

Parametric study of guided ultrasonic wave propagation in carbon-fiber composite plates

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Abstract. The aim of this work is to study the guided ultrasonic wave (GUW) behaviour in composite plates using 3D Finite Element Analysis (FEA). Two types of composite models are chosen: plates with and without damage. The damage is modelled as a circular-shaped delamination inside the plate, representing one kind of low-velocity impact damage. Parameters such as excitation frequency, monitoring directivity, plate thickness, delamination size and shape were used to investigate the influence of these parameters on the GUW propagation and scattering behaviour. The models were constructed and coded in Matlab platform, while the simulations were performed in ABAQUS Explicit. From the results, the received signals have shown a strong dependency on the parameters. Significant scattering from the models with delamination were also observed, which indicates the possibility of using GUW for rapid non-destructive monitoring of composite panels and structures.

1. Introduction

The use of composite materials has grown rapidly from the occasional application for a non-structural part to the construction of complete airframes. Previous research has shown that composite materials became favourable in various form because of its toughness, stiffness and high strength to weight ratio [1]. In general, composite laminates consist of layers of polymer matrix reinforced with high strength fibers. The combination of these two materials produces a material with characteristics different from the individual constituents. A composite laminate is typically made up of several plies with different fiber orientation. This laminate is weak when subjected to impact loading. The impact loading on a composite laminate can lead to barely visible impact damage that could potentially result in a catastrophic failure if exposed to repetitive loading [2]. Cracks in the polymer matrix, debonding between fibers and separation of laminae (called delamination) are the common damage modes observed in composite structures. Among those damage modes, attention is focused on the delamination, as it reduces the load-carrying capacity of a structure which might lead to a catastrophic failure.

In order to maintain the quality and reliability of a composite structure, non-destructive testing (NDT) is usually used. Visual inspection, ultrasonic testing, acoustic emission, X-ray radiography, liquid penetrant and eddy-current are amongst the NDE methods employed in aerospace inspection [3]. In the present trend for aircraft maintenance, the maintenance of aircraft must be accomplished within a scheduled time. However, for the large aircraft structures, most methods are very time consuming, costly and they normally interrupt the service of the aircraft. This indicates a need for rapid inspection



and cost-effective methods for monitoring large composite structures. One possible method, the guided ultrasonic waves (GUW), is chosen to be further explored in this study.

Using low excitation frequency, GUW can propagate over long distance with limited energy loss [4]. From a single location, the guided wave can cover large areas, which can help to reduce the inspection time. The reflection of the propagating wave at defects enables rapid detection of defects in large structures [5]. This method has been used successfully for the detection of defects in large metal plates and long pipes, i.e., corrosion and crack detection. However, the behaviour of the guided waves is somewhat more complicated in composite structures due to the physical properties of composites that are generally inhomogeneous and anisotropic in nature [6]. For waves propagating in composite laminates, the wave interaction depends on many factors such as the excitation frequency, geometry of the structure, material properties, direction of propagation, and inter laminar conditions [7], [8]. Knowledge of the group velocity and its direction are needed when considering the propagation path of a wave packet for calculating the arrival time, defect location and area coverage of the inspection.

In general, when a guided wave is incident on a structural discontinuity, it is scattered in all directions. Scattering characteristics such as arrival time, amplitude, frequency content, attenuation, reflected and transmitted waves are normally used to explain the wave propagation in the defective area [9]–[12]. Strong interaction between the incident wave and defect is important for sizing and localizing the defect [13]. However, the interactions are strongly dependent on the mode of the incident wave and the size of the damage [10], [13], [14]. The most important key in using guided waves successfully is to understand the relationship between the characteristic of a defect and the scattered waves.

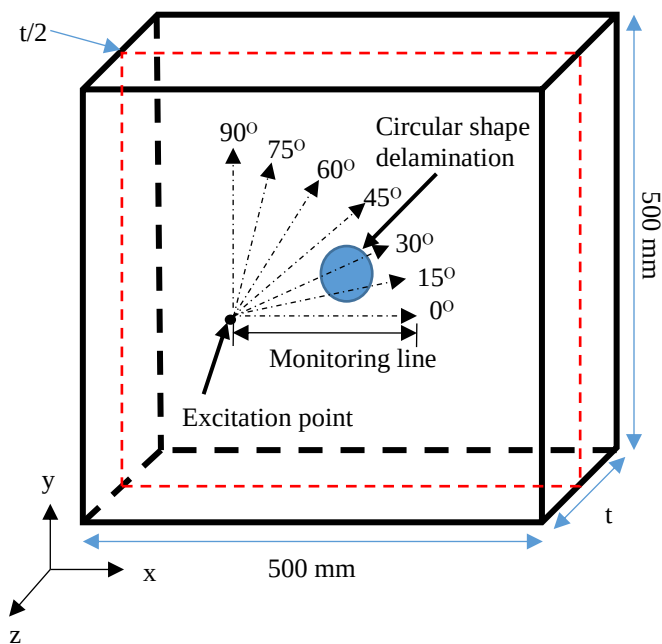
Building from the literature, it can be understood that the capability of the guided waves for the NDE of composite structures is still under investigation. Therefore, the objective of this research is to investigate the use of GUW for detecting typical impact damage, such as delamination that can occur on composite plates. This study aims to achieve a better understanding of the guided wave propagation in composite plates and its interaction with impact damage.

2. 3D Finite Element Modelling

A large cross-ply composite plate was constructed in MATLAB as detailed in [15] which was then simulated in ABAQUS/Explicit software. The plate consists of 8 layers through the thickness with the same $0^\circ/90^\circ$ layup direction. The material properties of each layer were modelled with properties of unidirectional composite plate as shown in table 1. The size of the model was set to 500 mm x 500 mm x thickness (t), where t is varied with 2 mm, 4 mm and 6 mm. Damaged plates were modelled with circular shape delamination at the center of the plates. An out-of-plane excitation was set to generate an A_0 Lamb wave mode propagating along the plate. The excitation frequency was chosen to be 100 kHz, where there was a good trade-off between lower wave attenuation and good transducer sensitivity. The excitation point was located at location 150 mm in x-direction, 250 mm in y-direction and half-thickness direction. The out-of-plane displacement was monitored using a line scan across the plates and a circular scan with 30 mm radius around the center of the plates. Parametric inputs and damage definition were controlled by using MATLAB which then saved as the input file for simulations in ABAQUS/Explicit. Figure 1 shows the illustration of the model with excitation point (EP) and circular crack.

Table 1. Material properties of the unidirectional plate; 2 MHz characterization frequency [16].

Stiffness constants of Carbon epoxy [0/90] (GPa)	
C11	12.15 + i0.34
C12	8.39 + i0.88
C13	7.73 + i0.65
C22	70.87 + i9.19
C23	5.60 + i0.60
C33	64.24 + i10.1
C44	4.70 + i0.28
C55	3.06 + i0.19
C66	2.97+ i0.20

**Figure 1.** Illustration of the carbon-fiber plate model (500 mm x 500 mm x t) with 200 mm monitoring points in different directions (0° to 90° with 15° interval); excitation point (150 mm, 200 mm, t/2); center of the circular-shaped damage located at the plate center.

3. Parametric study on undamaged carbon-fiber plates

3.1 Influence of excitation frequency

This part presents the simulation results for the A_0 mode propagation in undamaged laminate composite plates. Figure 2 shows the comparison between the received signals in order to investigate the influence of different excitation frequencies (50 kHz, 100 kHz and 150 kHz). Repeatable amplitude profiles can be observed, especially from the line scans in the 0° direction, although the amplitude values showed some great discrepancies. A similar observation can also be seen from the circular scan, where the 150 kHz excitation frequencies produced the lowest signal amplitudes while showing a very minimal steering effect. Meanwhile, a higher dispersion can be seen from the 50 kHz result (figure 2b). Since different frequency components in a wave packet travel at different speeds, the shape of the wave packet

is expected to have small distortion while traveling due to the differences in the arrival times of each frequency component. Using the 100 kHz frequency of the excited wave packet, the signal amplitudes are very strong and have less steering effect, which means the wave packet can retain its shape as it travels. This feature is desirable for the NDE of composites, and supports the decision to choose 100 kHz as the nominal excitation frequency for later simulations.

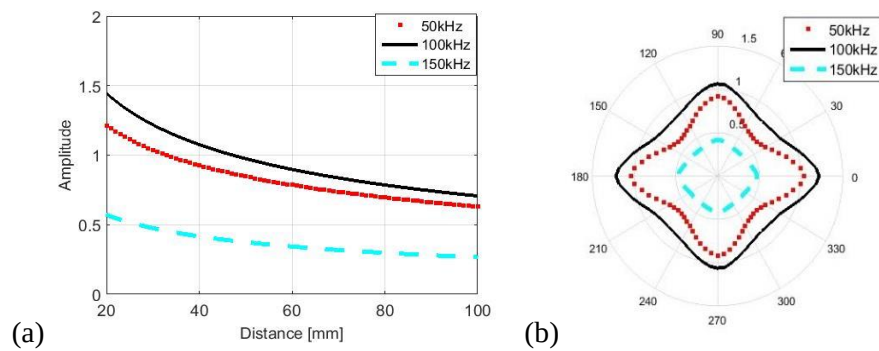


Figure 2. Maximum amplitude of signal envelope in 2 mm cross-ply plate (a) Line scan measured every 1mm step along 0° direction, (b) Polar plot of amplitude at 30 mm radius around the excitation point; different excitation frequencies.

3.2 Influence of plate thickness

Figure 3 shows the amplitude behaviour in composite plates with different thicknesses (2 mm, 4 mm and 6 mm). The GUV behaviours show that the amplitude decreased when the plate thickness was increased. The reason for this behaviour could relate to the increase of energy absorption. Study conducted by [16] showed thicker material leads to increase of energy absorption. This result may be explained by the fact that when energy absorption is high, the damping will increase and the wave intensity becomes low.

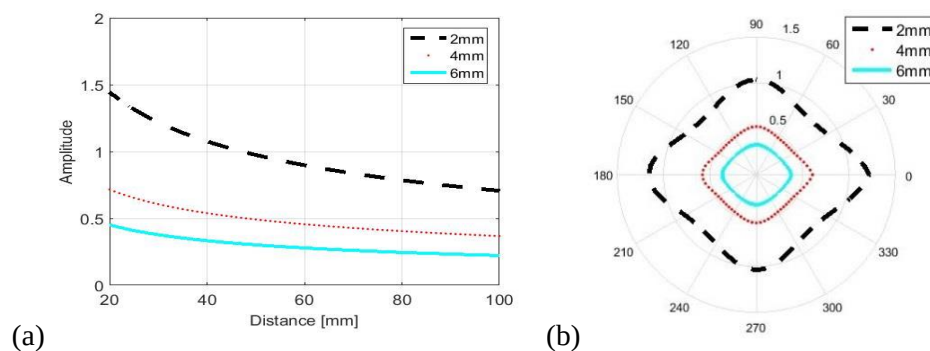


Figure 3. Maximum amplitude of signal envelope in composite plates for (a) Line scan measured every 1 mm step along line of 0° of monitoring point direction; (b) Polar plot of amplitude at 30 mm radius around excitation point for different thicknesses; 100 kHz frequency.

3.3 Influence of angular directivity

Results for wave propagation at different angular directivities (0°, 15°, 30°, 45°, 60°, 75°, and 90°) in composite plate is as shown in figure 4. Amplitude profiles of 0° and 90° directions show higher amplitude than others. Both directions are the same direction with layup orientation in the composite

plate. This situation could be related to the steering effect [6]. Steering effect is a phenomenon caused by the anisotropy of the material resulting in different directions of phase and energy velocity vectors. Nonetheless, 90° direction has slightly less value than 0° direction. This discrepancy may be caused by outer layer composite plate that has material orientation at 0° direction which is related to lower bending stiffness [16]. Angular directions of 30° , 45° and 60° show the lowest amplitude profile. This behaviour signifies that these directions slowing down the wave propagation. The amplitude for 15° and 75° directions are in between higher and lower amplitude because they are the closest direction to 0° and 90° .

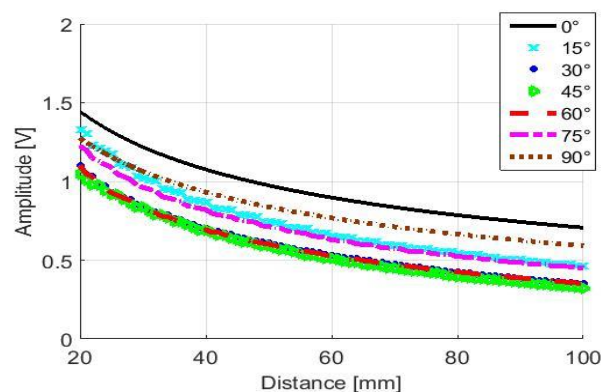


Figure 4. Maximum amplitude of signal envelope in cross-ply composite plates models; line scan measured every 1 mm step along line for different angle of monitoring point directivity; 2 mm thick; 100 kHz frequency.

4. Parametric study on damaged carbon fiber plates

4.1 Effects of angular dependency on wave scattering

Figure 5 shows the simulated signals on 2 mm thick composite plates with 10 mm radius circular-shaped damage, monitored in different directions (from 0° to 90° with 15° interval). The location of excitation point and damage are shown in figure 1. From figure 5, it can be seen that there are disturbances in the amplitude profile monitored in directions of 15° and 30° . A very minimal disturbance can also be observed from the monitoring line in 0° direction. Meanwhile the rest monitoring lines remain unchanged. About a similar reflection has been seen from a previous study [6], but on a composite plate with a rectangular-shaped damage. A possible explanation for this behaviour is the damage detected in between 0° , 15° and 30° directions of monitoring line. Throughout these findings, only monitoring line across the damage could give the accurate location of the damage.

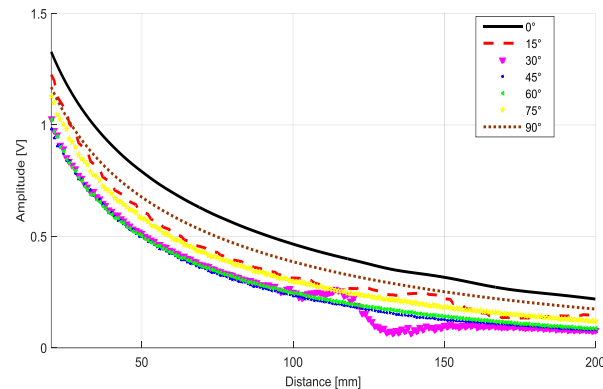


Figure 5. Amplitude profiles in layered composite plate with a circular-shaped delamination; 200 mm line scan measured every 1 mm step along in different direction; circular damaged (radius: 10 mm) at 1 mm depth from the surface; 100 kHz excitation frequency.

4.2 Effects of damage size and depth on wave scattering

Figure 6(a) shows the amplitude profiles of GUV on composite plates with different damage sizes (10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm). The amplitude profiles shows inconsistency for different delamination sizes. Amplitudes over the intact part of the model (before the delamination) were exactly the same as the baseline data. A small fluctuation in the amplitude profile for all case studies, about 7% compared to the baseline data, can be seen within 10 mm to 20 mm distance before the delamination entrance. This is due to the reflected waves were interfering with the incident waves. Significant changes in amplitudes levels can be observed in the defective area, for all case studies. This could be due to the newly generated modes that travel with different speeds, as well as interferences between each group of new modes that are being reflected within the delamination sideways [15].

Behind the delamination, the amplitudes for all case studies started to show different patterns and much bigger discrepancies compared to the baseline data. This finding may support the previous observations on the analysis of the large defect wave fields, where a part of several groups of waves with dissimilar wave speeds are reflected at the delamination exit and transmitted out from the delamination. This event created different amplitude profiles compared to the baseline data even though the waves now travelled in the area behind the delamination. Figure 6(b) shows the scattered field for the different damage sizes effect. Some small variations were observed in the forward (0° direction) scattered amplitude. The results for each different damage sizes show different amplitude propagation. This unexpected behaviour reveals that different damage sizes propagate at different directions for circular scans.

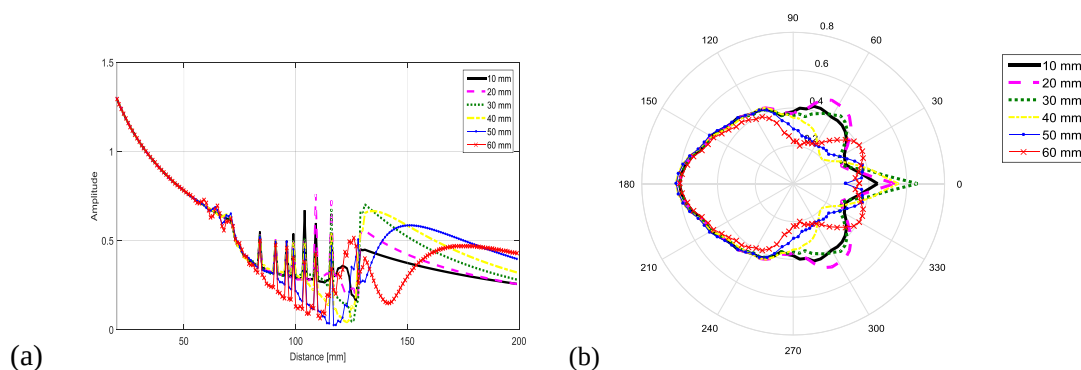


Figure 6. Comparison between different size of damage (diameter: 10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm) at 1 mm depth: (a) Amplitude of signal envelope over defective area of composite plate, (b) Scattered amplitude around various size of damage; 100 kHz excitation frequency; 2 mm thick.

Figure 7 shows the amplitude profiles for effect of different damage depth (0.25 mm, 0.50 mm, 0.75 mm and 1 mm) for each damage diameter size (10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm). The amplitude pattern becomes higher as the depth going towards 1 mm (center of plate) where it was the closest distance with the excitation point. The closer the damage to the excitation point, the stronger the GUV reflection towards the damage.

The scattered waves around delamination were investigated and the results are as shown in figure 8. The left side of the graph shows before GUV entered the damage and the other side was after damage. The 1 and 0.75 mm depth amplitudes were about the same where they were consistently high. This could be due to the nearest damage distance with the excitation point. Meanwhile, 0.5 and 0.25 mm amplitudes did not show a clear pattern. Surprisingly, 0.50 mm damage depth shows the lowest amplitude, not at 0.25 mm depth. This behaviour could be related to wave velocity in different layup. Layup in 0.50 mm depth has fiber arranged in 90° direction. Thus, the velocity reduced as the monitoring line was in 0° direction. It is supported by the data in table 2 which shows the effect of additional 90° layup reduces the velocity and lower the amplitude.

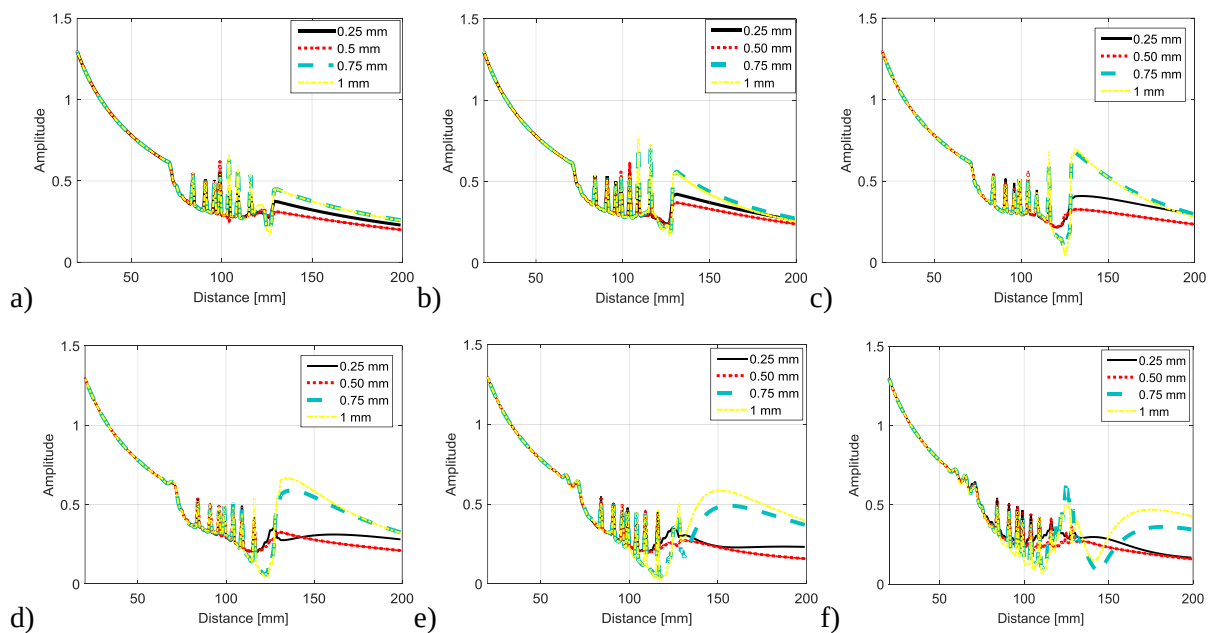


Figure 7. Amplitude of signal envelope across various damage circular diameter: a) 10 mm, b) 20 mm, c) 30 mm, d) 40 mm, e) 50 mm and f) 60 mm; at different depths (0.25 mm, 0.5 mm, 0.75 mm and 1 mm); 2 mm thick; 100 kHz excitation frequency.

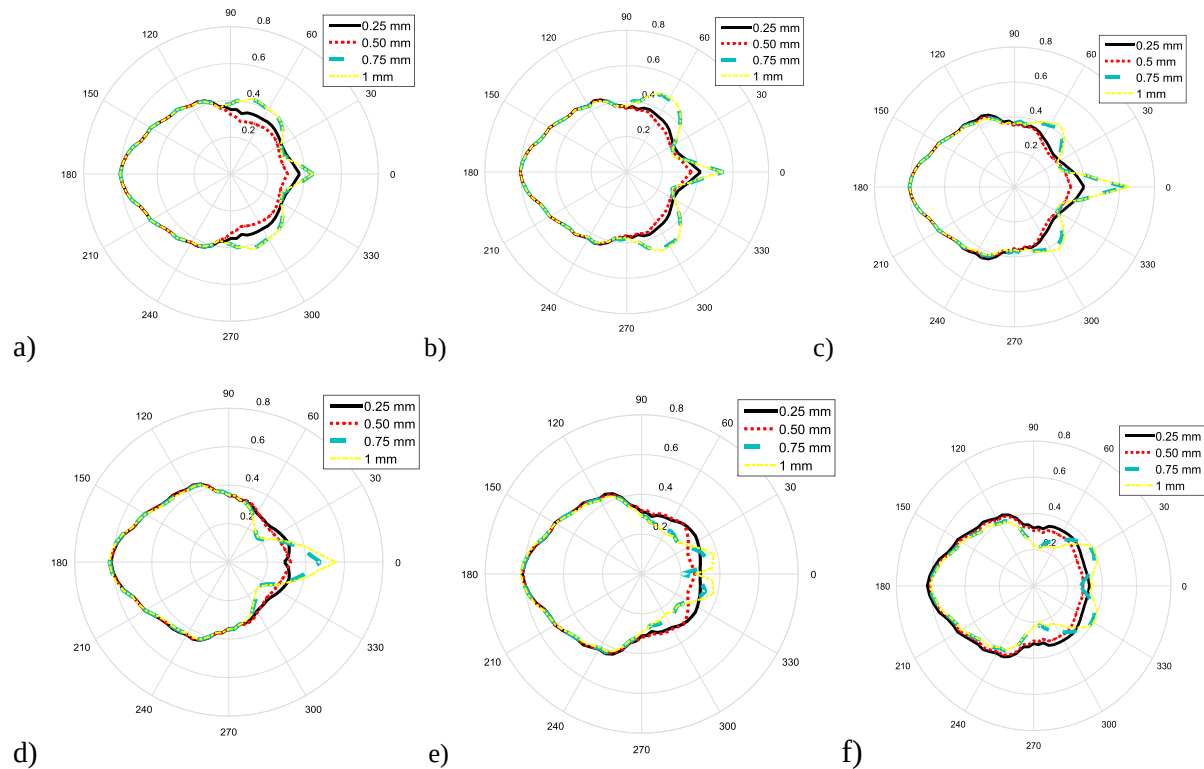


Figure 8. Scattered amplitudes around various damage diameter: a) 10 mm, b) 20 mm, c) 30 mm, d) 40 mm, e) 50 mm and f) 60 mm; at different depths; measured every 5° at 30 mm radius around center of the damage; 2 mm thick; 100 kHz frequency.

Table 2. Wave dispersion attenuation and angular dependency data comparison between FEM and DISPERSE for different layup orientations [16].

Layup orientation (plate's thickness)	Group velocity, C_g (m/s)		Phase velocity, C_p (m/s)		Attenuation, (dB/mm)
	FEM	DISPERSE	FEM	DISPERSE	
0/90 (0.5mm)	1062	1064	1042	600	0.3567
0/90/0/90 (1mm)	1246	1255	1235	866	0.1604
0/90/0/90/90/0 (1.5mm)	1366	1385	1333	1074	0.1180
0/90/0/90/90/0/90/0 (2mm)	1372	1388	1351	1134	0.1098

5. Conclusion

This paper studied the behaviour of the wave propagations towards damaged and undamaged carbon fiber plates. Based on the undamaged composite plate study, 100 kHz frequency was found as the most effective frequency where it has strong signal amplitude and less steering effect. Meanwhile, a thicker material increased the damping, which resulting in a slower wave intensity. For damaged plate study, the analysis found that the additional of 90° layup in composite plates decrease the velocity and the amplitude of the GUW.

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