SH-mode guided-wave impact damage detection in thick quasi-isotropic composites

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ABSTRACT

Due to the extensive use of composite materials in aerospace structures, they are highly susceptible to various types of damage including barely visible impact damage (BVID) due to low-velocity impact events such as bird strikes and runway debris. Implementation of guided-wave based structural health monitoring (SHM) for BVID detection in composites has been extremely challenging due to the anisotropic nature of composites and the complex wave-damage interaction with impact damage. This paper presents a new methodology for the detection of BVID in composites using selectively pure SH0 mode guided waves generated by angle beam transducers (ABT) and received by phased array transducers (PAT). In this methodology, pure SH0 wave excitation was achieved using the angle beam transducers and variable angle wedges and after propagation in the composite it was received by the phased array transducer. First, the semi-analytical finite element (SAFE) method was used to generate the guided wave dispersion curves and the corresponding tuning angle for the SH0 mode excitation was obtained based on Snell’s law. Then, pitch-catch experiments using the ABT-PAT transducer pair were conducted to validate the pure SH0 mode excitation. After this, impact damage experiments were conducted on multiple quasi-isotropic carbon fiber reinforced polymer (CFRP) composite plates having different thicknesses by conforming to the ASTM D7136 standard to generate controlled impact damage size of 1". Next, impact damage detection experiments using pure SH0 mode at 500 kHz, were conducted using the ABT-PAT transducer pair. It was observed that pure SH0 mode was sensitive to the impact damage as a significant decrease in the signal amplitude and mode conversion was observed. With our experiments, we demonstrated the validity and usefulness of this technique for impact damage detection in composite structures. An invention disclosure describing the use of angle beam transducers for SH wave excitation method has been filed and is in the process of becoming a provisional patent.

Keywords: Composite structures; Barely visible impact damage (BVID); structural health monitoring (SHM); SH guided waves; Damage detection; Angle beam transducer (ABT); Phased array transducer (PAT)

1. INTRODUCTION

1.1 Background and Significance

Barely visible impact damage (BVID) is a specific type of damage that can occur in aerospace composite materials during the manufacturing stages due to accidental tool drops on the shop floor or due to low-velocity impacts of runway debris or large hailstones during inclement weather during the service life of the structure. In low-velocity impact events, complete penetration of the composite material by the impactor may not occur but may still create considerable damage internally which is barely visible i.e. BVID from the outside. BVID represents surface dents which are too small or too difficult (due to lighting conditions, coatings of paint) to be seen during visual aircraft inspections and can propagate and lead to extensive overall strength reduction of the structure thereby causing catastrophic failure if not properly inspected and repaired.

The ideology of BVID was introduced in the early 1980s with respect to understanding the damage tolerance of composite laminates [1][2]. In subsequent years, BVID became important in the inspection of composite aircraft where the damage needed to be characterized as BVID or visible impact damage (VID). According to the military handbook for composite materials [3], BVID is defined as damage that is visible at a distance of less than 1.5 m, and VID is defined as damage that is visible at a distance of 1.5 m or greater. This clarity in distinguishing between BVID and VID during aircraft inspections can determine if a composite repair is needed or not at the location where an impact has occurred. If a damage is characterized as VID it needs repairs to be conducted to the composite immediately. However, there is a loophole to these definitions. A situation may arise where the damage is characterized as BVID based on visual inspections but may
have an impact damage size of 1" or greater. An impact damage size of 1" or greater may significantly deteriorate the strength of the composite part (see Figure 1) and may need immediate repairs to be conducted. This impact damage must not be discounted from repairs despite being characterized as BVID. From Figure 1 we can also observe that in comparison to a 1" damage diameter of any damage type (delamination, porosity, open hole), an impact damage having a diameter of 1" or greater can significantly reduce the compressive strength of the composite structure. This is the significance and importance of detecting and monitoring impact damage having a diameter of 1" or greater [4].

![Figure 1: Effect of impact damage size on compressive strength of composite](image)

With the increasing occurrence of BVID in composites, nondestructive evaluation and structural health monitoring methods needed to be developed to characterize the impact damage. Ultrasonic testing was one of the first methods to be used for impact damage inspection and detection [5]-[8]. Eddy current methods have been explored by researchers to detect manufacturing flaws and operational damage such as impact damage in CFRP composites [9]-[12]. Researchers have also explored microwave nondestructive evaluation techniques to investigate low-velocity and high-velocity impact damage in composites due to environmental effects [13]-[20]. Infrared thermography is also being explored by scientists as a viable option of detecting impact damage in a rapid manner [21]-[23]. X-ray computed tomography is also being used by researchers to give a 3D assessment of impact damage in composite structures [24]-[26]. Guided wave propagation in composite laminates has been used to see the interaction with impact damage. Advanced guided wave methods are currently being explored for rapid, reliable, and large area assessment of composite structures subjected to controlled impact damage [27]-[31].

Guided have been widely used in the structural health monitoring (SHM) of composite structures due to their long propagation distance and low loss of energy. Among guided waves, Lamb-wave based SHM technologies have been widely used to detect various types of damage in composite structures, including delamination and impact damage [32]-[34]. Compared with the widely used Lamb waves, the fundamental shear horizontal (SH0) wave is relatively simpler because they are only mildly dispersive in typical composites [31] compared to Lamb waves which are highly dispersive. However, SH0 wave has been less investigated for composite SHM applications.

In recent years, adjustable angle beam transducers (ABT) have been utilized to achieve single-mode Lamb wave excitation and detection [35], [36]. For exciting SH0 wave in metallic structures, electromagnetic acoustic transducers (EMAT) are typically used [37]. In recent years, the applicability of SH0 wave mode has promoted the development of novel methodologies to overcome the difficulties associated with SH0 wave generation in composites. SH-wave piezoelectric transducers based on either thickness-shear mode or face-shear mode [38] piezoelectric wafers, and piezoelectric fiber patches [39] have been developed for SH0 wave generation with limited success since these SH-wave transducers must be permanently bonded to the structure. More recently, adjustable angle beam transducers were used to excite pure SH0 wave in quasi-isotropic composite plates of various thicknesses [29].

1.2 Objectives of the current paper

In this paper, the authors have described a new methodology for effectively detecting the presence of 1" impact damage in thick quasi-isotropic CFRP composite coupons by using pure SH0 mode generated using angle beam transducers (ABT) and received using phased array transducers (PAT). The ABT is displayed in Figure 2 (a) and the PAT is displayed in Figure 2 (b).
First, the ABT and PAT tuning angle of SH0 mode was calculated from the theoretical phase-velocity dispersion curve based on Snell’s law. Then, pitch-catch experiments were performed on a 3-mm and 4-mm quasi-isotropic CFRP coupons to validate that the SH0 mode was indeed being generated by the ABT and being received by the PAT. A schematic of the ABT-PAT transducer pair used to generate the pure SH0 mode in a composite laminate is displayed in Figure 3. Furthermore, pitch-catch experiments using the ABT-PAT transducer pair were conducted to detect 1” impact damage in 3-mm and 4-mm quasi-isotropic CFRP composite coupons having a size of 12” x 6”. For the sake of convenience, angle beam transducer will be referred to as ABT and phased array transducer will be referred to as PAT in this entire paper.

Figure 2: (a) ABT- Angle beam transducer with variable angle wedge having a wedge velocity of 2720 m/s; (b) PAT-Phased array transducer having a wedge velocity of 2330 m/s

Figure 3: Schematic of the ABT-PAT experimental setup for pure SH0 mode excitation

2. MANUFACTURING PROCESS

2.1 Manufacturing process of quasi-isotropic CFRP composites

Quasi-isotropic CFRP composite plates to cut out the coupons with the correct sizes for impact testing conforming to the ASTM D7136 standard, were manufactured using the CYCOM® 5320-1 epoxy resin system with the Hexcel IM7 12K fiber in a compression molding (hot press) machine using the manufacturer’s cure cycle. To manufacture quasi-isotropic composite plates with the correct thicknesses an appropriate stacking sequence with the appropriate number of layers had to be chosen. The quasi-isotropic stacking sequence was chosen based on the work done by previous researchers [40]-[42]. A [-45/90/+45/0]3S stacking sequence was chosen for manufacturing the composite plate with 24 layers having a nominal thickness of approximately 3-mm. Similarly, a 4-mm composite plate was manufactured having a [-45/90/+45/0]AS stacking sequence with 32 layers. After the manufacturing process in the compression molding machine, the thickness of the manufactured plates was a little more or less than anticipated. The cure cycle, compression molding machine, and one of the manufactured composite plates are displayed in Figure 4. From the large composite plates, the 6” x 4” standard size coupon for the ASTM D7136 testing was cutout as displayed in Figure 4 (c).
Figure 4: Manufacturing of quasi-isotropic composite plates: (a) Cure cycle; (b) compression molding machine; (c) Final composite plate with 6” x 4” cut-outs

3. IMPACT TESTING EXPERIMENTAL SETUP

3.1 Experimental setup for ASTM drop weight impact testing

Figure 5: Dynatup 8200 drop weight impact testing machine instrumented with load cell and velocity sensor
A drop weight impact tower, displayed in Figure 5, with low friction guide rails is used to produce collision between a mass of known weight (impactor) and a fixed composite coupon of dimensions 6” x 4”. The controlled impact event is recorded by a piezoelectric load cell which can accurately record data of the applied impact force, energy absorbed by the coupon and the displacement of the coupon during the event. Using variable impact heights, data is collected that shows how the coupon behaves under impacts of varied magnitude, and these impact tests can be conducted in sequence to see how damage forms in the coupon over repeated impacts on the same coupon or on different coupons. This data can then be used to predict the future behavior of the material such as crack propagation and other complex damage formation. These tests are particularly useful when studying composite materials. Since composites are designed to distribute damage throughout the volume of a material, damage formation and the propagation of cracks can be difficult to predict accurately through theory and simulation alone. Also, difficulties in predicting important properties such as stiffness of the material and the amount of energy it is capable of absorbing before experiencing failure make drop weight impact testing a valuable process in experimental mechanics of composites.

Before the test is conducted, it is important to make sure that the impact carriage and conveyor is secured safely above the clamping platform. The coupon is placed on top of the support fixture centering it on top of the 5” x 3” cut-out and the assembly is clamped into place. A protective cover is placed over the coupon to prevent accidental damage. After this the conveyor is slowly raised or lowered using the hoist control to the desired distance above the coupon and is fastened into place using the shaft collars. This distance is measured using the laser height indicator and determines the drop height which is calculated before based on the potential energy of the impactor. All the equipment is checked to ensure that the data acquisition system is recording the data properly and then the coupon cover is removed and the impactor is engaged. The trigger mechanism is then activated, initiating the drop impact event and capturing the force and velocity data for the duration of the impact test. The impactor can be caught safely after rebounding from the coupon to avoid a secondary impact on the composite coupon. It is also possible to avoid secondary impact if the drop weight impact testing machine has an anti-rebound device or stop block installed. The data is saved and the impact carriage is lifted away from the coupon and is locked back into place on the conveyor. The protective cover is placed over the coupon to ensure no further damage to it as the conveyor’s shaft collars are unlocked and the hoist mechanism is used to lift the carriage away from the clamping assembly. The detailed experimental setup is displayed in Figure 5.

Since the standard coupon size for ASTM drop weight impact testing is only 6” x 4” [ASTM ref], it is very difficult to accommodate the ABT-PAT pair on this small size coupon for impact damage detection. To perform accurate impact damage detection experiments, preliminary impact experiments conducted on 6” x 4” composite coupons were extended to a composite coupon with the largest dimensions possible that could be accommodated on the existing ASTM D7136 fixture and that could be used for efficient impact damage detection using the ABT-PAT transducer pair. Since the in-plane dimension of the D7136 fixture on the drop weight impact testing machine was 12” x 6”, a coupon of this size was used for further impact tests to create approximately 1” impact damage size in the 3-mm and 4-mm composite coupons using engineering judgment.

3.2 Modified experimental setup for drop weight impact testing

To accommodate a larger size coupon (12” x 6”) on the D7136 fixture for conducting impact experiments on the drop weight impact testing machine, certain improvisations needed to be made. First, the existing four clamps on top of the D7136 fixture which were used to clamp the 6” x 4” had to be removed. After this, a large boundary frame set displayed in Figure 6 was designed and manufactured using low carbon steel. This boundary frame set consisted of a 0.5” thick top frame and a 1” thick bottom frame between which the impact coupon was sandwiched. The bottom frame had to be made thicker in order to allow the impact coupon to undergo bending at the time of impact without being in contact with any surface below it.
This large boundary frame set with the impact coupon sandwiched in-between the top and bottom frames was placed on top of the existing D7136 fixture (recall that clamps were removed). This entire assembly was clamped to the existing D7136 fixture using multiple C-clamps. The drop weight impact testing machine with the modified fixture and clamping assembly is displayed in Figure 7. With the modified fixture and clamping assembly it was possible to conduct controlled impact tests on larger size composite coupons (12” x 6”) on which damage detection experiments could be performed.
4. IMPACT DAMAGE DETECTION EXPERIMENTAL SETUP

4.1 Ultrasonic NDE before and after impact testing

UT (Ultrasonic testing) scans were conducted using the RollerFORM inspection and in the ultrasonic immersion tank on the CFRP composite coupons before and after impact to obtain the B-scan and C-scan images and compare a pristine coupon with a coupon that underwent impact damage and to see the size and shape of the impact damage. In the case of the RollerFORM inspection, a thin layer of water is sprayed on the composite coupon to be inspected and a phased array wheel probe is moved along the composite coupon and the B-scan and C-scan images of the scanning area are displayed on the OmniScan system. In the case of the immersion tank inspection, a 10 MHz, 1” focused, 0.375” diameter ultrasonic transducer was used in the pulse-echo mode for conducting the UT scans. Post-processing of the data obtained from the ODIS software interface is able to give us a clear C-scan image, B-scan image, and A-scans in the pristine and impacted coupons. The experimental setups for these inspection techniques are displayed in Figure 8.

![Figure 8: UT scans were performed using (a) RollerFORM inspection (b) Immersion tank inspection](image)

4.2 ABT-PAT experimental setup for pitch-catch experiment to generate pure SH0 mode

Before conducting the impact tests on the composite coupons, preliminary pitch-catch experiments were conducted on the pristine composite coupons as displayed in Figure 9. In these experiments, the transmitter ABT with the variable angle wedge was set to an angle at which the pure SH0 wave mode could be generated in the composite coupon and the receiver PAT was placed at different distances (marked by red crosses in Figure 9) away from the transmitter. The ABT was used to transmit a 500 kHz 3-count tone burst excitation signal into the composite coupon and the PAT was used to receive the signals at different angles. The received signals were then used to determine the experimental group velocity to validate if pure SH0 mode was indeed generated in the composite coupon. The results of these experiments are described in section 5.

![Figure 9: Pitch-catch experiment to generate pure SH0 mode in quasi-isotropic composite](image)
4.3 ABT-PAT experimental setup for impact damage detection using pure SH0 mode

For impact damage detection, a pitch-catch experiment using the ABT-PAT pair was conducted on the composite coupon for the pristine scenario as well as the impact damage scenario, as shown in Figure 10. The distance between the ABT and PAT was kept as 40 mm. A 500 kHz 3-count tone burst excitation signal was transmitted using the ABT at an angle corresponding to generating the pure SH0 mode in the composite coupon and the PAT was used to receive the signals interacting with the composite coupon at multiple angles. The received signals are compared to determine if the impact damage could be successfully detected or not. The results of these experiments are discussed in section 5.

Figure 10: Pitch-catch experiment for impact damage detection

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1 Impact damage detection in 3-mm composite coupon

To effectively transmit and receive the pure SH0 mode at 500 kHz, we first need to use the semi-analytical finite element (SAFE) method to determine the theoretical tuning angles for the ABT and the PAT for the 3-mm quasi-isotropic CFRP composite coupon. Figure 11 (a) displays the theoretical tuning angle vs. frequency plot for the ABT in which we can clearly see that at a frequency of 500 kHz, the variable angle wedge needs to be set at an angle of approximately 48 degrees to generate the pure SH0 mode in the 3-mm quasi-isotropic coupon using the ABT. From Figure 11 (b), we can observe the incident angle vs. frequency plot for the PAT. We can clearly see that at a frequency of 500 kHz, the PAT can capture the pure SH0 mode at an angle of 39.43 degrees. This information can be used for experimental validation to see if indeed SH0 mode is being transmitted and received.

Figure 11: Theoretical tuning angles for (a) transmitting ABT (b) receiving PAT
Now, keeping the angle of the variable angle wedge at approximately 48 degrees, we can generate the pure SH0 mode in the pristine 3-mm composite coupon. Using the PAT, we can receive the signal at various angles ranging from 0 degrees to 70 degrees as can be observed in Figure 12 (a). From this figure, we can see that the maximum amplitude of the signal is at a receiving angle of 39.75 degrees which matches very well with the theoretical value of the receiving angle of the PAT which was 39.43 degrees as displayed in Figure 11 (b). This clearly demonstrates that the pure SH0 mode was generated by the ABT and received by the PAT for the 3-mm quasi-isotropic CFRP composite coupon. The waveform of the receiving signal at 39.75 degrees is displayed in Figure 12 (b) which clearly looks like a pure SH0 mode.

Figure 12: (a) Receiving angle vs amplitude for PAT; (b) Waveform at 39.75 degrees

Furthermore, pitch-catch experiments were conducted using the experimental setup displayed in Figure 9 to generate the pure SH0 mode and the signals at different distances were measured using the PAT as displayed in Figure 13 (a). Using the signal envelope and the time of flight information, we can plot the time of flight vs. distance plot as displayed in Figure 13 (b). Taking the slope of the time of flight vs. distance plot, we can calculate the experimental group velocity as 3.51 mm/µs which matches very well with the theoretical group velocity (3.39 mm/µs) of the SH0 mode. In this way we can confirm that we can generate and receive the pure SH0 mode using the ABT-PAT pair in the 3-mm quasi-isotropic CFRP composite coupon.

Figure 13: Group velocity calculation - (a) Measured signals at different distances; (b) Time of flight vs. distance plot
Once we confirmed that the ABT-PAT transducer pair can be used to generate and receive pure SH0 mode, we conducted the modified ASTM D7136 drop weight impact testing on the 3-mm quasi-isotropic coupon having in-plane dimensions of 12" x 6" as described by the experimental setup shown in Figure 7. A mass, height, and energy combination estimated before from engineering judgment, was used to conduct the drop weight impact testing experiment to produce approximately 1" impact damage in the 3-mm composite coupon. The impactor of mass 3.06 kg was dropped from a height of 55.61 cm above the composite coupon with an energy of 16.69 J to produce approximately 1" impact damage size in the composite coupon.

The RollerForm inspection method as shown in Figure 8 (a) was used to obtain C-scan images from the top surface scan and the bottom surface scan as can be observed in Figure 14. From both the C-scan images it can be clearly seen that the impact damage looks like a rotating-fan like damage and has different damage patterns at different depths across the composite coupon. We can also estimate the impact damage diameter which is approximately 1”.

Prior to conducting the impact damage experiment, the pitch-catch experiment described in Figure 10 using the pure SH0 mode was conducted on a pristine area and the signals received by the PAT were recorded. After conducting the impact testing experiment that produces an impact damage size of approximately 1”, the same pitch-catch experiment was again conducted – now on the impacted area, for the detection of the impact damage. Figure 15 (a) displays the pure SH0 time-domain signals received by the PAT for the pristine scenario and the impact damage scenario and Figure 15 (b) displays the frequency spectrum of the waveforms. Upon comparing the measured signals by the PAT and their FFT results, for the pristine scenario and the impact damage scenario, we can clearly see an amplitude drop and a slight frequency shift in the signal due to the presence of an impact damage.
Next, if we plot the receiving angle of the PAT vs the amplitude for the pristine scenario and the impact damage scenario as displayed in Figure 16, we can clearly see from the comparison of the signals that there is an amplitude drop in the signal due to the presence of the 1" impact damage, however, the receiving angle of the maximum amplitude almost remains the same.

![Figure 16: Comparison of pristine vs. impact damage - receiving angle vs. amplitude for PAT](image)

5.2 Impact damage detection in 4-mm composite coupon

To effectively transmit and receive the pure SH0 mode at 500 kHz, we first need to use the semi-analytical finite element (SAFE) method to determine the theoretical tuning angles for the ABT and the PAT for the 4-mm quasi-isotropic CFRP composite coupon. Figure 17 (a) displays the theoretical tuning angle vs. frequency plot for the ABT in which we can clearly see that at a frequency of 500 kHz, the variable angle wedge needs to be set at an angle of approximately 48 degrees to generate the pure SH0 mode in the 4-mm quasi-isotropic coupon using the ABT. From Figure 17 (b), we can observe the incident angle vs. frequency plot for the PAT. We can clearly see that at a frequency of 500 kHz, the PAT can capture the pure SH0 mode at an angle of 39.43 degrees. This information can be used to for experimental validation to see if indeed SH0 mode is being transmitted and received.

![Figure 17: Theoretical tuning angles for (a) transmitting ABT (b) receiving PAT](image)
Now, keeping the angle of the variable angle wedge at approximately 48 degrees, we can generate the pure SH0 mode in the pristine 4-mm composite coupon. Using the PAT we can receive the signal at various angles ranging from 0 degrees to 70 degrees as can be observed in Figure 18 (a). From this figure, we can see that the maximum amplitude of the signal is at a receiving angle of 39.25 degrees which matches very well with the theoretical value of the receiving angle of the PAT which was 39.43 degrees as displayed in Figure 17 (b). This clearly demonstrates that the pure SH0 mode was generated by the ABT and received by the PAT for the 4-mm quasi-isotropic CFRP composite coupon. The waveform of the receiving signal at 39.25 degrees is displayed in Figure 18 (b) which clearly looks like a pure SH0 mode.

![Figure 18: (a) Receiving angle vs amplitude for PAT; (b) Waveform at 39.25 degrees](image)

Furthermore, pitch-catch experiments were conducted using the experimental setup displayed in Figure 9 to generate the pure SH0 mode and the signals at different distances were measured using the PAT as displayed in Figure 19 (a). Using the signal envelope and the time of flight information, we can plot the time of flight vs. distance plot as displayed in Figure 19 (b). Taking the slope of the time of flight vs. distance plot, we can calculate the experimental group velocity as 3.81 mm/μs which matches very well with the theoretical group velocity (3.52 mm/μs) of the SH0 mode. In this way we can confirm that we can generate and receive the pure SH0 mode using the ABT-PAT pair in the 4-mm quasi-isotropic CFRP composite coupon.

![Figure 19: Group velocity calculation - (a) Measured signals at different distances; (b) Time of flight vs. distance plot](image)
Once we confirmed that the ABT-PAT transducer pair can be used to generate and receive pure SH0 mode, we conducted the modified ASTM D7136 drop weight impact testing on the 4-mm quasi-isotropic coupon having in-plane dimensions of 12” x 6” as described by the experimental setup shown in Figure 7. A mass, height, and energy combination estimated before from engineering judgment similar to the case of the 3-mm coupon, was used to conduct the drop weight impact testing experiment to produce approximately 1” impact damage in the 4-mm composite coupon.

The immersion tank inspection method as shown in Figure 8 (b) was used to obtain the B-scan and C-scan images from the top surface scan as can be observed in Figure 20. From the B-scan image, the distribution of the impact damage across the thickness of the 4-mm composite coupon can be observed. It can also be observed that the very center of the impact location is undamaged as a clear back wall reflection from the center of the impact location is visible in the B-scan image. From the C-scan image it can be clearly estimated that the impact damage diameter is approximately 1” with the maximum damage occurring in the -45 degree direction.

Prior to conducting the impact damage experiment, the pitch-catch experiment described in Figure 10 using the pure SH0 mode was conducted on a pristine area and the signals received by the PAT were recorded. After conducting the impact testing experiment that produces an impact damage size of approximately 1”, the same pitch-catch experiment was again conducted – now on the impacted area, for the detection of the impact damage. Figure 21 (a) displays the pure SH0 time-domain signals received by the PAT for the pristine scenario and the impact damage scenario and Figure 21 (b) displays the frequency spectrum of the waveforms. Upon comparing the measured signals by the PAT and their FFT results, for the pristine scenario and the impact damage scenario, we can clearly see an amplitude drop and slight frequency shift in the signal due to the presence of the 1” impact damage.
Next, if we plot the receiving angle of the PAT vs the amplitude for the pristine scenario and the impact damage scenario as displayed in Figure 22, we can clearly see from the comparison of the signals that there is an amplitude drop in the signal due to the presence of the 1" impact damage. We can also see that due to the presence of the 1" impact damage a new peak at 19.5 degrees has also appeared. This new peak has appeared due to mode conversion.

Now, if we take a closer look at the plot of receiving angle vs. amplitude for the impact damage scenario as displayed in Figure 23(a), we can see that there is a new peak at 19.5 degrees which is close to the tuning angle of the A1 mode. The theoretical tuning angle of the A1 mode can be observed in Figure 17(b) as 21.5 degrees. If we look at the time-domain waveform at the 19.5-degree peak, it will look like the signal displayed in Figure 23(b) which represents a dispersive, mode converted A1 mode. Figure 24(a) displays the time-domain waveform at 19.5 degrees and Figure 24(b) displays the FFT of the time-domain waveform.
Figure 23: (a) Receiving angle vs amplitude for PAT; (b) Waveform at 19.5 degrees

Figure 24: (a) Waveform at 19.5 degrees; (b) FFT of waveform
6. SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 Summary
In this paper, the application of the pure SH0 mode was used for impact damage detection in quasi-isotropic composite coupons of two different thicknesses, 3-mm and 4-mm. This was done by modifying the fixture and clamping assembly of the existing ASTM D7136 standard test method for drop weight impact testing to accommodate a larger size coupon of size 12” x 6” which could be impacted and used for impact damage detection experiments using an ABT-PAT transducer pair.

First, the theoretical tuning angles for the ABT and PAT to generate the pure SH0 mode in the 3-mm and 4-mm coupons were determined using the SAFE method. Subsequently, experimental validations were conducted to determine if the SH0 mode was indeed generated using ABT inside the composite coupons and that it was received effectively by the PAT by comparing theoretical and experimental group velocities.

Pitch-catch experiments were conducted on the pristine and impacted 3-mm and 4-mm coupons and the signals received by the PAT were compared. From the comparison of the signals for the 3-mm coupon, it was found that the 1” impact damage causes a drop in the signal amplitude. From the comparison of the 4-mm coupon, it was found that apart from amplitude drop there is also mode conversion due to the presence of impact damage.

6.2 Conclusions
The method demonstrated in this paper was successfully used in exciting the pure SH0 mode in the quasi-isotropic CFRP composites using ABT. The SH0 mode signal after interacting with the quasi-isotropic CFRP composite coupon was received successfully by the PAT.

From the experimental results, it was observed that impact damage can be successfully detected using the pure SH0 mode in quasi-isotropic composites. It was also observed that in the 3-mm coupon there was amplitude drop due to the presence of impact damage and in the 4-mm coupon there was mode conversion in addition to amplitude drop due to the presence of impact damage.

The methodology proposed in this paper i.e. measuring the change in the amplitude and frequency spectrum is reliable, robust, and suitable for the quick and large-area inspection. In this method, a baseline measurement is not necessary, which is important in practical applications.

An invention disclosure [43] covering our novel findings has been prepared and is in the process of becoming a provisional patent.

6.3 Future work
Further, controlled impact tests will be conducted on quasi-isotropic CFRP composite coupons of different thicknesses (less than 3-mm and more than 4-mm) to obtain multiple impact damage sizes for a comparative study of signals for different damage sizes. Also, an imaging method will be developed by which impact damage can be visualized and its shape and size can be accurately measured using the proposed method.

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