and 8-12% reflectivity occurring at the interface of the CFC and Teflon defects.

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Vita

Jordan Scott Hitter was born and raised in El Paso, Texas. He attended and graduated as Valedictorian from Eastlake High School in 2019 before enrolling at The University of Texas at El Paso to begin his studies in Metallurgical and Materials Engineering. Jordan graduated Summa Cum Laude with his Bachelor of Science in Metallurgical and Materials Engineering in December of 2022. Throughout his time at UTEP, he found himself involved in many organizations including the American Foundry Society, Alpha Sigma Mu Honor Society, and Tau Beta Pi Honor Society. As both an undergraduate and graduate student, he was employed as a Teaching Assistant where he helped in classes such as Material and Energy Balance, Failure Analysis, Advanced Failure Analysis, Nanofunctional Physical Metallurgy, Mechanical Behavior and Alloys while also helping and training students in the laboratory. Aside from school, he completed three internships with the Aeronautics division of Lockheed Martin. Upon graduation, Jordan will begin his career working in the aerospace field.

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