Ultrasonic NDE Techniques for Impact Damage Inspection on CFRP Laminates

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Received: August 3, 2011 Accepted: August 23, 2011 Published: January 1, 2012
doi:10.5539/jmsr.v1n1p2 URL: http://dx.doi.org/10.5539/jmsr.v1n1p2

Abstract

This study investigates the different types of ultrasonic inspection, when applied to assess the impact damage in Carbon Fiber Reinforced Plastic CFRP laminates. The study surveys the two most used ultrasonic testing approaches first; namely the pulse-echo and the through-transmission modes. Then, the manuscript discusses and analyzes the enhanced ultrasonic testing methods that use the polar scattering, the thickness independent techniques, air-coupled, and the techniques based on the Ultrasonic Rayleigh and Lamb Waves. Additionally, presented study demonstrates some of these techniques to test a CFRP sample with embedded defects, along with the processing required for the acquired results such as the wavelet transformation.

Keywords: CFRP, Impact damage, Pulse-echo, Lamb waves

1. Introduction

Composite materials have been competitive alternatives to traditional metallic materials for a while, due to their lower density, higher stiffness, higher strength, and better fatigue resistance when compared to steel or aluminum. Such properties enable composites to be a candidate material for structural applications in aerospace and automotive products. Carbon Fiber Reinforced Plastics (CFRP) with laminated structures are one of the most concerned types of composites, thusly attracting research attentions for the last two decades. The incentives to study the impact damage inspection strategies of CFRP laminated structures are not only due to the increase in their demand, but also because CFRP structures suffer more severely from such damage than other composite materials.

The CFRP fibers exhibit better mechanical properties than these of their matrix or their fiber to matrix bonds, as a result CFRP materials are anisotropic. Hence, a reduction in their strength occurs when the impact loads are applied normal to the fiber direction. On the other hand, when the fiber orientation is parallel to the laminate surfaces, the loads applied in the through-thickness direction are always normal to the fiber direction. Thus, leading to a weaker through-thickness than in-plane mechanical performance. Minor damage areas in these structures can be formed as a result of impact loading either accidentally in the phase of design and manufacturing or anticipated in the service environment. The impact damage reduces the structural strength significantly and also affects the fatigue failure, which can happen due to cyclic low-velocity and low-energy impact loading. Therefore early and proactive detection of these embedded impact damages are important from both the mechanical performance and the safety perspectives.

Nondestructive evaluation (NDE) methods have been extensively studied for the purpose of identifying and quantifying the CFRP laminates impact damage. Ultrasonics is currently one of the most frequently used and accepted NDE techniques that are proven to provide effective and reliable results at relatively low cost.

Basically three phases of impact damage are recognized in CFRP; initially matrix cracks are generated by shear or tensile stresses mainly in the intermediate or back-wall layers; then delaminations grow from the crack tips between layers of different orientation; finally fiber fractures appear initially on the surface of the sample and may propagate into intermediate layers (Aymerich & Meili, 2000). It has been stated that Ultrasonic NDE techniques are necessarily used to examine the first two modes when defects are still invisible. This presented manuscript starts by investigating two conventional methods of ultrasonic testing that include through-transmission and pulse-echo techniques, for evaluating matrix cracks and delaminations caused by impact loading. Based on conventional ultrasonic pulse-echo techniques, the application of polar backscattering gives a better understanding of matrix cracking conditions through the laminate thickness. In addition, during the recent decade some advanced ultrasonic techniques have been developed and studied on detecting impact damage of laminated composites in the effort of exploring more capable and practical methods for in-situ inspection work. Air-coupled ultrasonics and ultrasonic Lamb Waves are two successfully demonstrated new techniques. Enhancement techniques (Wooh & Daniel, 1990) are usually needed for ultrasonic echo signals and various ultrasonic signal processing methods are also discussed mentioned in this manuscript.

Secondly, presented study will demonstrate a preliminary experimental work of applying the ultrasonic pulse-echo methods for detecting inner defects in a CFRP laminate sample. A-scans for individual measuring positions are obtained by the aid of an immersion tank equipped with three-dimensional motion controller. Based on four customized evaluation gates, C-scan images under each gate are formed to reveal the inner situation of the sample at a predefined depth and range through the sample thickness. The technique behind the evaluation gate is referred to as thickness segmentation (Steiner, 1992).

2. Two Conventional Ultrasonic Testing Modes

2.1 Pulse-echo Mode

Pulse-echo, also named as reflection method, is based on the ultrasonic energy reflection from the median interfaces. One transducer is used as both transmitter and receiver. When ultrasonic waves encounter the interface of impact damage, the reflected energy in the form of pulse-echo amplitude can be distinct from a normal situation when there is no damage.

However, for damage detection on laminated composites, pulse-echo signals are limited for distinguishing layer-by-layer information. Confusion and poor resolution can be caused in case of either superimposed defects occurring in multiple layers or superimposed back wall signals happening in relatively thin laminated plates due to incompetent range resolution (Prakash, 1980). As a result, Time-of-Flight (TOF) scan has been developed in order to allow delamination or cracking to be identified and localized with a better accuracy. The principle of TOF measurement is based on the object distance and the time-of-flight relations, which can be expressed simply by equation (1);

$$d = [c \times T.o.F.]/2 \tag{1}$$

where c is sound velocity. Ultrasonic pulse echoes against time can be gated by the TOF method for evaluating the corresponding depth or ply within the laminate. A real-time digital time-of-flight measurement algorithm based on the use of a cross-correlation functionhas been presented for pulse-echo ultrasonic applications in (Marioli, Narduzzi, & Offelli, 1992).

The Aeronautical Research Laboratory (ARL) developed a low-cost ultrasonic scanning system by recording the time-of-flight to the first return echo in the A-scan as a function of the position. Figure 1 shows the block diagram of this experimental system, which mainly includes a motion controller (not graphed in the diagram) that moves the ultrasonic probe, a thickness gauge used to provide an ultrasonic analogue signal proportional to the time-of-flight, as well as a microcomputer for digitizing the analogues signal for data collection and manipulation. Corresponding time-of-flight C-scan image of a 56-ply carbon fiber coupon is shown in Figure 2, which use different colors and patterns to present inner conditions at different depths (Preuss & Clark, 1988).

Nowadays TOF scan technique has typically been integrated in commercial ultrasonic instruments. UltraPackII in association with Ultrawin Software is utilized in the literature for obtaining ultrasonic TOF C-scan of composite laminated materials with defects (Hasiotis, Tsouvalis, & Badogiannis, 2007).

Other studies by (Steiner, 1992; Kaczmarek & Maison, 1994; Kaczmarek, 1995) have used different terms for describing the ultrasonic TOF scanning method, such as thickness segmentation or gating technique. TOF is the commercially and commonly recognized term for depicting the associate technique, in which gate delay is the elapsed time between the first echo and the beginning of the gate. Gate width is the elapsed time between the beginning of the gate and the end of the gate. At least, one gate around the backwall surface must be set to obtain initial C-scan image since the backwall surface echoes are influenced by the occurrences throughout the entire thickness of the test sample. In Figure 3, an example using two gates on the A-scan image of midsection surface and backwall surface was given (Steiner, 1992). Another study by (Potel, Chotard, François de Belleval, & Benzeggagh, 1998) analyzed the delamination mechanism over five slices of the specimen at different depth and constructed a three-dimensional ultrasonic C-scan image as shown in Figure 4. This enhanced processing method is helpful in monitoring the propagation of matrix cracking and ply-by-ply delaminations.

In case of difficult interpretation of superimposed backwall signals in thinner laminates, higher transducer frequency should be selected in order to obtain sufficient resolution of discovering through-thickness occurrences. However, ultrasonic pulse-echo signals travels two times through the sample thickness thus this type of scans is not feasible for relatively thicker samples because more energy is attenuated during propagation. In this case, through-transmission method can be considered because it only requires one pass through the sample.

2.2 Through-transmission Mode

Through-transmission is the most conventional ultrasonic testing mode, in which two transducers are used- one transmitter placed on one side of the sample, one receiver on the reverse side of the sample. When defects exist on the penetrating path, the signal would be attenuated thus revealing their presence. The ultrasound waves only travel one time through the sample thickness, hence the attenuation of the waves is less for through-transmission mode than pulse-echo and pitch-catch mode, which requires the waves travel twice the sample thickness. This enables through-transmission mode more capable for inspection on relatively thicker composite laminates. Gross flaws within thick composite laminates can be obtained by conventional through-transmission C-scan, but more subtle imperfections require additional signal processing (Kline & Chen, 1988).The ultrasonic wave propagation behavior in thick anisotropic material can be affected by such phenomena as beam skewing, material focusing/defocusing, etc., however this effect can be neglected in the nondestructive evaluation of thin anisotropic composite structures (Balasubramaniam & Whitney, 1996). Large amount of work by (Hosten & Castaings, 1993; Djordjevic & Green, 1994) has been done to perfect the interpretation of the through-transmitted signal, based on the determination of the material properties. Both ultrasonic velocity and ultrasonic reflection coefficients are concluded as sensitive to the global effects of the fiber-matrix inter-phase properties (Balasubramaniam & Ji, 1995). A major limitation for through transmission testing is the transducer installation problem on the testing facility. During ultrasonic through-transmission testing, two transducers are required to be mounted on the motion system for C-scans, but most available C-scan immersion systems are designed as capable of handling only one transducer. One solution is a facility as shown in Figure5, with horizontally opposed ultrasonic transducer coupled by a water jet from the transducer holder. This equipment is capable of conducting through-transmission C-scan testing over a wide range of component sizes, and is used to detect the size as well as the depth of a disband or delamination within a composite structure. (Teagle, 1983) However this type of equipment designed for through-transmission testing usually requires larger space and costs much more than pulse-echo testing. Hence, the need for access to both sides of the testing sample has limited the application of through-transmission method for non-destructive evaluation especially for on-site inspection field.

3. Enhancement Techniques and Methods

3.1 Polar Backscattering (PBS) Technique

Conventional ultrasonic transducer is posed normal to the examined surface of the specimen, while in backscattering technique the ultrasonic waves are incident with an oblique angle. The comparative setting diagram of the traditional (left) and backscattering (right) ultrasonic scanning systems is shown in Figure 6.

As delaminations due to impact damage can be revealed by conventional ultrasonic method easily as discussed in previous paragraphs, the reason for adopting polar backscattered ultrasonics is due to its advantage in matrix cracks evaluation. Matrix cracks occur at the initial stage of impact damaging development, and usually exist individually meanwhile are most often perpendicular to the surface thus they do not offer a wide enough reflecting surface as delaminations for normally incident ultrasonic waves. The backscattering technique is found out capable for detecting matrix cracks more sensitivity to conventional normal incidence. Gorman (Gorman, 1991) has concluded from experiments on graphite/epoxy laminates with transverse matrix cracks in both 90°

and 45° ply groups that backscattered signal from these matrix cracks are two to five times stronger than the signal reflected back from the fibers. Similar works have also been done by other workers (Steiner, Eduljee, Huang, & Gillespie, 1995; Moran, Crane, & Andrews, 1985; Aymerich & Meili, 2000).

3.2 Thickness-Independent Technique

As mentioned in previous paragraphs, both pulse-echo and through-transmission signals are affected by thickness of the specimens. On the other hand, the peak amplitude received is based on either the attenuation coefficients or the ultrasound velocity which could be affected greatly by minor difference in microstructures. This thickness related effect can be seen from Figure 7, three thicknesses of specimens were tested using a 5MHz ultrasonic transducer and their backwall echoes varied largely. With the increase of the frequency, this variation is growing even larger. (Roth, 1997)

Due to the large number of experiments required in ultrasonic evaluation on composite laminates, unified peak backwall echo amplitudes should be obtained for different thickness, also for different positions in the same laminate. For this purpose, thickness-independent and microstructural variations-irrelevant technique was noted in several literatures, both pulse-echo and through-transmission modes were involved. (Bashyam, 1990; Gruber, 1988; Roth, 1997) Roth explained an algorithm for immersion ultrasonic testing of calculating the peak amplitude of backwall echoes, or time-of-flight derived velocity without prior knowledge of the thickness. Comparative images based on peak amplitude, apparent velocity and thickness-independent algorithms in Figure 8 indicate dramatic improvement in the quality of image within certain error tolerance.

3.3 Air-coupled Ultrasonic Technique

Traditional ultrasonic testing always need the aid of couplant (water or gel) for transmitting of the ultrasound because high frequency ultrasound waves tend to attenuate rapidly when they are travelling through the air. A recent and promising air-coupled ultrasonic transducer has been studied and improved greatly and now is available for ultrasonic inspection without the need of liquid couplant. The most common air-coupled transducer arrangement methods are through-transmission and pitch-catch, (Kažys, Demčenko, Žukauskas, & Mažeika, 2006) where both methods need two separate transducers for transmitting and receiving ultrasonic signals. In the pitch-catch mode, two transducers can be placed on one side of the specimen, thus it is attractive for ultrasonic evaluation of large size components. Experiments have obtained results of high quality C-scan images using the air-coupled ultrasonic transducer as shown in Figure 9 (Stößel, 2004). Apparatus shown in Figure 10 was used for CFRP laminates delaminations detection. (Lissenden & Rose, 2008) However, the resolution is sacrificed slightly due to the lower frequencies which are used to obtain sufficient energy for air-coupled ultrasonics.

3.4 Ultrasonic Rayleigh and Lamb Waves

Apart from conventional longitudinal and transverse ultrasonic waves, Rayleigh and Lamb waves are two useful wave modes for ultrasonic inspection. Rayleigh (or Surface) waves travel the surface of a solid material penetrating to a depth of one wavelength, hence Rayleigh waves are more appropriate for inspection of surface defects. Pitch-catch contact mode is normally associated with the use of Rayleigh wave transducers with an experimental configuration as shown in Figure 11. Yang et al. have presented ultrasonic inspection of both impact damages and fiber orientation on CFRP laminated composites using the Rayleigh pitch-catch technique. Experimental results demonstrated the pitch-catch signal more sensitive than normal incidence backwall echo of longitudinal wave to subtle flaw conditions in the composite. A comparison between normal incidence pulse-echo signal and pitch-catch signal of a CRRP laminate is shown in Figure12. The pitch-catch signal was found to have certain sensitivity advantages in addition to the fact that it does not require a backwall echo as a normal pulse-echo signal. (Yang, et al., 2008; Yang, et al., 2009) On the other hand, Lamb waves are more useful for inspection of thin plate and shell structures. (Giurgiutiu & Cuc, 2005) Figure 13 shows the four types of ultrasonic waves mentioned above, including longitudinal, shear, Rayleigh and Lamb waves, and they are presented in a plate of thickness T (Djordjevic B. , 2000).The generation and detection of ultrasonic guided Lamb waves have been studied a lot during the recent decade and it was proved to be useful in optimizing the modeling of the ultrasonic propagation associated with impact damage (Matzkanin & Yolken, 2007). This method can be used in the structural health monitoring (SHM) mode served for damage detection on laminated composite structures to determine the current state of health and predict the remaining life. Figure 14 illustrated an ultrasonic lamb wave based testing method in pitch-catch mode, where the propagation of these waves is disturbed by the presence of damage (Giurgiutiu & Cuc, 2005). Castaings et al. has done the work of using air-coupled ultrasonic transducer based on the generation and reception of the Lamb waves for the inspection of CFRP plates with impact damage induced delaminations. Figure 15 shows the change of the amplitude of the ultrasonic B-scan signals over a defective sample, and the result is compared to the numerical predictions based on a finite element model. Very good agreement between numerical predictions and experimental measurements has been obtained when the delamination appears between the first and second layer, but much worse agreement has been shown when delamination position appears deeper or induced by impact damage (Castaings, Cawley, Farlow, & Hayward, 1998).Remarkable progress has been achieved associated with ultrasonic Lamb waves inspection technique but considerable work remains to be done, such as to refining the theoretical analysis and experimental studies to determine the reconstruction error for different types of damage. (Ng & Veidt, 2009)

3.5 Various Techniques of Ultrasonic Signal Processing

The difficulties in interpreting and understanding ultrasonic echoes are commonly recognized, and distorted or degraded of acquired signals sometimes are produced due to extraneous noise, imperfection of the acquisition system, etc. (Wooh & Daniel, 1990) Therefore proper signal processing is needed for different inspection objectives. Various signal processing methods (Benammar, Drai, & Guessoum, 2008) have been studied on and new techniques have yet to emerge. Conventional distance amplitude correction (DAC) technique so far has been adopted widely and built in display in ultrasonic scanning systems (Halmshaw, 1996) while a Spectral DAC was explored for improvement in spatial resolution and in the possibility forthe detection of small defects for composites evaluation. (Pfeiffer & Hillger, 2006) Thickness-independent technique and thickness segmentation using wavelet transform method were respectively discussed in the above paragraphs. Split-spectrum processing (SSP) were introduced (Bilgutay, Bencharit, & Saniie, 1989) based on frequency analysis, and polarity thresholding (PT) algorithm (Shankar, Karpur, Newhouse, & Rose, 1989) was developed for SSP for ultrasonic noise suppression. By contrast wavelet transform (WT) is based on time analysis and comparison between WT and SSP was carried out in the literature. (Abbate, Koay, Frankel, Schroeder, & Das, 1997) The ultrasonic echo signals in nature are statistical data because the randomness of their generation. (Dutt, 1995) Hence statistical analysis of ultrasonic echoes is useful for determination of variation about locations and reflection situations, which are decisive factors of final amplitude of echo signals. Statistical histogram analysis (Steiner, 1992) was introduced early last century and 'meanfield theory' based analysis (Stanullo, Bojinski, Gold, Shapiro, & Busse, 1998) were demonstrated helpful in monitoring the correlation between statistical parameters and amount of damage.

4. Experimental Results

A 400×500 mm2 CFRP plate sample with thickness of around 2 mm was placed on a testing table in a water tank. An immersion ultrasonic scanning system USIP 40 with C-scan motion-control and imaging system manufactured by Krautkramer Ultrasonic Instrument was utilized. Both A and C scans under pulse-echo mode were used, in order to detect the inner defects in the sample, which were formed during the manufacturing stage. Four evaluation gates were used, and one of them were set as the gate for initial echo. By adjusting the evaluation depth, width and amplitude of the gates, the specimen could be divided into at most four different segments. Each evaluation gate would record an individual C-scan image which reflects the situations of the monitored segment through the sample thickness. A focus immersion transducer with working frequency of 25MHz was posed strictly perpendicular to the surface of the sample.

The inner defects existed in this sample are mainly delaminations between two adjacent plies induced by the inconsistencies involved in the hand lay-up process. Delaminations caused by impact damage were not studied in the present experiments. However both kinds of delaminations have similar change in structures. Ultrasonic signals have a poorer transmission coefficient and correspondingly a larger reflection coefficient at the boundary of plastic-to-air compared with plastic-to-adhesive. As a result, an abnormally large ultrasonic echo would reveal the presence of delamination. Figure 16 is a C-scan image of a section of the specimen with detecting length of 100mm and width of 50mm. It is obtained by setting evaluation gates at the backwall echoes and calculating the average or sum of all the amplitudes within the gates. The calculated averages or sums over each measuring point over the tested area are scaled into a certain amount of levels and assigned corresponding colors. From the color blue to red, the levels increase which means stronger gated signals or earlier reflected signals at red regions, thus indicating the presence of delaminations. The bottom middle areas of the detected section with red colors indicate the presence of delaminations. Figure 17 below is the A-scan image of the spot marked in Figure 16. Delamination appears at the depth of around 0.7mm to 0.8mm, and this could be simply read on the A-scan image. The horizontal axis corresponds to the through-depth thickness of the specimen. The normal echoes are expected to be lower than the evaluation gates, but the amplitude of actual pulse-echoes from 0.7mm to 0.8mm exceeds the upmost gate thus determined as defects. Another section on the sample with same test area in Figure 18 is shown without any red regions or without obvious delaminations. In addition, the software supports detection without the knowledge of the material of the specimen. The testing table surface depth has been calibrated and recorded before testing. The distance between the immersion transducer and the testing table can be measured by motion-controller. Hence the thickness of the specimen can be simply calculated. By capturing the surface and backwall echoes, the time-of-flight through the specimen can also be calculated, thus the ultrasonic velocity in the specimen can be estimated. The software could detect a wide range of materials from metals to plastics with different acoustic velocity.

5. Conclusions

Impact damage induced defects have three different stages; the first two of them are not detectable by naked eyes. Ultrasonic non-destructive inspection method is considered as a solution of discovering inner matrix cracks or delaminations. Both pulse-echo and through-transmission modes are effective form, however limitations do exist. Pulse-echo mode is more effective for relatively thinner sample because the signal travels two times through the specimen. Thickness segmentation method is needed if information of different layers is to be discovered. The presented experiment involves four thickness segmentations, which is executed by adding appropriate evaluation gates between the initial surface echoes and backwall echoes.

Further techniques such as polar-backscattering could enhance the identification of transverse matrix cracks, which helps an earlier revelation of impact damage. Thickness-independent technique could be used as a data processing method for a stronger interpretation of the ultrasonic images, to provide comparative results among different samples eliminating effects of material thickness and microstructures induced change in ultrasonic velocity and attenuation coefficient. Other testing mode, such as pitch-catch mode with the principle of detecting ultrasonic Lamb waves has been developed dramatically recently. With the development of air-coupled ultrasonic transducer, portable detection gains a promising future while the resolution is limited by its relatively lower frequency so far. Signal processing techniques associated with ultrasound should always be considered as the major tools for better understanding and interpretation of the testing objects.

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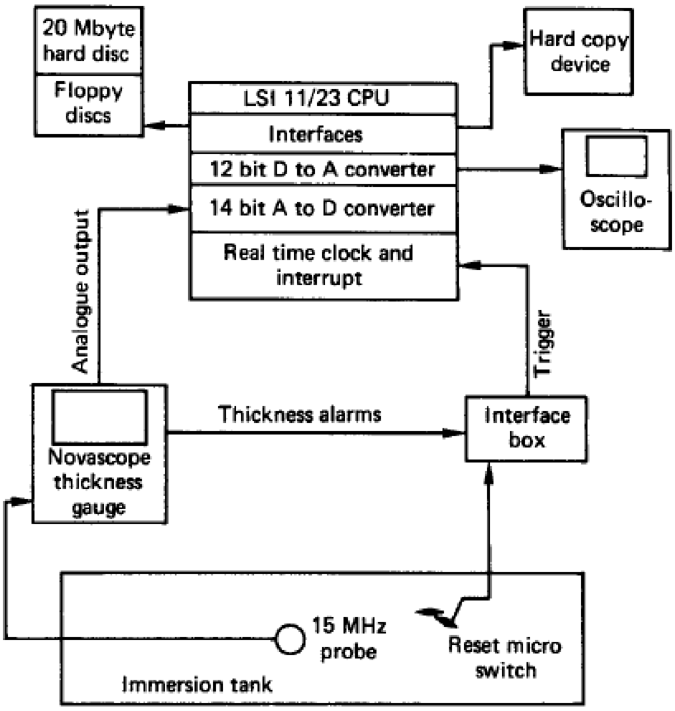


Figure 1. Block Diagram of ARL Time-of-flight C-scanning System (Preuss & Clark, 1988)

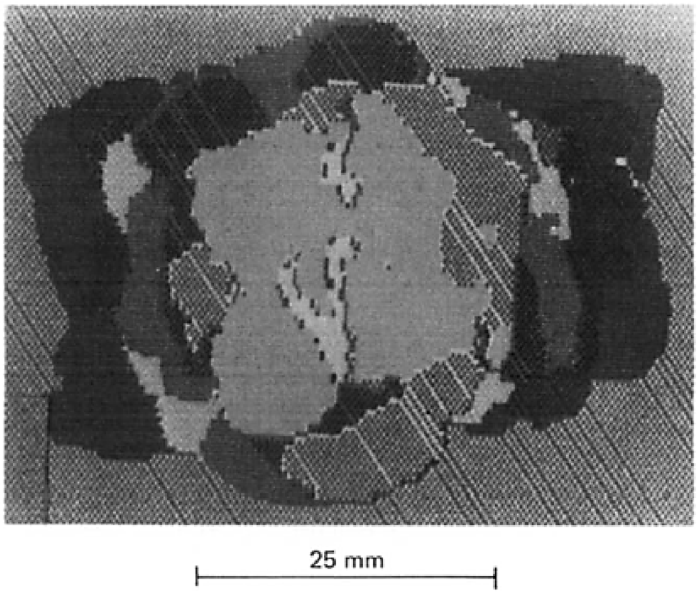


Figure 2. TOF C-scan image represent the damage structure in an impact-damaged 56-ply carbon fiber coupon. The different colors indicate damage extent at different depths (Preuss & Clark, 1988)

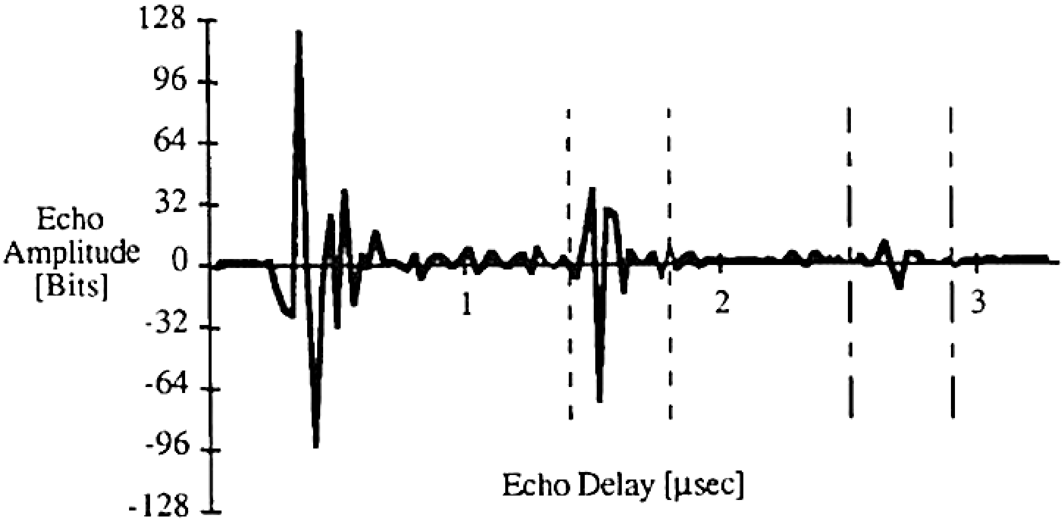


Figure 3. Two thickness segments (midsection and backwall) are used on ultrasonic pulse-echo waves for delamination monitoring of 64-ply graphite-epoxy panel (Steiner, 1992)

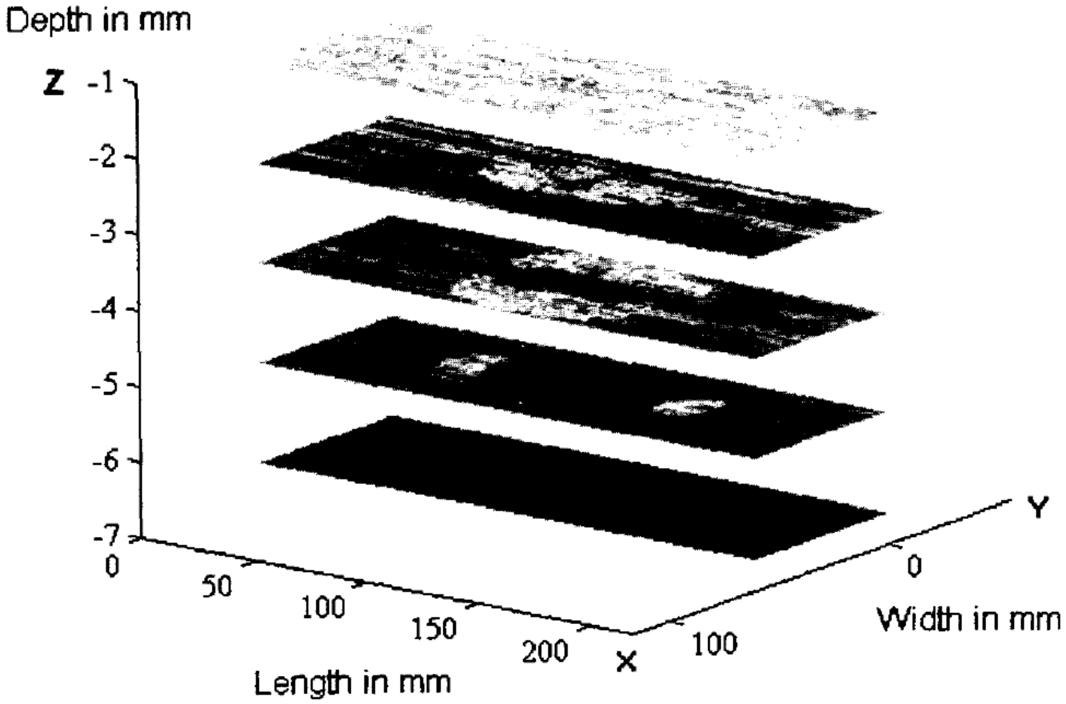


Figure 4. Three dimensional ultrasonic C-scan using thickness segmentson an impacted beam (POTEL, CHOTARD, FRANÇOIS DE BELLEVAL, & BENZEGGAGH, 1998)

Figure 5. Through transmission water jet probe system (Courtesy of Meccasonics Limited)

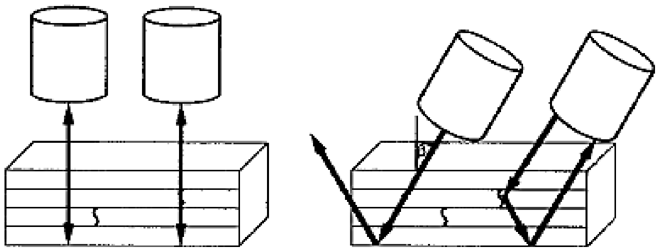


Figure 6. Ultrasonic Rayleigh pitch-catch measurement configuration(Yang, et al., 2008)

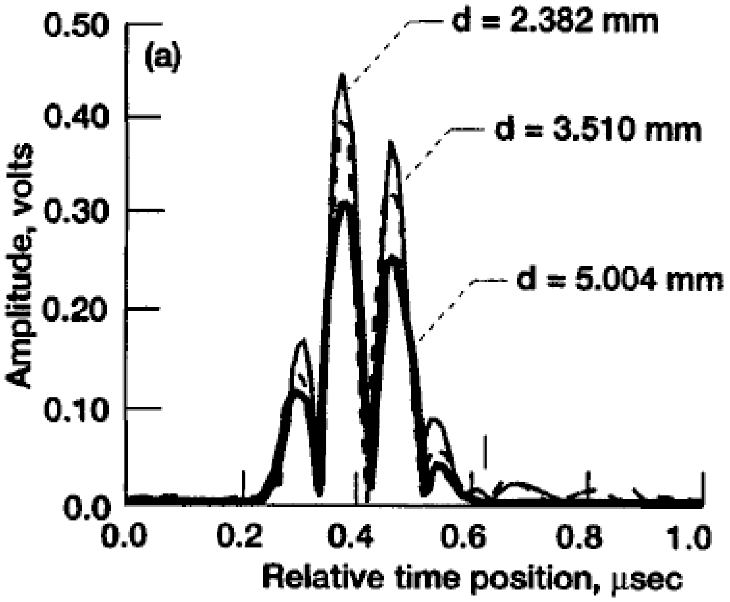


Figure 7. Effect of thickness on ultrasonic echo peak amplitude for PMR-15 sample: backwall echoes of three thicknesses using 5MHz broadband transducer (ROTH, 1997)

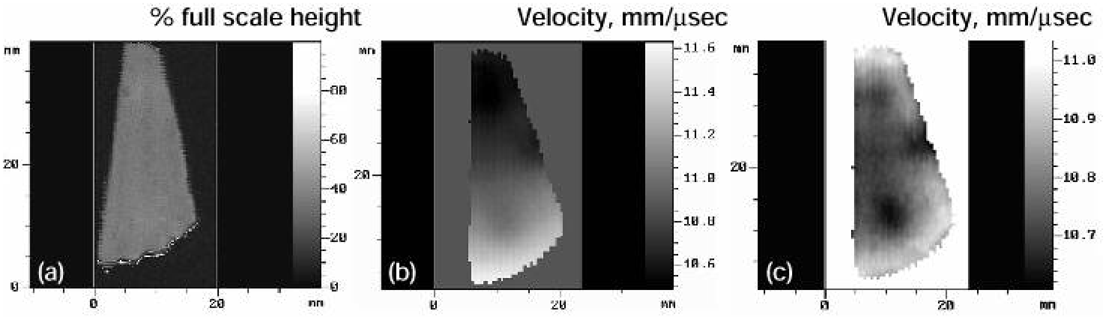


Figure 8. Three comparative C-scans of silicon nitride wedge with certain fraction of pore imperfections, and a 300μm thickness gradient edge-to-edge: (a) 50MHz, peak amplitude image where backwall was gated (b) 20MHz, apparent velocity image based on time-of-flight (c) 20MHz, thickness-independent image. (ROTH, 1997)

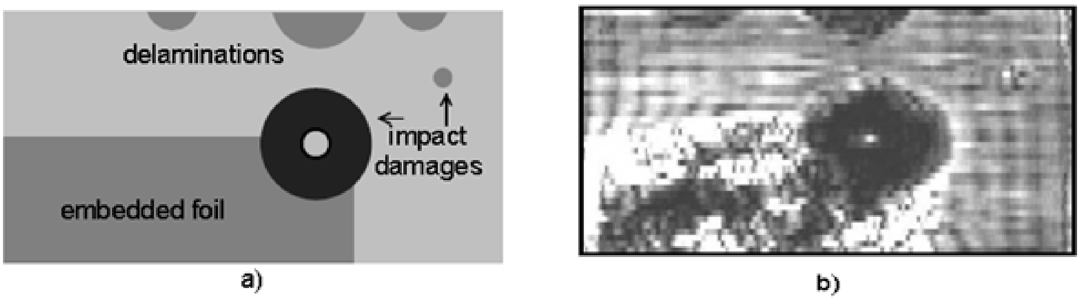


Figure 9. (a) CFRP-sample (150mm×100mm×4mm) with artificially made delaminations at the edges, two impact damages, and embedded foil; (b) air-coupled ultrasonic C-scan image under through-transmission mode (Stößel, 2004)

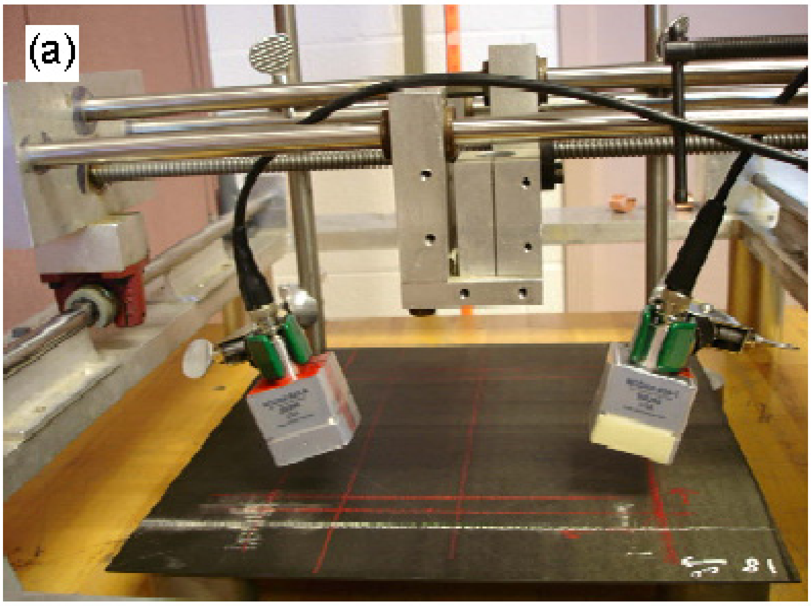


Figure 10. Delamination detection with air coupled transducers and imaging mechanism (LISSENDEN & ROSE, 2008)

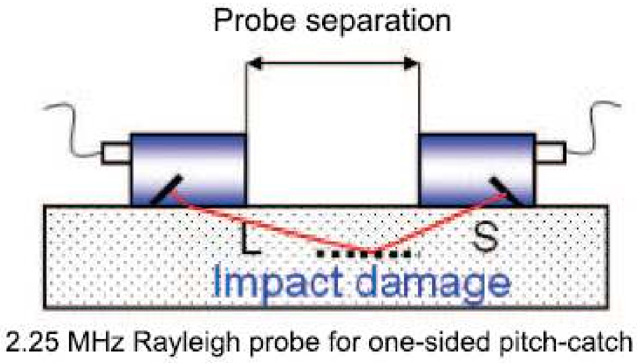


Figure 11. Ultrasonic Rayleigh pitch-catch measurement configuration(YANG, ET AL., 2008)

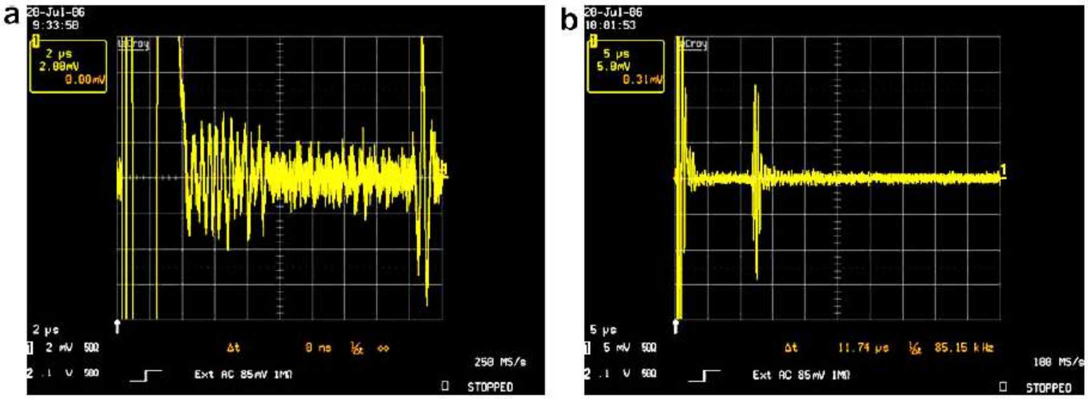


Figure 12. A comparison between a normal incident pulse-echo signal and a Rayleigh pitch-catch signal of a unidirectional CFRP laminate (Yang, et al., 2009)

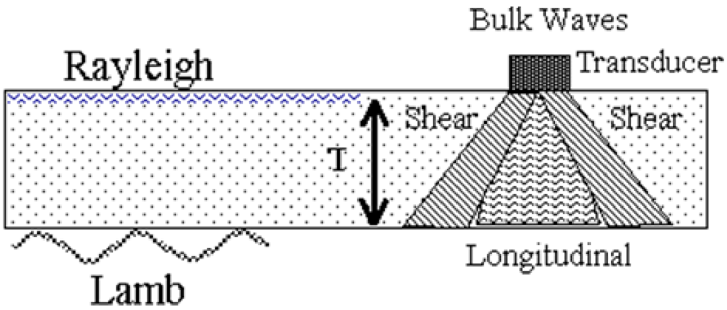


Figure 13. Ultrasonic stress wave types present in the plate thickness T. (Djordjevic B. , 2000)

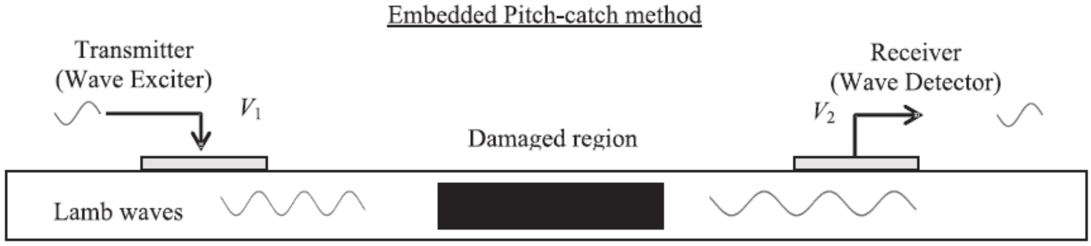


Figure 14. Embedded ultrasonics damage detection techniques with the pitch-catch method (GIURGIUTIU & CUC, 2005)

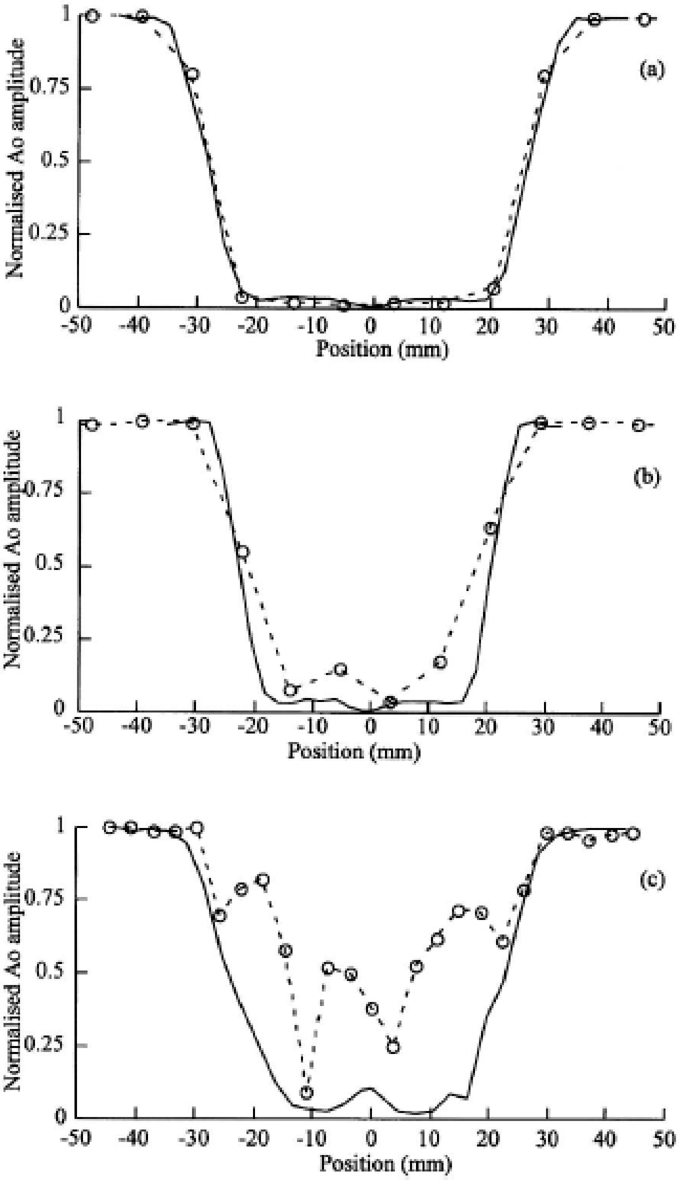


Figure 15. Air-coupled, Lamb wave scans over CFRP plates compared with simulation prediction (a) a delamination between layers 1 and 2; (b) a delamination between layers 3 and 4; (c) impact damage (CASTAINGS, CAWLEY, FARLOW, & HAYWARD, 1998)

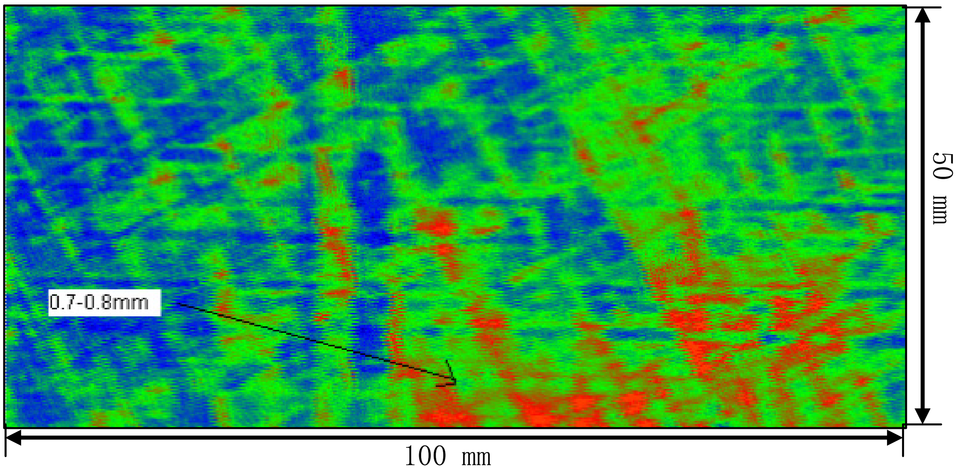
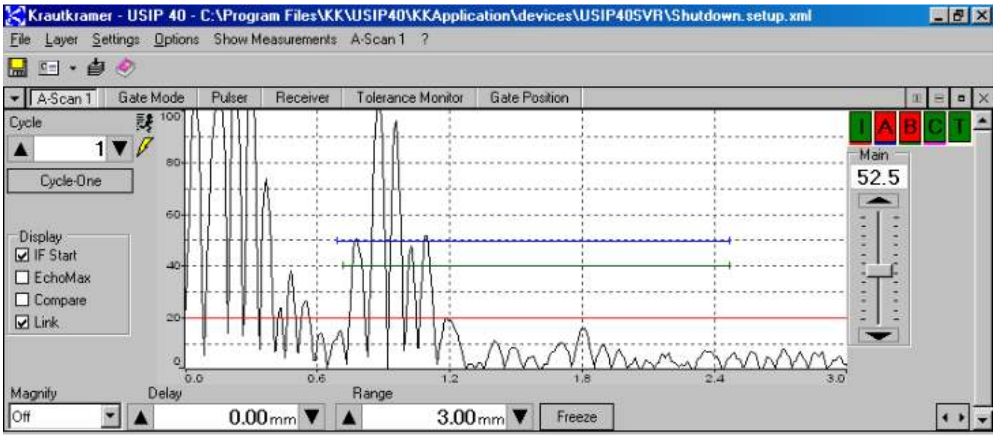


Figure 16. The C-scan image of the sectional CFRP specimenwith defects gated at the backwall echoes


Krautkramer - USIP 40 - C:\Program Files\KK\USIP40\KKApplication\devices\USIP40SVR\Shutdown.setup.xml

Cycle 1

☑ IF Start
☐ EchoMax
☐ Compare
☑ Link

Main 52.5

Magnify Off

Delay 0.00mm

Range 3.00mm

Figure 17. Time-domain A-scan image of a spot with delamination between plies in the CFRP specimen at the depth of 0.7-0.8mm

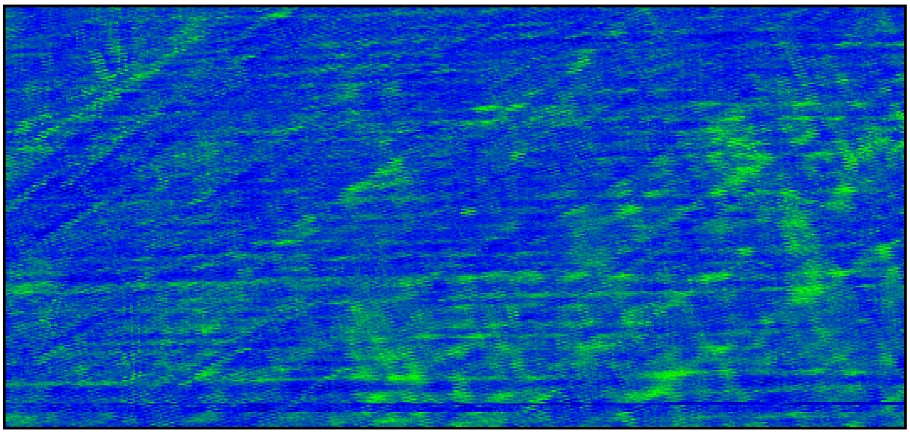


Figure 18. The C-scan image of the sectional CFRP specimenwithout defects gated at the backwall echoes