Measurement of Elastic Constant Matrix of Carbon Fiber Composites with An Ultrasonic 2D-Array Transducer

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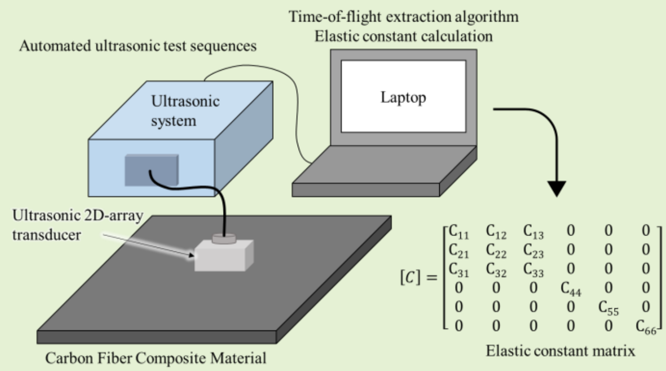
***Abstract* — The use of carbon fiber reinforced polymer (CFRP) composites is gaining popularity in various industries. Due to its anisotropic nature, the characterization of the mechanical properties of CFRP is challenging. The current practices for determination of the elastic properties of CFRP materials are through destructive testing methods, which is not feasible in many *in-situ* scenarios. This paper presents an *in-situ* and non-destructive method to characterize elastic properties of CFRP plates by using an ultrasonic 2D-array transducer. The ultrasonic 2D-array transducer was made of 64 piezoelectric elements and the measurement is automated by an advanced ultrasonic system. An automated time-of-flight extraction algorithm was used based on peak detection of ultrasonic signals. The elastic constants of the CFRP plates were calculated based on the Christoffel equation. This method was validated by ultrasonic through-transmission method by using two discrete ultrasonic transducers. Complete elastic constant matrix measurements for unidirectional and quasi-isotropic CFRP plates were demonstrated using the proposed method. This method has higher positional accuracy, faster testing speed, and better consistency compared to through-transmission method. This work can also be applied for in-situ structural health monitoring of elastic properties changes of materials and structures.**



***Index Terms*— Anisotropic, Composite materials, Elasticity, Piezoelectric transducers, Ultrasonic transducer 2D-arrays**

I. Introduction

COMPOSITE materials are becoming commonly and widely used in various industrial applications, such as in the fields of aerospace, automotive, and construction. This is mainly due to their lightweight and excellent mechanical properties, which allow them to replace conventional metal alloys in numerous applications [1]. Unlike homogenous materials such as metal alloys, composite materials are highly anisotropic in their elastic properties. This is because composite materials have various configurations on lay-ups of layers, depending on applications. The determination of the mechanical properties, especially elastic properties, for composite materials is crucial for assuring its performance. Due to their anisotropic nature, it is challenging to characterize elastic properties for composite materials.

Current active standards, such as American Society of Testing Materials (ASTM) standards [2, 3] for determination of elastic properties for composite materials were based on destructive testing methods. These testing standards typically require multiple samples to be prepared to the specified dimensions and shapes before testing. In addition, each of these tests is aimed to obtain a single elastic parameter. For example, a tensile test is used to obtain the Young's modulus in the tensile direction and a shear test is used to obtain shear elastic property. As a result, these tests are laborious, time consuming and costly to determine a complete set of elastic constants for a composite material. Therefore, it is much favourable to obtain the elastic properties of the composite parts, in a non-destructive and *in-situ* manner.

Velocity of sound in a material is associated with elastic modulus, Poisson's ratio, and density of the material. In principle, the elastic properties of a material can be obtained by measuring wave velocities propagating in the material. Elastic properties for an isotropic material can be determined

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easily by measuring longitudinal and shear wave velocities in thickness direction of the material, using off-the-shelf ultrasonic contact transducers [4]. This is because that the elastic properties of an isotropic material are the same in all directions. However, for a composite material, it is difficult to use such simple method to obtain the elastic properties due to its anisotropic nature, where the elastic constants vary along different directions. Zimmer and Cost [5] determined elastic constants of a unidirectional fiber composite using ultrasonic through-transmission technique. This method required to measure velocities of longitudinal and shear waves in specified directions to determine the elastic constants in each direction.

The feasibility of applying ultrasonic technique for determination of elastic modulus for a composite material was first demonstrated by Markham [6] by using immersion techniques. The test specimen was mounted on a turntable with two ultrasonic transducers installed on both sides. By changing the incident angle using the turntable, quasi-longitudinal wave (QL) and quasi-transverse wave (QT) will be generated and propagate in the test specimen. Elastic constants were derived from ultrasonic wave velocities travelling in the CFRP composite. Improvements on immersion technique to determine elastic modulus for a composite material were reported over the years [7]. These methods were based on multiple immersion tests with complex experimental configurations as it required experimental data at different angles to determine the elastic moduli. In addition, these methods could not obtain a complete set of elastic constants experimentally. In most cases, the composite material must be sized down and an immersion tank is required, which make it not possible for *in-situ* measuring applications.

A non-destructive and *in-situ* method of measuring elastic properties of an orthotropic material (cross-laminated timber) was demonstrated by Santoni *et al.* [8]. Short excitation pulses were excited to propagate acoustic wave into the plate and the transverse acceleration was measured by five accelerometers in a group for different angles. An acousto-ultrasonic technique for determination of elastic modulus for composite materials was investigated by Minachi *et al.* [9]. Two transducers were placed on the same side of the sample and time-of-flight (TOF) of the obliquely reflected acousto-ultrasonic signals were obtained to calculate the elastic constants. The test was conducted using combination of shear and longitudinal wave transducers placed in different separation distance between the transmitter and receiver on the same surface of the test specimen. Yang *et al.* [10] arranged a pair of angle beam ultrasonic transducer in pitch-catch configuration and measurements were conducted at one side of the substrate. It was demonstrated that this method can effectively detect and image ply orientation of a unidirectional carbon fiber reinforced polymer (CFRP) laminates. From the literatures, there is limited investigation on *in-situ* determination of elastic properties for anisotropic CFRP materials by only accessing the one surface of a composite plate.

In this work, an ultrasonic 2D-array transducer made of 64 piezoelectric elements is employed to measure the elastic properties of CFRP materials by only assessing one side of the material. Unidirectional and quasi-isotropic CFRP plates were tested. The calculation is based on the Christoffel equation and the relationship between the group velocity and the phase velocity. Algorithms for elastic constant calculation and TOF extraction are developed for *in-situ* determination of elastic constants of the anisotropic CFRP materials. This method is validated by using two discrete ultrasonic transducers arranged in through-transmission mode. The method provides a solution for high-efficient measurement of full elastic constants of anisotropic composite materials.

II. ELASTIC CONSTANT ESTIMATION

The elastic constants of a material can be calculated from group velocity of ultrasonic signals, which is obtainable from ultrasonic testing using the ultrasonic 2D-array transducers. The methodology on obtaining elastic constants from ultrasonic group velocity is described in this section.

In the subsequent analysis, *i*, *j*, *l*, and *m* are the tensor indexes. The bulk wave propagation in anisotropic media can be described by the Christoffel equation [11]:

$$\left|\Gamma_{im} - \rho V_p^2 \delta_{im}\right| = 0 \tag{1}$$

Where, ρ is density; V_p is phase velocity; δ_{im} is Dirac delta symbol; Γ_{im} is related to elastic constants and is given as:

$$\begin{aligned}\Gamma_{im} &= C_{ijlm}\eta_j\eta_l \\ &= C_{i11m}\eta_1^2 + C_{i22m}\eta_2^2 + C_{i33m}\eta_3^2 \\ &\quad +(C_{i12m} + C_{i21m})\eta_1\eta_2 + (C_{i13m} + C_{i31m})\eta_1\eta_3 \\ &\quad +(C_{i23m} + C_{i32m})\eta_2\eta_3\end{aligned} \tag{2}$$

where, C is elastic constant, and η is the direction cosine. The Eq. (1) can be further re-written as,

$$\begin{vmatrix}\Gamma_{11} - \rho V_p^2 & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{12} & \Gamma_{22} - \rho V_p^2 & \Gamma_{23} \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33} - \rho V_p^2\end{vmatrix} = 0 \tag{3}$$

Considering wave propagation in the 1-3 symmetry plane, the above equation is then written as:

$$\begin{vmatrix}\Gamma_{11} - \rho V_p^2 & 0 & \Gamma_{13} \\ 0 & \Gamma_{22} - \rho V_p^2 & 0 \\ \Gamma_{13} & 0 & \Gamma_{33} - \rho V_p^2\end{vmatrix} = 0 \tag{4}$$

The Eq. (4) can be solved as:

$$\rho V_{p(QL)}^2 = \frac{\Gamma_{11}+\Gamma_{33}}{2} + \frac{\sqrt{(\Gamma_{11}-\Gamma_{33})^2+4\Gamma_{13}^2}}{2}$$

$$\rho V_{p(QT)}^2 = \frac{\Gamma_{11}+\Gamma_{33}}{2} - \frac{\sqrt{(\Gamma_{11}-\Gamma_{33})^2+4\Gamma_{13}^2}}{2} \quad (5)$$

$$\rho V_{p(T)}^2 = \Gamma_{22}$$

where, the first solution represents a quasi-longitudinal wave (QL), the second one represents a quasi-transverse wave (QT) and the last one represents a pure transverse wave (T). Their corresponding polarizations are calculated as:

$$\mathbf{P}_{(QL)} = \left(\frac{1}{\sqrt{1+\xi_{(QL)}^2}}, 0, \frac{\xi_{(QL)}^2}{\sqrt{1+\xi_{(QL)}^2}}\right)$$

$$\mathbf{P}_{(QT)} = \left(\frac{1}{\sqrt{1+\xi_{(QT)}^2}}, 0, \frac{\xi_{(QT)}^2}{\sqrt{1+\xi_{(QT)}^2}}\right) \quad (6)$$

$$\mathbf{P}_{(T)} = (0,1,0)^T$$

Where the parameter ξ is defined as

$$\xi_{(QL),(QT)} = \frac{\rho V_{p(QL),(QT)}^2 - \Gamma_{11}}{\Gamma_{33}} \quad (7)$$

Thereafter, the group velocity is calculated based on the phase velocity and the polarization vector P:

$$V_g = \frac{C_{ijlm}P_l P_j \eta_m}{\rho V_p} \quad (8)$$

where C_{ijlm} is the elastic constant, P_l and P_j are the elements of the polarization vector P, η_m is the direction cosine, and V_p is the phase velocity. The tensor form of C_{ijlm} can be converted to matrix form by following the procedures in [11].

Once the group velocity is obtained, the corresponding theoretical arrival time can be calculated. The unknown elastic constants can be determined by minimizing the sum of squares of the deviations between the theoretical and experimental time-of-flight (TOF):

$$\min_{C_{nm}} \sum_{k=1}^{K} (t_i^T - t_i^E)^2 \quad (9)$$

where K is the number of velocity measurements in different directions, t_i^T and t_i^E are the theoretical and experimental TOFs, respectively. The theoretical arrival time is calculated based on the theoretical group velocity and the wave propagation distance,

$$t_i^T = \frac{d_s}{v_g} \quad (10)$$

where t_i^T, d_s, and v_g denote the time-of-flight, the wave propagation distance, and the group velocity, respectively.

The experimental arrival time is estimated from the experimental data. The flowchart of the calculation process of the elastic constants is given in Fig. 1.

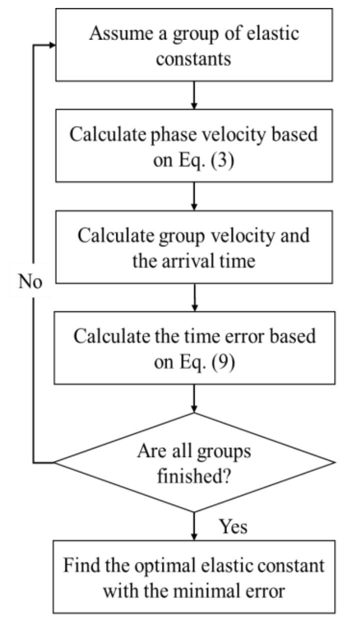

Fig. 1. Flowchart of calculation process of the elastic constants

III. Experimental Methodology

Two types of anisotropic CFRP plates are used in this work, which are a unidirectional CFRP plate (laminated from plies with same fiber orientation of 0°) and a quasi-isotropic CFRP plate (laminated from plies with fiber orientation of 0°, ±45° and 90°). The dimensions of these specimens are 200 mm (length) x 200 mm (width) x 8 mm (thickness), with density of 1560 kg/m^3.

To obtain the elastic properties of these anisotropic materials, the TOFs of the ultrasonic pulse-echo (PE) of the longitudinal wave, and pitch-catch of the quasi-longitudinal wave (QL) and quasi-transverse wave (QT) propagating in the medium which is illustrated in Fig. 2, need to be obtained.

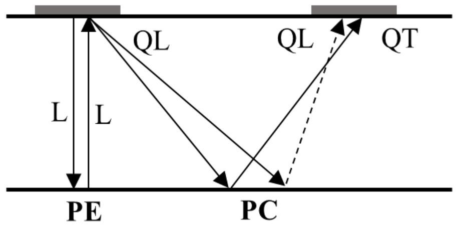

Fig. 2. Different signal reflection paths, where arrow with solid and dashed lines are the longitudinal and transverse waves, respectively, and PE is the pulse-echo of the longitudinal wave, QL, and QT are the pitch-catch (PC) of the quasi-longitudinal, and quasi-transverse waves received by the piezoelectric elements, respectively.

To generate and receive ultrasonic waves on the same surface, a 2D array ultrasonic probe made of 64 piezoelectric ultrasonic elements were customized and implemented. The 2D array ultrasonic transducer was designed by the team and fabricated by Guangzhou Doppler Electronic Technologies. Fig. 3 shows the arrangement and dimension of the piezoelectric ultrasonic elements.

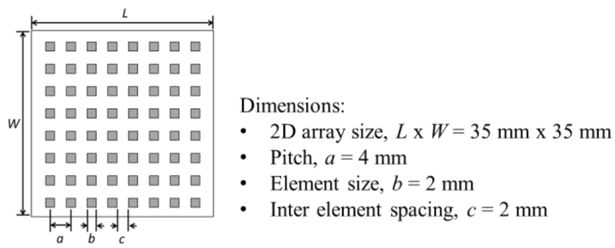

Fig. 3. Elements and dimension of the 2D array ultrasonic probe.

The 2D-array ultrasonic probe is designed with a central frequency of 5 MHz. The piezoelectric elements are arranged in a linear configuration of 8 rows by 8 columns, with the pitch of 4 mm. Each of element can transmit and receive ultrasonic waves. By strategically controlling the generation and reception of ultrasonic waves from different piezoelectric ultrasonic elements, a matrix of ultrasonic signals can be obtained without repositioning the probe. The ultrasonic 2D-array transducer is designed to obtain ultrasonic signals from different scan sequences and directions so that averaged elastic constants can be obtained from single testing. To obtain ultrasonic signals among different transmitter-receiver pairs, different scan sequences and repetitions are devised, as shown in Fig. 4.

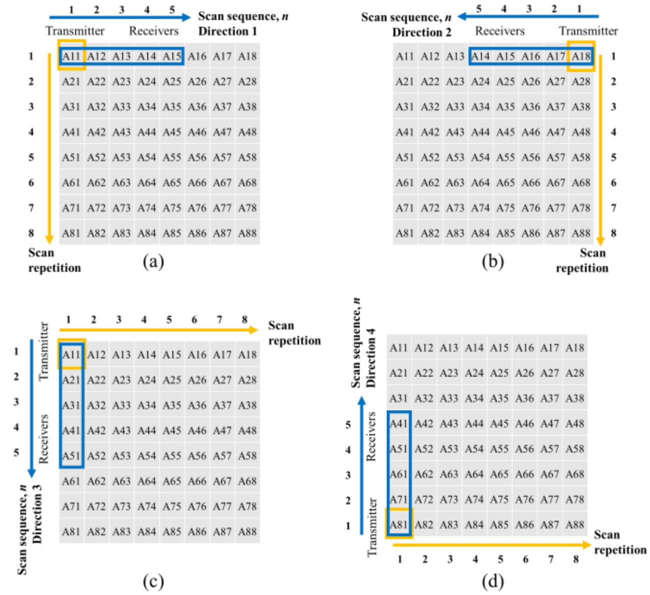

Fig.4. Scan sequence, and repetition for ultrasonic acquisition of: (a) scan direction 1, (b) scan direction 2, (c) scan direction 3, and (d) scan direction 4.

For testing of unidirectional CFRP plate, scan direction 1 and 2 were aligned to the fiber orientation, i.e., 0°. Whilst for testing of quasi-isotropic CFRP plate, the ultrasonic 2D-array transducer was aligned to the sample's length and width directions. A matrix of ultrasonic signals for computation of elastic constants is summarized in Table I, showing different receiver sequences 'n'. When the receiver sequence $n = 1$, the ultrasonic signal collected is via pulse-echo method, while when the receiver sequence $n > 1$, the ultrasonic signal collected is via pitch-catch method.

TABLE I
COMPLETE MATRIX OF ULTRASONIC SIGNALS FOR COMPUTATION OF ELASTIC CONSTANTS.

Direction	Scan repetition	Transmitter	Receiver at scan sequence, *n*				
			1	2	3	4	5
1	1	A11	A11	A12	A13	A14	A15
	2	A21	A21	A22	A23	A24	A35
	…	…	…	…	…	…	…
	8	A81	A81	A82	A83	A84	A85
2	1	A18	A18	A17	A16	A15	A14
	2	A28	A28	A27	A26	A25	A24
	…	…	…	…	…	…	…
	8	A88	A88	A87	A86	A85	A84
3	1	A11	A11	A21	A31	A41	A51
	2	A12	A12	A22	A32	A42	A52
	…	…	…	…	…	…	…
	8	A18	A18	A28	A38	A48	A58
4	1	A81	A81	A71	A61	A51	A41
	2	A82	A82	A72	A62	A52	A42
	…	…	…	…	…	…	…
	8	A88	A88	A78	A68	A58	A48

A 16 × 64 ultrasonic system (Multi2000 Pocket, M2M) was used for ultrasonic wave generation and data acquisition. An image of the test setup is given in Fig. 5. A single excitation pulse with pulse width of 0.1 µs and a peak voltage of 70 V was applied to drive the ultrasonic transducer element. The ultrasonic signal received by the transducer elements were recorded at a sampling frequency of 100 MHz. A time-domain averaging function was also used to average up to 64 sweeps to improve the signal-to-noise ratio (SNR).

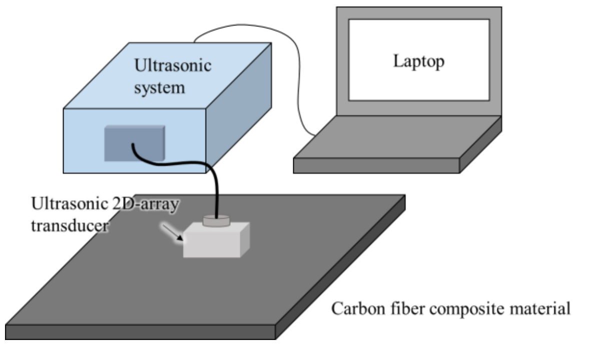

Fig. 5. Experimental setup for ultrasonic testing using ultrasonic 2D-array transducer.

With this experimental setup, the non-destructive evaluation of the composites' elastic constants can be determined. By analyzing PE, QL and QT from different wave propagation paths, a complete elastic constant matrix for the CFRP plate can be derived from a single test.

Once the complete matrix of ultrasonic signals was acquired, each of the ultrasonic signals was post-processed using bandpass filtering (central frequency of 5 MHz, bandwidth 4 MHz) and signal rectification. Next, each of the scan sequences were passed to a TOF extraction algorithm, which was designed to obtain TOF of PE, QL, and QT of the *n-th* sequence, storing in QL(n) and QT(n), respectively. A flowchart of the algorithm used to extract QL(n) and QT(n) from a scan sequence is illustrated in Fig. 6.

To begin the detection process, three input parameters were required and they were represented as start time Ts, T_{QL} and T_{QT}. Ts eliminates false detection of QL by setting the detection algorithm to start after the signal peaks due to electromagnetic interference (EMI). The time constants T_{QL} and T_{QT} are the length of the time window for peak detection for QL and QT waves, respectively.

The variable 'n' represents the sequence number of the ultrasonic signals that the algorithm will run through with $n = 1$ representing the pulse-echo signal, and $n > 1$ representing the signal obtained from the *n-th* receiver's sequence. The algorithm is designed to process these sequences to ensure the TOFs obtained from the peak amplitudes detected in increasing sequences are increasing in time due to theoretical reasoning where the TOFs of the QL and QT waves increase as the separation distance increases.

Once the algorithm obtained QL(1), it searches time window of QL(1) < t < QL(1) + T_{QL} in order to obtain QL(2). The interval T_{QL} limits the detection for QL waves to a fixed time window after the previous sequence QL TOF to avoid the detection of QT waves as in certain sequences. The algorithm then iterates and obtains TOF of QL for all sequences.

Once TOFs of QL for all sequences are obtained, the algorithm initiates detection routine for TOFs of QT for all sequences. Due to close to zero incident angle of the ultrasonic wave, there will be no QT in the first sequence. For the detection of QT(n), the algorithm looks for peak amplitude within interval of QL(n) + T_{QT1} < t < QL(n) + T_{QT2}, whereby the *n-th* QT wave will arrive slower than the *n-th* QL wave due to slower wave velocity.

A summary of time constants for ultrasonic TOF extraction algorithm is tabulated in Table II. With this method, the detection of both QL and QT TOFs can be conducted automatically without manual inspections of the time-domain graphs and therefore speeds up the elastic constant measurement process.

TABLE II
TIME CONSTANTS OF DIFFERENT CFRP PLATES FOR ULTRASONIC TOF EXTRACTION ALGORITHM.

CFRP plate type	Ply orientation	T_s (μs)	T_{QL} (μs)	T_{QT1} (μs)	T_{QT2} (μs)
Unidirectional	0°	1.0	0.4	0.5	1.5
Unidirectional	90°	1.0	0.9	0.4	2.0
Quasi-isotropic	N/A	1.0	0.6	0.6	2.5

IV. RESULTS AND DISCUSSIONS

The ultrasonic testing was conducted on unidirectional and quasi-isotropic CFRP plates using the ultrasonic 2D-array

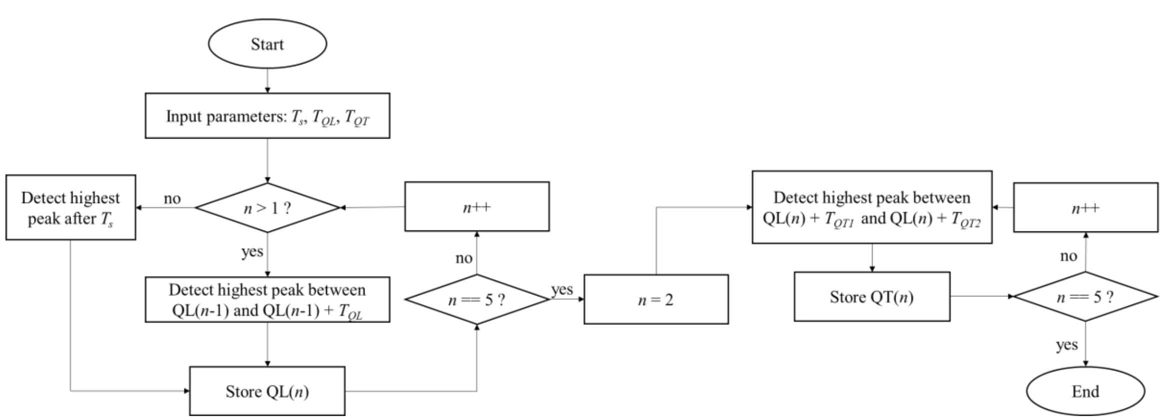

Fig. 6. Flowchart of the TOF extraction algorithm used to extract QL(n) and QT(n) from a scan sequence.

transducer, following the test setup shown in Fig.5. For the ultrasonic testing of unidirectional CFRP plate, scan directions 1 and 2 were aligned 0º to the fiber orientation, while scan direction 3 and 4 were 90º to the fiber orientation (refer to Fig.4 for scan directions). Scan repetitions were performed for each direction. Next, the TOFs for PE, QL and QT were extracted using peak extraction algorithm (refer to Fig.6). Ultrasonic signals measured on unidirectional CFRP plate for scan repetition 1 is given in Fig.7.

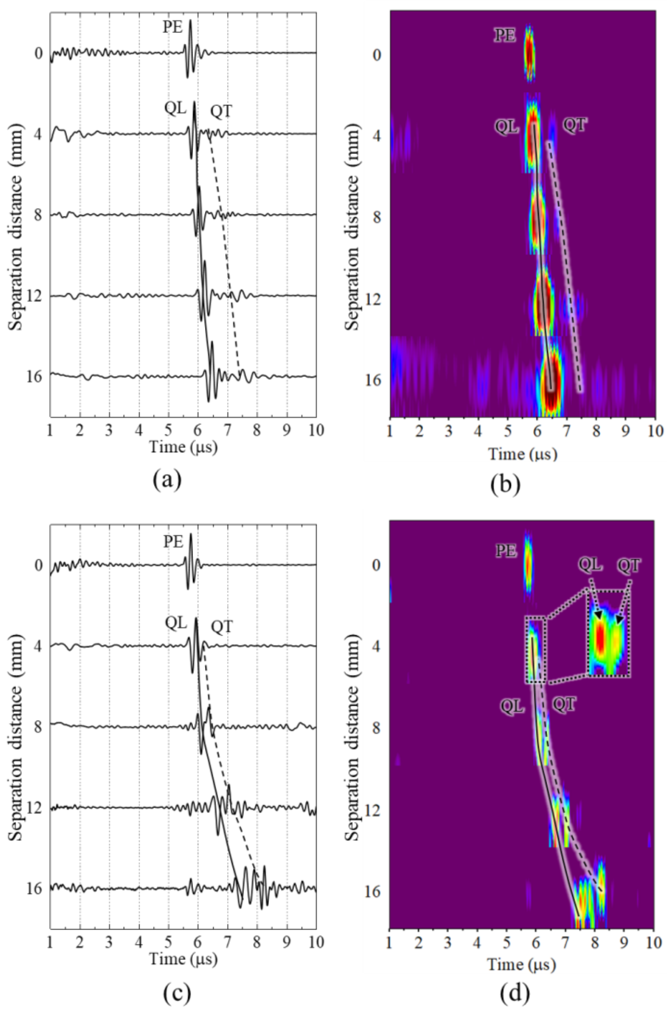

Fig. 7. Ultrasonic signals measured on unidirectional CFRP plate: (a) voltage-time graphs and (b) spectrograms for scan direction 1 and scan sequence 1, with scan direction 0° to fiber orientation (c) voltage-time graphs and (d) spectrograms for scan direction 3 and scan sequence 1 with scan direction 90° to fiber orientation.

In Fig. 7, the TOFs estimated using the TOF extraction algorithm for PE, QL and QT are marked. It is observed from Fig.7 (a) and (c) that the separation of QL and QT wavelets are not clear, especially when the ultrasonic waves are propagating 90º to the fiber orientation. For better visualization of these two wavelets, Short Time Fourier Transform (STFT) [12] was performed on the ultrasonic signals to obtain the respective spectrograms. The spectrograms were calculated using STFT with a rectangular window length of 20 samples and overlapping length of 18 samples. The spectrograms show that the TOFs of PE, QL and QT are successfully extracted.

Subsequently, the TOFs for PE, QL and QT with the same scan sequence were averaged for scan direction 1 and scan direction 2, as well as for all scan repetitions. By doing so, the TOFs for PE, QL and QT of each scan sequence that are measured 0º to the fiber orientation were obtained. TOFs for PE, QL and QT that are measured 90º to the fiber orientation were obtained using similar method for scan direction 3 and 4. These processes are automated. Due to this, the test can be repeated three times effortlessly. The TOF measurements for three sets of experimental data are summarized in Fig. 8. From Fig. 8, the TOFs from the same separation distance do not deviate much from their respective averaged value, with the maximum standard deviation of 0.19 µs.

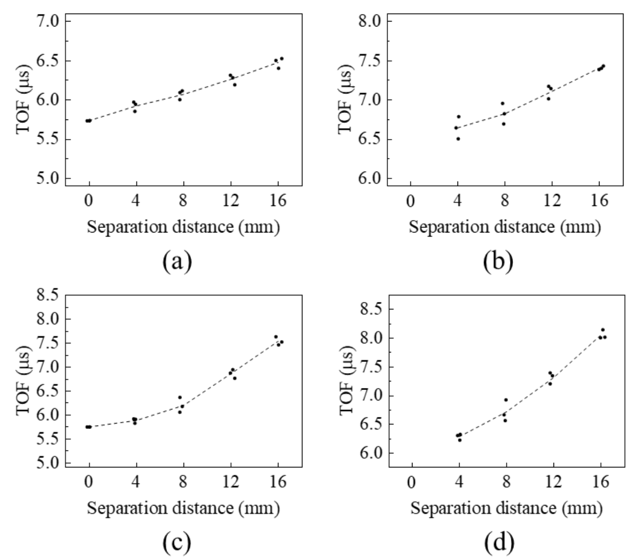

Fig.8. Time-of-flight (TOF) measurements for three sets of experimental data on unidirectional CFRP plate, where the dotted lines are the averaged value, for: (a) QL measured from scan direction 1 and 2 (0º to the fiber orientation); (b) QT measured from scan direction 1 and 2 (0º to the fiber orientation); (c) QL measured from scan direction 3 and 4 (90º to the fiber orientation); (d) QT measured from scan direction 3 and 4 (90º to the fiber orientation).

The ultrasonic testing was also conducted on quasi-isotropic CFRP plate, using the same methodology. The ultrasonic signal measurements for quasi-isotropic CFRP plate, scan sequence one, is shown in Fig.9.

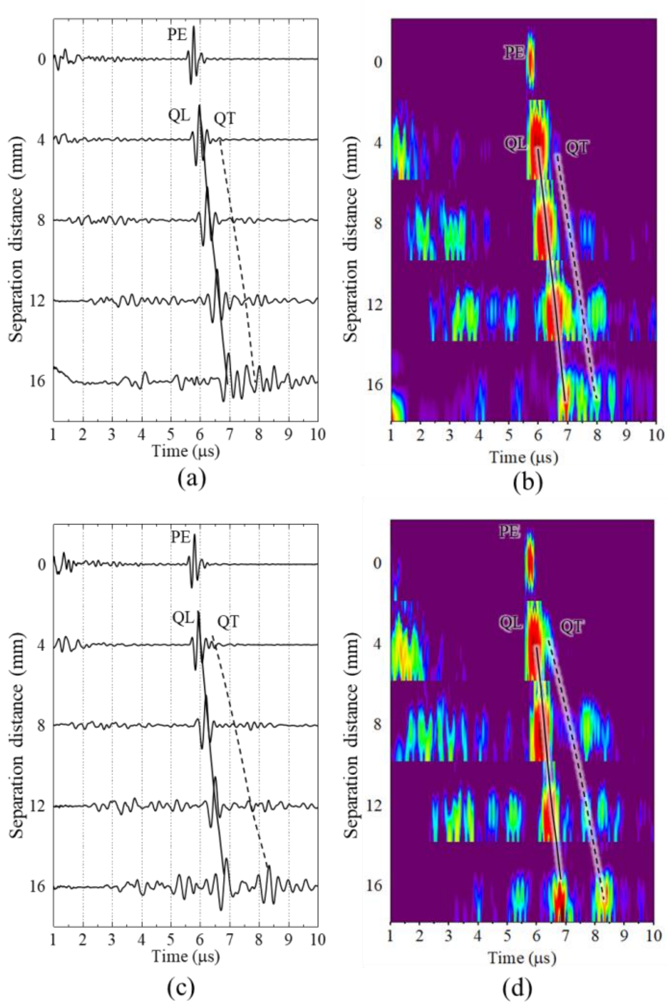

Fig.9. Ultrasonic signals measured on unidirectional CFRP plate: (a) voltage-time graphs and (b) spectrograms for scan direction one and scan sequence one, with scan direction 0° to fiber orientation) (c) voltage-time graphs and (d) spectrograms for scan direction three and scan sequence one with scan direction 90° to fiber orientation.

The TOF measurements for quasi-isotropic CFRP plate were conducted using same methodology as described for unidirectional CFRP plate. The TOF measurements for three sets of experimental data for quasi-isotropic CFRP plate were given in Fig.10, with the highest standard deviation of 0.18 µs.

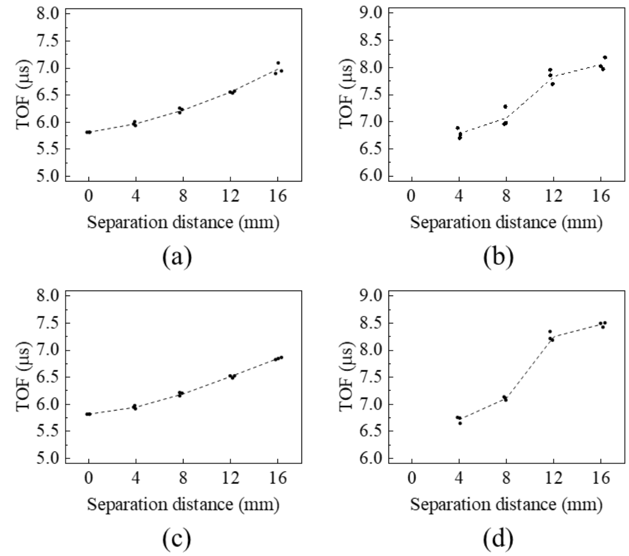

Fig.10. Time-of-flight (TOF) measurements for three sets of experimental data on quasi-isotropic CFRP plate, where the dotted lines are the average measurement value, for (a) QL measured from scan direction 1 and 2; (b) QT measured from scan direction 1 and 2; (c) QL measured from scan direction 3 and 4; (d) QT measured from scan direction 3 and 4.

The TOFs and separation distance relation obtained in the experiments for the two CFRP plates were not linear. This is due to the nonlinearity relation between the group velocity and separation distance attributed to the anisotropic nature of the CFRP structure, which is described as a nonlinear system by the Christoffel equation [13]. Once the TOFs are obtained, the elastic constants for the CFRP plate can be estimated using elastic constant calculation process in Fig.1. The complete elastic constant matrix is obtained using the ultrasonic 2D-array transducer, measuring on one side of the CFRP plate. The elastic constant matrix for unidirectional and quasi-isotropic CFRP plates calculated from experimental TOFs are listed in Table III.

TABLE III
COMPLETE ELASTIC CONSTANT MATRIX FOR UNIDIRECTIONAL AND QUASI-ISOTROPIC CFRP PLATES

CFRP plate type	Elastic constant (GPa)						
	C_{11}	C_{13}	C_{55}	C_{22}	C_{23}	C_{44}	C_{33}
Unidirectional	140.0	4.0	5.5	18.0	3.0	6.0	12.97
Quasi-isotropic	60.0	4.0	4.8	60.0	4.0	4.8	12.40

V. METHOD VALIDATION

To validate the elastic constants obtained using the ultrasonic 2D-array transducer, a pair of discrete longitudinal ultrasonic transducers with central frequency of 5 MHz were used in through-transmission testing, as shown in Fig. 11.

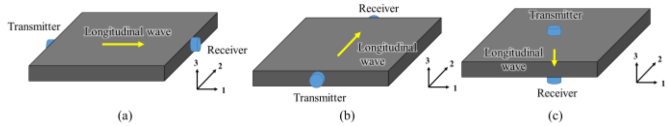

Fig. 11. Experimental setup for ultrasonic through-transmission modes, where the longitudinal wave is propagating in (a) direction 1, (b) direction 2, and (c) direction 3.

Velocities of the longitudinal wave propagating in directions 1-3 can be calculated using Eq. (10). Thereafter, the elastic constants C_{11}, C_{22}, and C_{33} can be determined by using the following equations:

$$C_{11} = \rho V_{L,1}^2 \tag{11}$$

$$C_{22} = \rho V_{L,2}^2 \tag{12}$$

$$C_{33} = \rho V_{L,3}^2 \tag{13}$$

where, $V_{L,1}$, $V_{L,2}$, and $V_{L,3}$ are the velocities of longitudinal wave propagating in directions 1-3, respectively.

Ultrasonic testing using through-transmission was conducted on unidirectional and quasi-isotropic CFRP plates (refer Fig. 11for experimental setup). This is to validate elastic constants obtained using ultrasonic 2D-array transducer. Voltage-time graphs for the ultrasonic signals measured are given in Fig.12. TOF for the earliest wavelet was recorded.

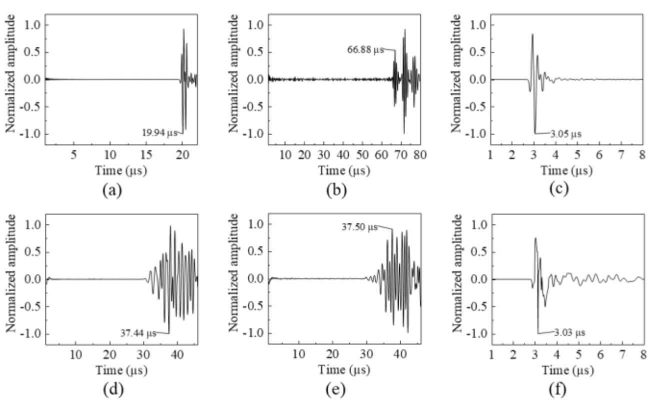

Fig. 12. Voltage-time graphs for longitudinal wave measured using through-transmission method on: unidirectional CFRP plate in (a) direction 1 (0° to fiber orientation), (b) direction 2 (90° to fiber orientation), (c) direction 3; quasi-isotropic CFRP plate in (d) direction 1, (e) direction 2 and (f) direction 3.

The ultrasonic testing for each direction was repeated five times, with the highest TOF standard deviation recorded to be 0.15 µs, which is from TOF measurement in direction 2 of the unidirectional CFRP plate. Once TOFs were identified, C_{11}, C_{22}, and C_{33} can be calculated using (11), (12), and (13), respectively. For unidirectional CFRP plate, C_{11}, C_{22}, and C_{33} are calculated as 162.3 GPa, 14.5 GPa, and 12.2 GPa, respectively. Comparing the proposed ultrasonic 2D-array transducer with through-transmission method using a pair of discrete longitudinal ultrasonic transducers, the highest percentage difference was found for C_{22}, 33.3 %. C_{22} is calculated using QL and QT propagating 90° to the fiber orientation. When ultrasonic wave propagating in the direction 90° to the fiber orientation, scattering of ultrasonic signal is expected. As a result, the measured ultrasonic signals can be hard to interpret. Multiple peaks were noted in Fig. 12(b) using discrete ultrasonic transducers, which could lead to wrong selection of wavelets. Moreover, the TOF deviates from its averaged value the most for this direction, which contributed to the high percentage difference. On the other hand, for the case of ultrasonic 2D-array transducer, the ultrasonic signals were collected in sequence as shown in Fig. 7(c) and (d). As a result, false detection of QL and QT can be mitigated. Meanwhile, the C_{11}, C_{22}, and C_{33} for quasi-isotropic CFRP plate are calculated as 46.3 GPa, 46.3 GPa, and 11.4 GPa, respectively. Comparing to the C_{11}, C_{22}, and C_{33} calculated using data from ultrasonic 2D-array transducer, the percentage difference is less than 9%. The elastic constant estimation via the ultrasonic through-transmission method with two discrete ultrasonic transducers took much longer time as the transducers have to be positioned accurately to avoid inaccurate TOF measurement. In addition, the discrete ultrasonic transducers have to be repositioned for each elastic constant measurement, which is very time-consuming as compared to the ultrasonic 2D-array transducer method.

The proposed ultrasonic 2D-array transducer method can be improved by introducing a greater number of piezoelectric elements into the 2D-array transducer with smaller pitch. By increasing number of piezoelectric elements into the 2D-array, a greater number of TOF measurements can be obtained during ultrasonic testing. This will improve the accuracy on the elastic constant measurement, which is based on the Christoffel equation. Meanwhile, as the pitch of the piezoelectric element decreases, propagation distance of the bulk wave decreases as well. As a result, it will mitigate the attenuation of the ultrasonic signals received by the piezoelectric elements and improve the signal-to-noise ratio. Lastly, machine learning based algorithm for TOF measurement and elastic constant calculation can be investigated for improvements in accuracy, repeatability, and efficiency of the elastic constants' measurements.

VI. Conclusion

A non-destructive and *in-situ* measurement of elastic constants of composite materials using 2D ultrasonic array is demonstrated in this paper. The ultrasonic 2D-array transducer made of 64 piezoelectric elements were used to measure the full elastic constant matrix for anisotropic CFRP plates. The proposed method can successfully obtain the complete sets of elastic constant matrix for both unidirectional and quasi-isotropic CRFP plates by only accessing to one side of the plates. Compared to ultrasonic through-transmission method using a pair of discrete ultrasonic transducers, this method has higher positional accuracy, faster testing speed and better consistency. With the successful demonstration of this method, further improvement and development is needed for practical deployment. The piezoelectric element size and pitch can be further optimized to improve signal-to-noise ratio. In addition, the elastic constants calculation can be improved by considering more ultrasonic signals propagating in different angle orientations.

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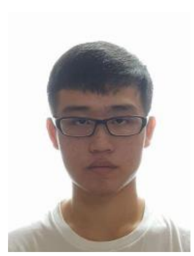

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