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UNDERSTANDING THE PROPAGATION OF GUIDED ULTRASONIC WAVES IN UNDAMAGED COMPOSITE PLATES

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ABSTRACT

This project is motivated by the goal to improve the understanding of guided ultrasonic wave propagation in composite plates. Wave dispersion, attenuation and their angular dependency were investigated in composite plates with different fibre arrangements. The 3D finite element (FE) composite models are constructed in MATLAB, which the parameters can be altered easily, and the simulations were performed using ABAQUS/Explicit. The simulated wave characteristics for different composite models were compared to the experimental results. An approximation propagation of the A_0 wave mode using the FE analysis is established and validated. In this study, the complexity of the wave characteristic being dependent on the fibre arrangement is shown. The properties of the A_0 wave mode in unidirectional composite plate show a significant directional dependency. This could affect the detection sensitivity when the guided waves is monitored not in principle directions. This complication is crucial to be understood in order to improve the interpretation of received signals, particularly for defect characterization.

Keywords: Guided ultrasonic waves, composite plates.

1. Introduction

Guided ultrasonic waves (GUW) have the potential for the efficient monitoring of large structures, as they can propagate over considerable distances at low excitation frequencies [1, 2]. This could significantly reduce the inspection time for large structures and be employed as part of a structural health monitoring (SHM) system [3]. The ability to inspect a structure from a single transducer position results in a simple and fast inspection. The potential of guided wave inspection has been summarized by Rose [4]. The capacity for material characterization has been shown [4, 5]. The characteristics of guided waves have been used to determine the anisotropic elastic constants, damping parameters and dimensional properties. Guided waves have also been proven to be effective in characterizing critical defects in composites like cracks [6, 7], delaminations [8, 9], and the quality of bonding [11].

However, the propagation and scattering characteristic of guided waves in a composite plate is a complex problem [11, 12], which is due to the anisotropic and inhomogeneous properties of the composites. Many other factors could also affect the wave propagation and scattering characteristic. The plate geometry, material properties, fibre arrangement, fibre orientation, transducer frequency, excitation mode and interlaminar conditions are among the factors [14–16]. Moreover, guided waves in plates propagate with different velocities depending on the plate thickness and the excitation frequency [17]. This is known as the wave dispersion. There will be an increase in the pulse width and decrease in amplitude with propagation distance due to the broadening distribution of wave energy. The reduction in amplitude limits the propagation distance, and the increase in signal duration worsens the resolution that can be obtained. Together with typically high attenuation values for composite materials, this makes monitoring and inspection using higher guided wave modes difficult [18].

In addition to those factors, multiple reflections from guided waves propagating in a plate can form an infinite number of wave modes through the thickness. Wilcox et al. [1] identified that the modes can be either symmetric, noted as S_n (S_0, S_1, S_2.....S_n), or antisymmetric, noted as A_n (A_0, A_1, A_2…..A_n), and these modes are generally dispersive. Each wave mode has a different speed, a different wavelength and a different wave pattern (mode shape) across the thickness, which can add to the complexity of the received signals [1, 19]. Typically, it has been found to be advantageous to operate with a single wave mode at low frequency in order to avoid complications in the signal analysis and high attenuation [1, 20].

Although the benefits of using guided waves are huge, these factors describe the difficulties in using guided waves for composite inspection. The capability of the guided waves for the use on composite structures is still under investigation. Hence, knowledge of the properties of guided wave propagation in composites is important for the successful implementation in non-destructive evaluation. Therefore, the objective of this study is to investigate the propagation of guided ultrasonic waves for detecting impact damage in composite plates. This study aims to achieve a better understanding of guided waves propagation in composite plates and their influencing parameters. It is important to examine how the guided waves change in different type of composites.

2. Experimental procedure

Two sets of guided wave experiments were performed. The first set of experiments was performed on undamaged cross-ply carbon fibre plate. The plate was constructed from 24-prepreg plies in alternating [0°/90°] orientations, with symmetry at the mid-plane. Each ply has a nominal thickness of 0.15 mm, giving the total plate thickness of 3.6 mm. The second set of experiments was performed on undamaged unidirectional plate. The plate was constructed from 24-prepreg plies in parallel alignment [0°]. The material and total thickness were the same as the first plate. The aim was to measure wave propagation characteristics for a comparison with the FE analysis.

The setup for the guided wave measurements consists of an existing modular scanning rig controlled via LabView interface from a computer [21]. The excitation signal is generated by a function generator as a voltage signal, amplified by a wide band amplifier and then applied to a piezoelectric transducer. A piezoelectric transducer was used to excite the A_0 wave mode. The excitation frequency was 100 kHz, and the wavelength was approximately 16 mm. The displacement field in the specimen is measured using a heterodyne laser vibrometer, controlled by a scanning rig. Fig. 1 illustrates the position of the laser monitoring on the undamaged specimens. For the purpose of observing the directionality pattern of the wave propagation, the laser head was moved parallel to the plate to perform line scans over a length of 100 mm from the excitation transducer with 1 mm step size, in different directions (from 0° to 90° with 15° step size). Circular scans were performed at 30 mm radius every 5° around the transducer in order to obtain the wave profile around the excitation. The time traces of the received signals were collected and further processed in MATLAB.

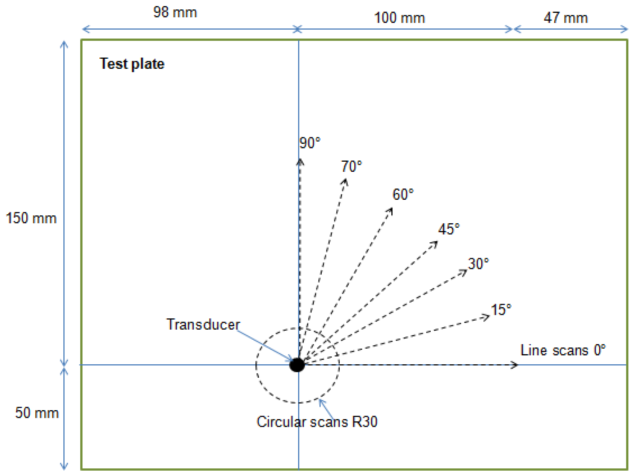

Fig. 1: Position of the laser monitoring; 100 mm line scans in 0° to 90° directions with 15° step size and 30 mm radius of circular scan around the excitation.

Table 1: Measured material properties of the unidirectional plate; 2 MHz characterization frequency [22].

Stiffness constants of Carbon epoxy UD (GPa)	
C_{11}	12.56+ i0.34
C_{12}	6.87 + i0.25
C_{13}	6.47 + i0.65
C_{22}	13.15 + i0.65
C_{23}	5.6 + i0.60
C_{33}	109.9 + i8.23
C_{44}	4.7 + i0.28
C_{55}	4 + i0.25
C_{66}	2.27+ i0.25

3. Finite Element Model

In order to obtain a realistic model of laminate composite plates, a layered model was used. An input file consisting of the layered composite model was programmed in MATLAB and the input file was imported to be used in ABAQUS/Explicit. Twenty four elements through the thickness direction (C3D8R) were used for the generation of the layers. All plates were modelled with a large size of 1 m x 1 m and element size of 1 mm in the x- and y- directions. Each layer of elements (across the plate thickness) were defined with their individual properties. As shown in Table 1, the orthotropic unidirectional properties were assigned to the individual layer. For the cross-ply model, the unidirectional properties were assigned alternately based on the ply orientation of the real specimens. For the detection of the A_0 mode, the monitoring points were placed in the middle of the plate thickness [23]. This is to obtain a single guided wave mode signal and to avoid the detection of the S_0 mode. Similar excitation and monitoring points as described for the experimental procedure were set. A simulation of a large layered composite model with dimension of 1000 mm x 1000 mm x 3.6 mm with elements size of 1 mm x 1mm x 0.15 mm (24 elements through thickness), using 6 parallel CPUs took more than 15 hours. The out-of-plane displacements of the A_0 mode at each monitoring points were collected via history output request and then imported into MATLAB for signal processing and analysis. Four characteristics of the wave propagation such as attenuation, group velocity, phase velocity and slowness are presented to analyze the angular dependency of the A_0 mode propagation.

To validate both simulation and experimental results, DISPERSE, a software developed in Imperial College London [24] was used to theoretically predict the guided wave propagation characteristics. The model was defined using lossy orthotropic stiffness properties, where both real and imaginary stiffness properties were used as the input for the material properties (refer Table 1).

4. Results & Discussion

4.1 Angular dependency of the A_0 mode in cross-ply carbon fibre plate

Fig. 2a presents the experimental amplitude curves of the A_0 mode in the directions of 0° to 90° with 15° interval, together with the FE results (Fig. 2b) for the 3.6 cross-ply composite plate. A similar level of amplitude concentration can be observed from both results, which indicates the accuracy of the numerical FE modeling. The amplitude curve measured in the 0° direction matched the amplitude curve in the 90° direction, with higher amplitudes compared to the other directions. This is due to the symmetrical fibre arrangement in the 0° and 90° directions. Comparable amplitude curves for the measurements in the 15° and 75° directions can also be observed. Meanwhile, the amplitude curves in the 30°, 45° and 60° directions shows a quite similar pattern, with amplitudes being the lowest. This shows that lower wave energy propagates in these directions, and indicates the beam steering towards the fibre directions. However, it is quite surprising to see that the FE results in the 15° and 75° directions predict higher amplitude especially at locations close to the excitation point. This is in contrast to the experimental measurements, where this behaviour cannot be observed clearly due to the closer amplitudes curves from measurements in the 30°, 45° and 60° directions. It is possible that the FE simulation results demonstrate that wave packets tend to steer towards the fibre direction, since the 15° and 75° directions are the closest directions to the principal directions. Another interesting observation is that the amplitudes started to decay similarly as obtained in the 30°, 45°, and 60° directions after propagating 60 mm from the excitation point. Hence, this indicates the higher energy loss within the near field region in the non-principal directions.

In order to investigate the angular dependency of the A_0 mode properties, Fig. 3 presents the angular plots of corrected attenuation coefficients (Fig. 3a), group velocities (Fig. 3b), phase velocities (Fig. 3c) and slowness profiles (Fig. 3d). Since the guided waves radiate symmetrically from a point source, the full angular profiles were plotted for a better presentation, although the measurements and calculations were made in directions between 0° and 90°. Both experimental and FE results were also compared to the DISPERSE predictions. As expected for a cross-ply composite plate, DISPERSE predictions for the attenuation coefficient, group velocity, phase velocity and the slowness profile are relatively uniform in all directions. The attenuation coefficient in all directions is less than 0.1 dB/mm and the average group and phase velocity is about 1400 m/s and 1200 m/s respectively. Since the phase slowness is the inverse of the phase velocity, all directions are expected to have a uniform value as well.

Turning to the experimental results, it can be observed that the measured attenuation coefficients are scattered around the DISPERSE prediction (Fig. 3a). The attenuation coefficient in the 30° direction is significantly higher, which could be due to measurements errors related to the laser monitoring in this direction. The FE results show slightly higher attenuation values in the 30°, 45° and 60° directions. Interestingly, these peaks have been observed in a similar manner by Asamene et al. [25]. They also found that the attenuation coefficients were lower in the 0° and 90° directions and were three times higher in the 30°, 45° and 60° directions.

However, the problem with the attenuation values in the 30°, 45° and 60° directions can be attributed to a numerical error from the location of the monitoring nodes.

As can be seen in Fig. 3b, the agreement between the experiments, FE and DISPERSE results for the group velocity is excellent for all directions. Slightly higher group velocities were obtained experimentally. This could be due to the higher uncertainty in the material properties used for the predictions [22]. Overall the group velocity of the A_0 mode in a cross-ply composite plate shows no angular dependency. For the phase velocity profile (Fig. 3c), comparable results were obtained between the experimental and DISPERSE results, with consistently higher phase velocities from the experiments. All three results matched for the phase velocity in the 0° direction. The FE results in directions between 15° to 75° were obtained from four monitoring nodes placed at the intended monitoring location, and then the phase values of these signals were interpolated using the bilinear interpolation method. This method results in a reasonable consistency (as shown in Fig. 3c) with the largest error can be observed in the 15° and 75° directions.

One of the ways to illustrate changes caused by the influence of anisotropy is by studying the slowness profiles. The slowness profile, as can be seen in Fig. 3d, presents the reciprocal of the phase velocities in different directions. The slowness profile of the A_0 mode in a cross-ply composite plate shows a relatively uniform propagation in all directions and indicates only a small angular dependency on the phase front direction.

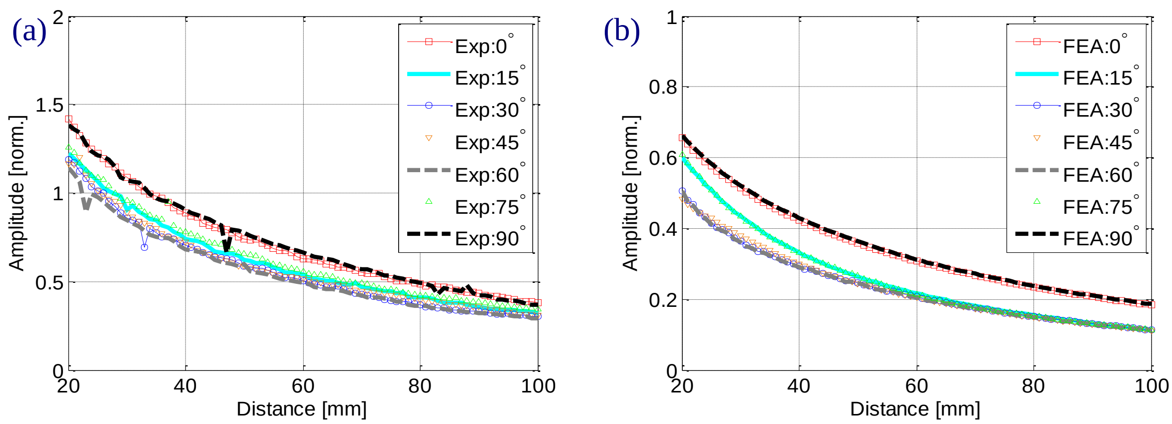

Fig. 2: (a) Experimental measurement and (b) FE simulations of maximum amplitude of signal envelope of propagating A_0 guided wave pulse; 100 kHz; cross-ply plate.

4.1 Angular dependency of the A_0 mode in unidirectional carbon fibre plate

A similar study as in the previous section was conducted for the 3.6 mm UD plate. Fig. 4 presents the measured (Fig. 4a) and simulated (Fig. 4b) amplitudes of the A_0 mode propagating along radial lines. Similar amplitude patterns can be observed from both results, which indicate the accuracy in the FE modeling with added Rayleigh damping. The highest amplitude was in the 0° direction, and then followed by the amplitudes in the 15° direction. Nearly comparable curves were obtained from the amplitudes in the 30°, 45°, 60°, 75°and 90° directions, where the amplitudes were the lowest. Comparing to the FE results in the 15° direction particularly, it is quite interesting that the FE can produce a very distinctive and similar amplitude pattern compared to the experimental curve. This contradicts the experimental and FE results shown for the cross-ply plate (Fig. 3), where this effect cannot be clearly observed. A similar level of amplitude drop (reduction by half) within the 50 mm propagation distance can be observed. After propagating about 80 mm distance, the guided wave in the 15° direction started to behave similarly as in other directions in the 0° direction, which was higher. Thus, it can be seen that the beam steering tends to steer the wave packet towards the fibre direction (0° direction). This suggests that it may be quite difficult for the A_0 mode to be used efficiently for defect characterization in the non-principal directions.

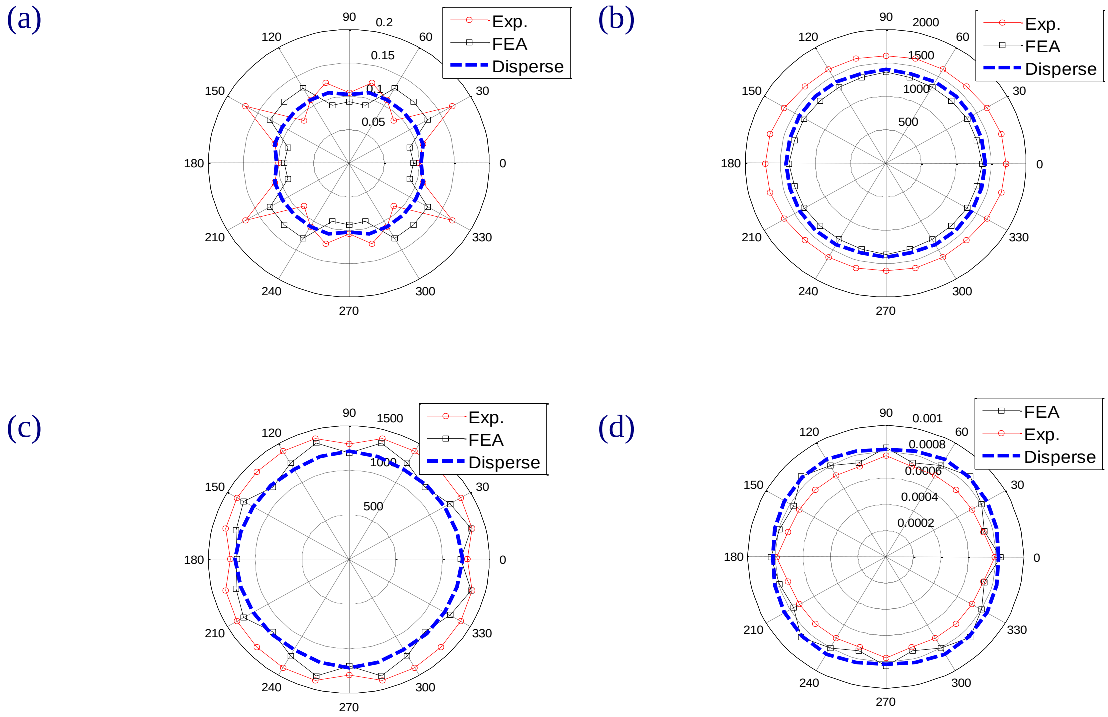

Fig. 3: Experimental, FE and DISPERSE values for: (a) attenuation coefficient, (b) group velocity, (c) phase velocity and (d) phase slowness; cross-ply plate.

The angular wave characteristics were calculated and plotted in a polar coordinate system. The measured angular patterns are displayed with comparison to the DISPERSE and FE simulations. Fig. 5a shows the expected angular-dependent attenuation coefficients predicted by DISPERSE. The experimental and FE results show almost similar attenuation in all directions, while DISPERSE predicts much higher value in the 90° direction. The scattered FE result was due to the numerical error as explained previously in [24]. From the calculation of the group velocity as a function of angular direction (Fig. 5b), good agreement between the trends of the three results can be observed. The experimental measurements show slightly higher group velocities between the 0° and 30° directions. The FE predicted slightly lower group velocities than the DISPERSE result in the directions between 30° and 60°. According to the DISPERSE prediction, the highest group velocity is in the 0° direction (approximately 1500 m/s), and then slowly decreased by 25% when propagating in directions between 45° and 90° (approximately 1200 m/s). In a similar pattern, DISPERSE predicted the angular-dependent phase velocity. The phase velocity is highest in the 0° direction then reduced to more than 30% in the 90° direction. The experimental results are comparable to the DISPERSE prediction, but, the FE results show a slight variation in the phase velocities between directions of 15° to 75°. The FE result was extracted from interpolated signals of four neighbouring nodes in order to reduce the numerical error. Overall the measurement results are consistent with data obtained from DISPERSE.

Fig. 5d presents the slowness profile where the slowness is the inverse of the phase velocity. As for the phase velocity results, overall a good agreement between measurements and FE and DISPERSE predictions can be observed. Due to the higher angular dependency in the UD plate, significant guided wave steering perpendicular to the phase slowness curve, especially in the directions close to the fibre direction, can be predicted. In this context the attenuation guided waves plays an important part, since it determines how far waves can travel and be detected by a sensor. For example in the UD plate, the received signals of the A_0 mode will diminish quickly in the 90° direction due to the highest wave attenuation. With the FE models and the procedure presented in Section 3, the A_0 mode wave properties in any propagation direction can be predicted, enabling the optimization of an efficient sensor network. However this result show that this imposes a challenge for an efficient NDE and SHM system of composites if the guided modes cannot propagate or be detected in certain directions. The obvious implication for structural monitoring is that ignorance of the steering angle and group velocity could lead to significant errors in the calculation of defect location. Therefore, it is crucial to be aware of the changes in the characteristics of the guided waves in other directions although this study is a more complex area of research.

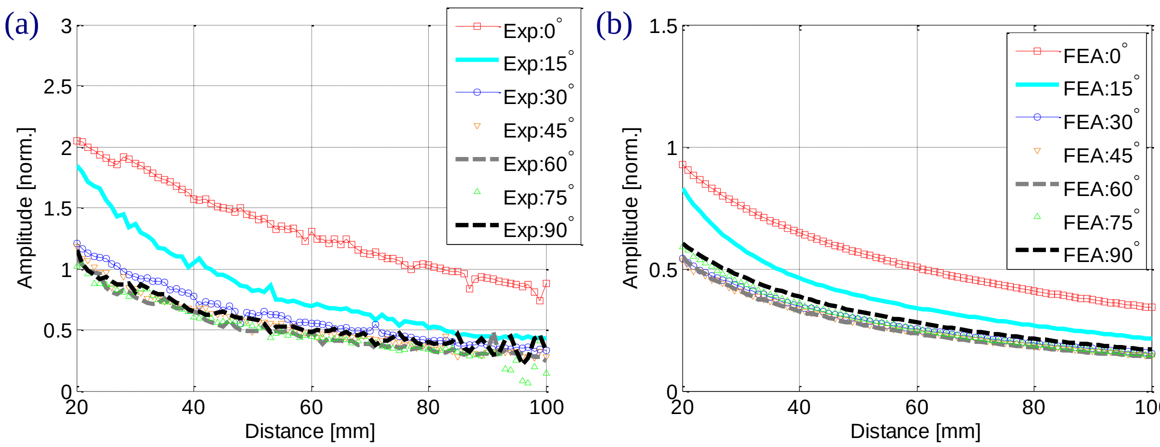

Fig. 4: ((a) Experimental measurement and (b) FE simulations of maximum amplitude of signal envelope of propagating A_0 guided wave pulse; 100 kHz; unidirectional plate.

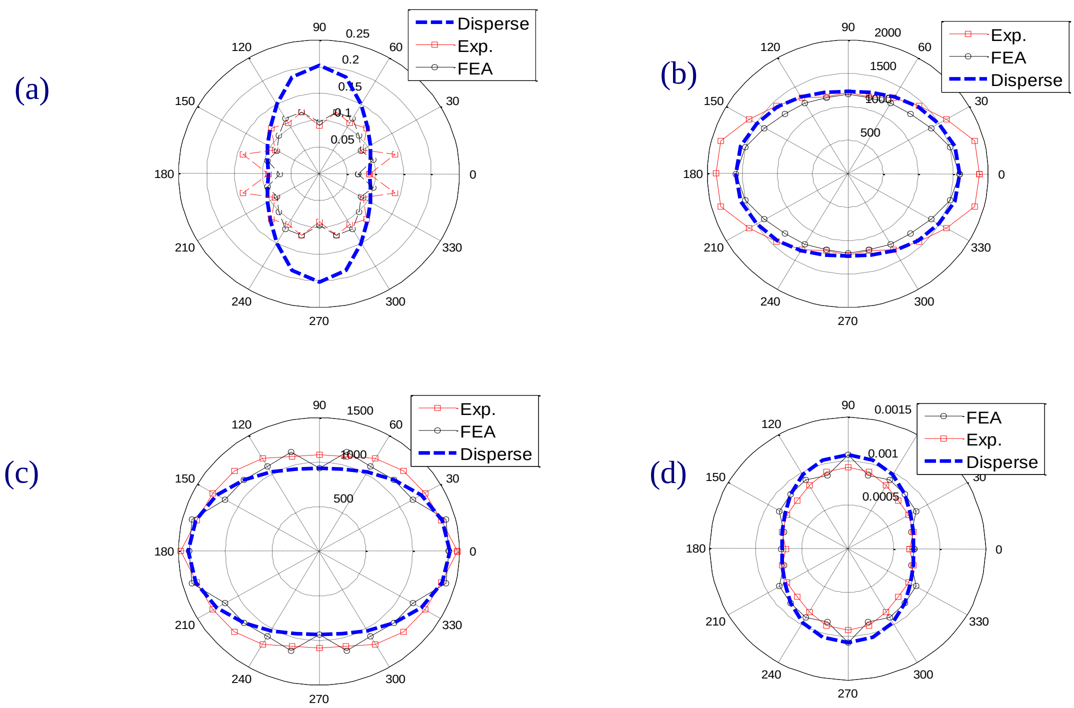

Fig. 5: Experimental, FE and DISPERSE values for: (a) attenuation coefficient, (b) group velocity, (c) phase velocity and (d) phase slowness; unidirectional plate.

4. Conclusions

The results presented in this chapter provide the guided wave characteristics and properties for two types of composite plates. An approximation of the A_0 mode wave propagation simulation using the 3D FE approach was established and compared to the experimental results. Results from both experimental and FE models are reasonably consistent, suggesting that in principle this model could be employed to simulate and characterize the guided wave propagation in composite plates without defects. From the results, the group and phase velocities of the A_0 mode in a cross-ply plate were observed to be almost independent of the angular direction. Since the wave travels at the same velocity in any direction, this makes the development of an algorithm to locate and size the damage simpler. In contrast, the wave properties of the unidirectional plate show the expected angular dependency. There was a reasonable similarity between the experimental and FE results, where the wave behaviour related to the beam steering can be clearly observed for both plates. An implication of this is the possibility of reduced detection sensitivity for damage located not in the main principal (fibre) directions. This information will help to improve future optimization strategies for the SHM of composites. Overall, this study has satisfactorily shown that the FE simulations can effectively model the angular characteristics of the A_0 mode wave propagation in anisotropic composite plates. These complications are crucial to be understood in order to improve the interpretation of received signals, particularly for composite and defect characterization.

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