

Article

A Finite Element-Inspired Method to Characterize Foreign Object Debris (FOD) in Carbon Fiber Composites

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Abstract

This study investigates ultrasonic wave propagation in carbon fiber reinforced polymer (CFRP) composites containing foreign object debris (FOD) by introducing a novel method to characterize the depth and size of FOD, from a single captured waveform generated by an out-of-focus spherically focused transducer. Current methods of inspection utilize a raster approach to both detect and quantify FOD, which is limited to identifying FOD smaller than 4 mm. The method introduced in the present paper allows for a single point scan to detect and quantify FOD, as small as 0.5 mm, with the highest error in the depth estimation being less than 8%. This paper presents experimental testing to inform a finite element analysis of a full waveform simulation of an immersion tank inspection environment and compares waveforms between testing and simulation. A transient pressure acoustic model is developed in the COMSOL Multiphysics environment to simulate wave propagations. Simulation results provide waveform reflection and transmission at material interfaces, which will occur when there is an acoustic mismatch between materials. The transmitted ultrasonic wave is partially reflected toward the transducer upon encountering material interfaces between the water, CFRP laminate, and the FOD. Simulation results show that the acoustic profile and pressure of the reflected wave captured by the transducer allows an accurate identification of FOD depth and size within the composite structure, suggesting an alternative method of inspection to quantify FOD characteristics faster than through conventional approaches. Results show an increase in captured signal pressure of over 125% between the 0.5 mm FOD and the 1 mm FOD located on the mid-plane of the laminate, and 500% between the same 0.5 mm FOD and 1 mm FOD placed near the front wall. These results suggest the potential sensitivity limits for physical component. This work demonstrates that small FOD, which are often difficult to resolve and quantify under conventional raster-based inspection, can be reliably identified by intentionally positioning the specimen within the defocused region of a spherically focused transducer. Results are presented to correlate the reflected acoustic pressure amplitude to defect depth, transducer-specimen distance, and FOD size, providing an approach to quantitatively discriminate small defects that would otherwise produce ambiguous signals.

Keywords: finite element analysis; ultrasonic non-destructive testing; carbon fiber laminates; foreign object debris (FOD)



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1. Introduction

The utilization of carbon fiber reinforced polymers (CFRP) in structural applications is often hindered by manufacturing challenges which can reduce material strength and compromise structural integrity, potentially leading to catastrophic failures [1–3]. These challenges include, but are not limited to, the following: ply orientation uncertainties [4], out-of-plane wrinkles, which may arise during manufacturing of thick laminates [5], and, of specific interest to the present study, foreign object debris (FOD), sometimes termed foreign object inclusions (FOI), which represent unwanted components from the manufacturing process trapped between lamina [6].

Undesirable foreign object debris, including tool fragments, peel-ply trimmings, gloving materials, and Kapton films, may be introduced either unintentionally or deliberately during manufacturing, service operation, or repair processes [7]. The incorporation of such foreign materials can degrade the mechanical integrity of woven carbon fiber reinforced polymer (CFRP) composites and introduce localized stress concentrations [7,8]. Owing to the structural incompatibility between the laminate and the embedded foreign materials, the resulting fracture and failure mechanisms become significantly more complex [9]. Furthermore, the presence of FOD can promote interlaminar damage, including the initiation and growth of delamination within the laminate [10]. Consequently, reliable detection and accurate sizing of FOD in CFRP laminates are critical for enhancing structural safety, extending service life, and preventing catastrophic failure during operation.

In the present study, we utilize non-destructive testing (NDT) to detect and quantify FODs in CFRPs. Ultrasound offers both depth resolution and internal imaging capabilities [11]. Hassen et al. [12] investigated foreign object inclusions of varying materials, shapes, and thicknesses embedded in thick glass-fiber/PP thermoplastic composites, using X-ray radiography, X-ray CT, and ultrasonic techniques. They demonstrated that, while X-ray CT provides reasonable through-thickness localization and sizing of FOD, it was unable to find many of the FODs inserted into the laminates. Conversely, the ultrasonic results were more robust for detecting foreign objects regardless of material, albeit how, in their study, it required a through transmission capture which required access to both sides of the laminate, something the authors noted as not desirable in industrial practice. In addition, the ultrasound results had difficulty in quantifying the dimensions of the inserted FOD due to acoustic distortion. Blackman et al. [13] developed a high-resolution immersion pulse-echo ultrasonic inspection system with advanced full waveform analysis to manually, from visualized waveforms, quantify the FOD geometry without prior knowledge of FOD shape. Specifically, they quantified the FOD to a mean diameter error of 0.11 mm for FOD sizes between 1.5 mm and 12.5 mm. Nargis et al. [6] presented an automated approach to analyze the full waveform for the detection, localization, and sizing of foreign object debris embedded in woven CFRP laminates. PTFE FODs with thicknesses of 0.05 mm and planar dimensions ranging from 7.6–12.7 mm were successfully characterized, resulting in dimensional errors of 0.1–1.6 mm for circular FODs and 0.6–3.3 mm for triangular FODs, presenting a substantial improvement over prior studies reporting errors of 4–14 mm. Poudel et al. [7] investigated FODs using acoustography in graphite-epoxy composites with thin Teflon film FODs. In their work, the FOD diameters ranged from 3 mm to 20 mm. FOD sizing results showed a good correlation with immersion c-scan and infrared thermography, where the effective spatial resolution was approximately 0.2 mm. Barry et al. [14] proposed an ultrasonic technique combined with neural network-based classification to locate and classify Teflon FODs in CFRP panels. The method successfully detected FODs with diameters of 2, 4, and 6 mm at varying depths within the laminate. Ma et al. [15] investigated ultrasonic phased array inspection of CFRP and reported a probability of detection of approximately 97% for the 3 mm FODs and 93% for the 6 mm FODs, but

they did not study FOD dimension quantification. Despite these advances, further work is needed to enhance the quantification of small (less than 3 mm) embedded FODs. In addition, there is a need for a deeper understanding of the physical nature of the waveform scatter to allow a better quantification of the FOD dimensions as a function of depth. This is particularly important as each of the aforementioned studies focused the transducer directly on the plane at which the FOD was located, something that would typically not be known a priori in an industrial setting.

Numerical simulations of ultrasonic wave propagation can provide a powerful framework to understand and predict wave–defect interactions in composite materials, including foreign object debris, wrinkles, and delamination [16]. Santos et al. [17] developed a high-frequency ultrasonic simulation framework to evaluate FOD detectability in composite structures, where numerical results were used to quantify FOD size and depth across varying excitation frequencies; their study considered multiple FOD types—including complete debonding, small delamination, foreign bodies, and damaged fibers—and showed a strong agreement between simulated and experimental results, validating the predictive capability of the model. Lints et al. [18] localized microcracking and delamination in carbon fiber composite plates with prior FOD information, demonstrating that signal-processing techniques combined with reciprocal time reversal can focus ultrasonic energy onto FOD at unknown locations. More recently, Zhang et al. [19] combined finite-element-based ultrasonic simulations of delaminated CFRPs with a Long Short-Term Memory neural network to localize FFOD demonstrating an improved detection accuracy while significantly reducing computational costs. While many numerical studies have focused on delamination or microstructural effects, relatively few have investigated ultrasonic wave interaction with thin foreign object debris in CFRP laminates, motivating the present simulation–experimental framework.

In this manuscript, a novel approach for inspection is proposed for detecting and quantifying foreign object debris (FOD) in carbon fiber reinforced polymers (CFRPs). This approach is motivated through a finite element study of a spherically focused transducer operating in pulse-echo mode. The proposed inspection approach enables the detection and quantification of FOD with characteristic sizes smaller than 4 mm. This study presents an ultrasonic scanning methodology in which the size of the FOD is estimated from the measured distance between the transducer and the specimen. By varying the transducer stand-off distance, the depth of the FOD within the CFRP laminate can also be identified. While prior numerical studies of ultrasonic wave propagation in CFRPs with internal FOD rely on simplified contact transducer models [16], the present work explicitly models an immersion-based ultrasonic inspection setup. Recent studies have demonstrated the use of finite element modeling combined with contact ultrasound transducers to quantitatively evaluate defects in CFRP laminates. Jing et al. [20] showed that pulse-echo signals obtained from a contact transducer can be accurately reproduced using FEM, with agreement between simulated and experimental A-scan responses in both amplitude and time-of-flight for embedded PTFE defects. In this research, the computational domain captures the transient wave propagation through the coupling medium, water–CFRP interfaces, and CFRP–FOD interfaces. To validate the effectiveness of the proposed method, numerical results are compared with experimental data obtained from immersion tank ultrasound scanning. The developed computational framework accurately predicts the acoustic responses associated with key structural features of the specimen, including FOD dimensions (thickness and diameter), and the laminate thickness. In conventional ultrasound testing, spherically focused transducers are typically positioned at a prescribed distance from a specimen based on the transducer focal length to inspect FOD [21–23]. In the present study, the transducer is positioned at a reduced stand-off distance from the specimen to

exploit beam convergence effects, enabling the rapid estimation of FOD depth and size within a CFRP laminate from a single A-scan response. This approach contrasts with conventional ultrasonic inspection methods that rely on time-consuming B-scan and C-scan raster scanning for FOD characterization [6]. Finally, a correlation map is established for FOD of various diameter sizes and depths in the CFRP, enabling the prediction of signal amplitudes and peak arrival time corresponding to different internal features. This study demonstrates the feasibility of a depth-resolved ultrasonic inspection strategy for FOD detection, in which systematic variation in the transducer's vertical position during A-scan acquisition enables a quantitative correlation between reflected acoustic pressure amplitude and FOD size. This approach provides a physics-based interpretation of amplitude variations that are typically treated qualitatively in conventional ultrasonic inspections. Prior numerical studies of ultrasonic FOD detection in CFRPs have reported simulation signal errors within 3% for depth in the simpler contact transducer configuration, with FOD sizes significantly larger than those used in the present manuscript [20]. The present study achieved errors less than 8% for FOD depth estimation and 4.35% for backwall detection using the immersion-based setup, while simultaneously providing a means to directly correlate pressure wave amplitude to that of FOD size as a function of depth.

2. Materials and Methods

2.1. CFRP Laminates with Foreign Object Debris Manufacturing Process

Carbon Fiber Reinforced Laminates (CFRP) are fabricated using unidirectional carbon fiber sheets (Toray T700 unidirectional fabric with a 250F resin system) purchased from Rockwest Composites (West Jordan, UT, USA). A 16 lamina CFRP, with all lamina having the same orientation along the x axis, is fabricated with polytetrafluoroethylene (PTFE) inserts placed between the 8th and 9th lamina. The PTFE inserts with a thickness of 0.06 mm and diameters of 12 mm, 10 mm, 7 mm, 5 mm, and 3 mm are inserted within the laminate stack as shown in Figure 1. The layup was placed in a Carver hot press (Wabash, IN, USA), with a pressure of 276 kPa and a heating rate of 2 °C/min, until reaching 135 °C. The CFRP laminates are held at 135 °C for 90 min at 276 kPa, followed by cooling at nominally 2 °C/min while holding the pressure to minimize thermal stress and potential deformations.

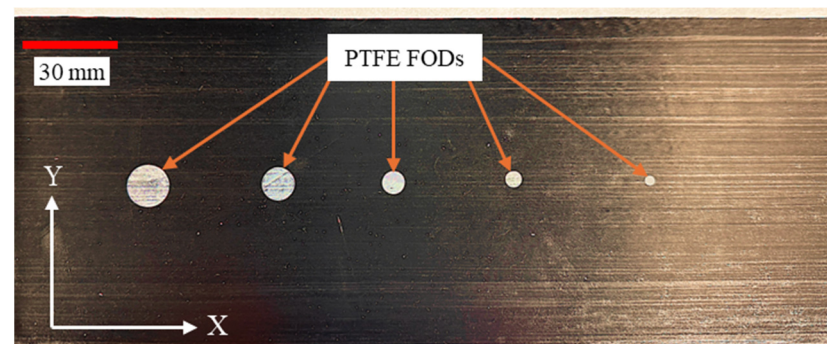


Figure 1. Position of each of the 5 FOD placed within the carbon fiber laminate.

2.2. Ultrasound Testing Process

In the present study, the fabricated laminates with embedded Teflon strips representing foreign object debris (FOD) are placed within an immersion tank for ultrasonic inspection. In this technique, the test specimen is fully immersed in water which acts as a coupling medium to efficiently transmit ultrasound waves between the transducer and the specimen. In the companion study Blackman et al. [24], we used spherically focused immersion transducers (7.5–10 MHz) with a planar scan resolution of 0.2 mm. From this previous

study, it was found that an immersion system can achieve an average FOD diameter error of 0.11 mm, compared to 0.21 mm for an out-of-tank portable configuration when performing a raster scan. The controlled water path in the immersion tank eliminates coupling variability and moving-fluid artifacts common to contact-based inspection or bubbler systems. In the previous study, it was observed that an immersion tank inspection enables reliable FOD boundary extraction and improved sizing accuracy, particularly for small and deeply embedded FOD. In the present study, we present an approach that extends the previous work on raster-based inspection within an immersion tank to allow a single inspection location to quantify the FOD sizing and depth.

The fabricated laminate, shown in Figure 1, was inspected with a custom ultrasonic immersion system. This system consists of an FOCUS PX (Olympus/Evident, Center Valley, PA, USA), Velmex stepper motors (Bloomfield, NY, USA), an immersion tank, and a 5 MHz spherically focused Olympus immersion transducer with a focal length of 38.1 mm as shown in Figure 2. The transducer was moved in a raster pattern of 0.1 mm step sizes. Note that for thicker specimens, with a raster scan approach, focusing on a plane other than the FOD will lead to a reduction in the quality of FOD detection. In this study, we intentionally place the transducer in a configuration, so as to not be in focus, and it is placed only 15 mm from the part surface. The individual A-scans corresponding to each FOD are extracted from the raster scan for later comparison with the finite element results.

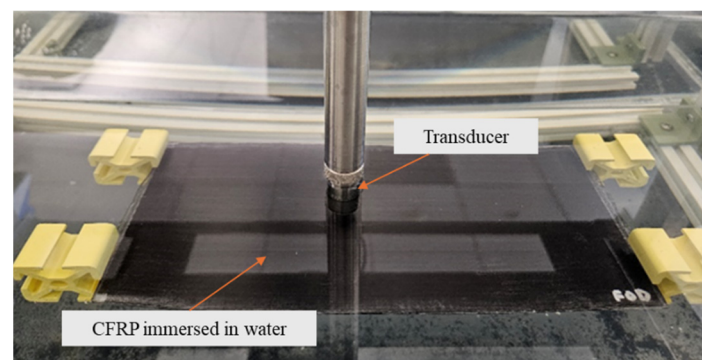


Figure 2. Ultrasound scanning setup showing the CFRP in the immersion tank.

Figure 3 depicts two typical A-scans for the CFRP specimens with and without FOD. In the case of a CFRP without FOD, a prominent initial peak—occurring earlier in time—corresponds to reflections from the front wall of the sample, and the second major peak appearing later in time represents reflections from the backwall of the sample. In the A-scan for the sample containing FOD, an additional intermediate peak is clearly observed between the front and backwall reflections. This peak is absent in the scan of the sample containing no FOD and is attributed to wave reflections from the embedded FOD. Using the method presented in the following section, the depth and size of the FOD can be estimated from variations in the acoustic amplitude of waves reflected from the FOD.

Figure 4 illustrates the wave behavior through a B-scan representation, providing a side-view cross-sectional image of the sample. A B-scan is formed by stitching a series of A-scans together along a single scan axis, providing, in essence, an acoustic slice through the composite being inspected. The B-scan highlights the relative positions of the front wall, backwall, and FOD reflections, offering spatial insight into the wave propagation and interaction within the laminates. By performing a full-area scan of the specimen, the locations of foreign object debris (FOD) can be identified. Subsequently, based on the B-scan results, the corresponding A-scan signals are extracted for cases where the transducer was positioned at the centroid of each of the embedded FOD.

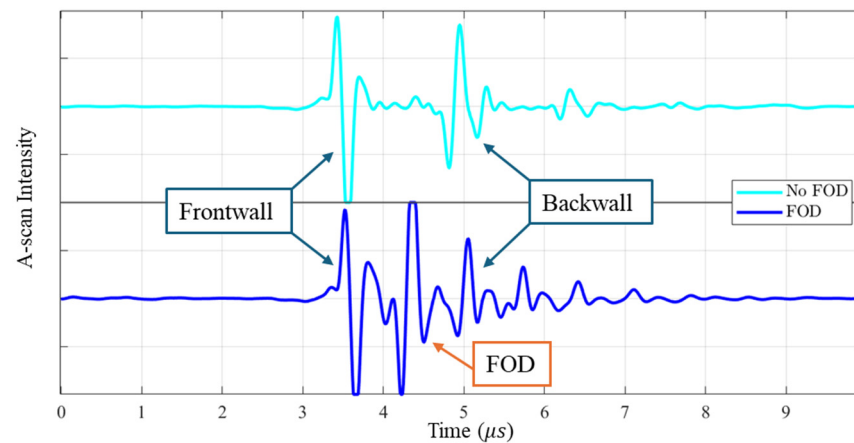


Figure 3. A-scan plot for two cases of CFRP with and without FOD.

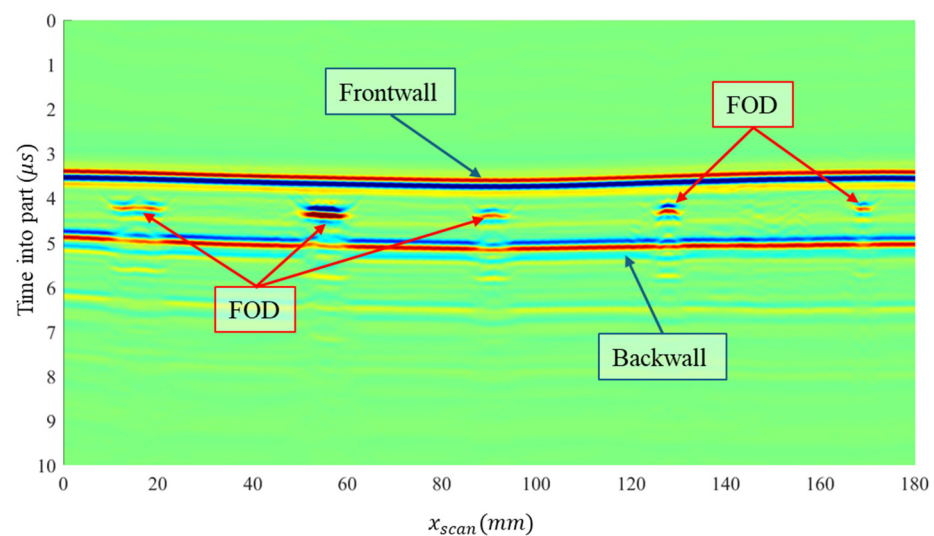


Figure 4. B-scan of the CFRP specimen with FOD in varying diameter sizes.

The intensity and amplitude of waves are strongly influenced by the quality of the interface bonding between CFRP and PTFE materials. Variations in bonding strength, which can appear from inconsistencies during the manufacturing process, result in different reflection intensities depending on the size and nature of the interface. In cases where the bonding is weak and small voids are present between the CFRP and PTFE layers, significant wave reflections are generated at the FOD location. As a result, a substantial portion of the wave energy is reflected rather than transmitted through the FOD, leading to a noticeable reduction in the intensity of the backwall wave signal.

2.3. Governing Equations and Domain Configurations

In this research, a model is constructed of the composite specimen with embedded FOD in a water immersion environment to match that of Figure 2. To extract the corresponding A-scans, a finite element simulation of the three dimensional ultrasonic wave propagation is performed using the transient pressure acoustic module in COMSOL Multiphysics (version 6.3, Burlington, MA, USA). The captured pressure profile on the transducer surface in the modeling domain is related to the voltage measurement of the transducer in the physical test environment.

2.3.1. Governing Equations

The pressure in a homogeneous isotropic acoustic medium is described as

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0 \quad (1)$$

where p is the acoustic pressure, c is the speed of sound in the fluid, and t is time.

The acoustic wave emitted from a spherically focused transducer propagates through the water domain to impinge upon the top surface of the CFRP. At the interface between the two media, part of the wave is reflected while the remainder is transmitted and also termed refracted. The relative proportions of reflection and transmission are governed by the acoustic impedance Z of the respective materials, expressed as

$$Z = \rho c \quad (2)$$

where ρ denotes density of the material. The reflection coefficient R and transmission coefficient T for acoustic pressure are given by the following equations:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (3)$$

$$T = \frac{2Z_2}{Z_2 + Z_1} \quad (4)$$

where Z_1 and Z_2 are the acoustic impedances of, respectively, the material with the incident wave and the material with the refracted wave.

CFRP composites in real-world applications have a layered configuration, where distinct interfaces exist between layers. These layers consist of spatially varying blends of fiber and resin and cause the waves to attenuate and scatter while passing through the CFRPs. This can be seen by the subtle horizontal lines in the B-scan of Figure 4 between the front wall and backwall reflections. These waves are significantly smaller than those of the reflection waves off the embedded PTFE FOD in the same B-scan. Thus, in the present model, we will treat the composite as a homogeneous domain with the bulk properties of the composite, extracting the wave component from the FOD reflection for analysis. In this research, the CFRP domain was modeled as a solid medium and the speed of sound perpendicular to fiber direction was set to 2800 m/s based on experimental observations made in an earlier study of the same material system [6].

2.3.2. Excitation Signal and Domain Properties

To induce an acoustic pressure wave, an acoustic velocity boundary condition was applied to the transducer boundary. The velocity equation is modeled as a two-parameter parametric function in terms of space r and time t as

$$V(t, r) = g(r)h(t) \quad (5)$$

where the function $g(r)$ is constructed to be zero at the transducer boundary edges. In this work, the function $g(r)$ is defined as $g(r) = 1 - \frac{r}{r_{\text{transducer}}}$ where r is the radial location and $r_{\text{transducer}}$ the radius of the transducer. The function $h(t)$ is selected to match the frequency characteristics of the physical transducer. In the present study, the product of a Gaussian with a sinusoidal curve is selected as

$$h(t) = -\exp\left(-\left(\frac{t - 2T_0}{T_0/2}\right)^2\right) \frac{\sin(2\pi f_0 t)}{2} \quad (6)$$

where f_0 is the experimentally observed peak frequency and $T_0 = 1/f_0$ is the period of the wave. It was found that after selecting the spread of the Gaussian function, the denominator term of the exponential in Equation (6), as $\sigma = T_0/(2\sqrt{2})$, a reasonable fit was obtained for the Olympus transducers used in the experimental component of this study. Figure 5 presents the actual pressure wave emitted by the transducer used in this study, illustrating the transducer voltage signal for the physical transducer and the surface velocity used in the numerical simulations. To allow a direct comparison of waveform shapes independent of physical units, both signals are normalized by their respective maximum amplitudes.

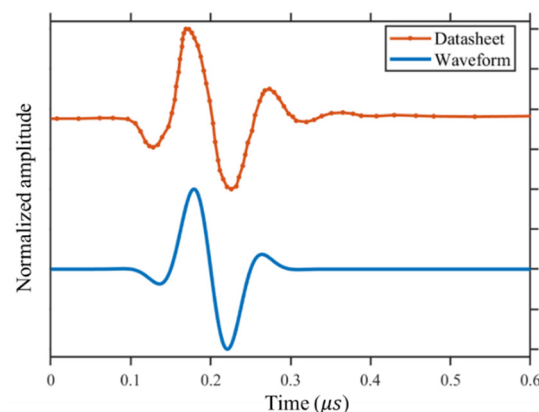


Figure 5. Excitation signal from the transducer used in the ultrasound test and FEA model.

In this study, three distinct domains are modeled: the CFRP, the water and the PTFE FOD insert. Table 1 shows the speed of sound and density for each domain with values taken from [6,20]. These values determine the wave speed in the domain along with the respective transmission and reflection coefficients in the interface.

Table 1. Acoustic properties of the modeled domains.

Domain	Speed of Sound (m/s)	Density (kg/m ³)
Water	1480	998
CFRP	2800	1500
PTFE	1218	2100

3. Finite Element Methodology and Results

This section provides the details for the finite element construction in parallel with the results from finite element analysis and experimental tests. Section 3.1 presents a study of the element size within the domain to identify an acceptable element size for convergence and a study of the sensitivity of the A-scan results to the transducer frequency. Sections 3.2 and 3.3 present typical results for the acoustic wave propagation within the domain to aid in conceptualization of the reflection and refraction waves during the simulation and to aid in results interpretation. The third study, presented in Section 3.4, is a comparison of experimental results with modeling simulations. The fourth study, presented in Section 3.5 investigates the sensitivity of the acoustic waveform to changes in the FOD size and depth, highlighting the ability to differentiate FOD sizes with only a single A-scan of data. The final study in Sections 3.6 and 3.7 expand on the fourth study and is a presentation of the returned acoustic pressure wave intensity as a function of FOD depth and size. Several numerical highlights are presented in Section 3.8 to highlight the sensitivity of the inspection approach.

3.1. Finite Element Domain

The domain used in this study for finding A-scans for each model is shown in Figure 6. To allow simulations to be performed in a reasonable time period, the domain is modeled using a two-dimensional axisymmetric model, indicative of a transducer being placed directly above the center of the circular FOD. The domain has three regions highlighted in Figure 6: the water domain, the CFRP domain, and the embedded FOD.

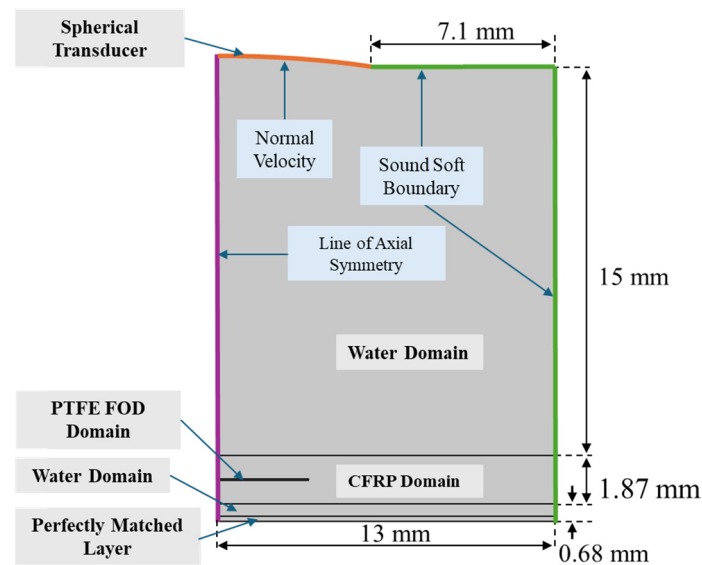


Figure 6. Geometry of the computational domain used in the simulation.

To ensure that the finite element model accurately represents the physical conditions of ultrasonic scanning, it is essential to minimize reflections from the computational domain boundaries. To avoid unnecessary computations, the domain is reduced to focus on the region where the reflections occur. In this study, sound soft boundary conditions, shown by the green line in Figure 6, are applied to the sides and top of the domain to absorb incident waves and emulate the open water environment. A perfectly matched layer (PML) was assigned to the bottom of the domain, as this region experiences higher wave interaction. The PML attenuates outgoing waves, preventing their reflection back into the domain [25]. Ultrasonic excitation was introduced into the domain corresponding to the transducer, shown by the orange line in Figure 6, through a normal velocity boundary condition applied to the transducer surface as expressed in Equation (6). Mode conversion was neglected in this study because the primary objective was to quantify changes in reflected acoustic pressure amplitudes associated with FOD size and depth, rather than to analyze shear wave phenomena. Given the near orthogonal incidence configuration for wave propagation in the current study, the contribution of mode-converted waves is expected to be minimal and to have a negligible influence on the measured A-scan response.

In finite element simulations of ultrasonic wave propagation, both the computational domain and mesh resolution must be carefully designed to capture the wave behavior accurately. The computational domain for each medium must be similar to, or larger than, the acoustic wavelength within the medium. In addition, the mesh size must be sufficiently fine to resolve the acoustic wavelength, while the overall domain should minimize boundary reflections [25]. In the present study, the smallest feature is the PTFE strip of 0.06 mm in thickness. Thus, to allow the acoustic wave to fully form within the PTFE, the wavelength should be greater than or similar to four times the PTFE thickness Δx_{PTFE} , specifically

$$f \gtrsim \frac{c}{4\Delta x_{PTFE}} = \frac{1218 \text{ m/s}}{4 \times 0.06 \text{ mm}} = 5 \text{ MHz} \quad (7)$$

In addition, the wavelength of the ultrasonic wave within the CFRP domain must be sufficiently large to allow the waveform to fully develop before the reflection wave from the interaction with the PTFE strip occurs. To ensure this condition, the wave frequency inside the CFRP can be determined using

$$f \gtrsim \frac{c}{\lambda} = \frac{2800 \text{ m/s}}{1.87 \text{ mm}/2} = 2.9 \text{ MHz} \quad (8)$$

where the 2 in the denominator is due to the use of the reflection wave instead of the transmission wave, and λ is the wavelength of the incident wave in the CFRP. To satisfy this condition, a conical spherical 5 MHz transducer was employed in the ultrasound immersion experiments. The finite element simulations explore the 5 MHz transducer and also investigate the consequences of using too small a frequency, specifically 2 MHz, as well as any perceived benefits of a higher frequency, specifically 7.5 MHz.

One of the main challenges in modeling ultrasonic wave propagation is the high computational costs, both for CPU usage and simulation time. The computational mesh required for accurate simulations is typically at least 5 elements per wavelength λ and, in the literature, some high-resolution studies have presented results for 10 elements per wavelength [25]. To ensure independence of the results from the mesh, three different mesh refinement criteria are evaluated with a maximum element size of $\lambda/5$, $\lambda/7$, and $\lambda/10$. The resulting element size and computational times are shown in Table 2.

Table 2. Number of elements in each domain based on the wavelength for 5 MHz excitation.

Domain	5 Elements per Wavelength	7 Elements per Wavelength	10 Elements per Wavelength
Water	151,787	301,732	629,038
CFRP	7915	14,775	28,883
PTFE	222	373	663
	Runtime = 80 min.	Runtime = 155 min.	Runtime = 306 min.

The spatial and temporal varying pressure results from the finite element domain can be linearly correlated to those of the voltage captured from the actual transducer through the instantaneous average surface pressure on the transducer boundary, the orange boundary in Figure 6. Typical results of the normalized captured pressure amplitude on the transducer surface as a function of time are shown in Figure 7, where the time has been shifted such that $t = 0$ occurs just before the return of the first reflection wave. As shown in Figure 7, the acoustic pressure changes as the mesh refinement increases from a maximum element size of $\lambda/5$ to $\lambda/7$, but the change from $\lambda/7$ to $\lambda/10$ is less significant. Thus, in the remaining results, a minimum of 7 elements per wavelength is maintained.

3.2. Frequency Sensitivity

Transducers operating at higher frequencies can detect thinner FOD due to the shorter wavelengths [26]; however, simulating high-frequency waves is computationally expensive. Figure 8 shows the normalized acoustic amplitude for a model with a FOD that has a 0.06 mm thickness and a 3 mm diameter at a depth of 0.948 mm for three distinct transducer frequencies, 2 MHz, 5 MHz, and 7.5 MHz. The first observation is that the reflection from the FOD is hard to distinguish within the 2MHz wave signal. Looking at the 5 MHz and the 7.5 MHz waves, the FOD is clearly identified around 1.3 μ s to 1.4 μ s. A second metric in choosing a transducer frequency is the temporal resolution, which is correlated to the

through-thickness spatial resolution. For example, the thickness Δx of the laminate can be estimated from the acoustic wave, in pulse-echo mode, as

$$\Delta x = c_{CFRP} \Delta t / 2 \quad (9)$$

where Δt is the time difference between the front wall and the backwall peaks in the A-scan, and c_{CFRP} is the speed of sound of carbon fiber composite. Using Equation (9), the model estimates a specimen thickness of 1.93 mm and 1.90 mm for, respectively, the 5 MHz and 7.5 MHz transducers. Although the higher frequency provides a closer thickness estimate to the actual 1.87 mm thickness, it requires a substantially higher computational cost. Requiring 80 min for the 5 MHz simulation as compared to 183 min for the 7.5 MHz simulation running on a system with an Intel (R) Core™ i9-10940X with a clock speed of 3.3 GHz, an NVIDIA RTX 2060 video card and 256 GB RAM.

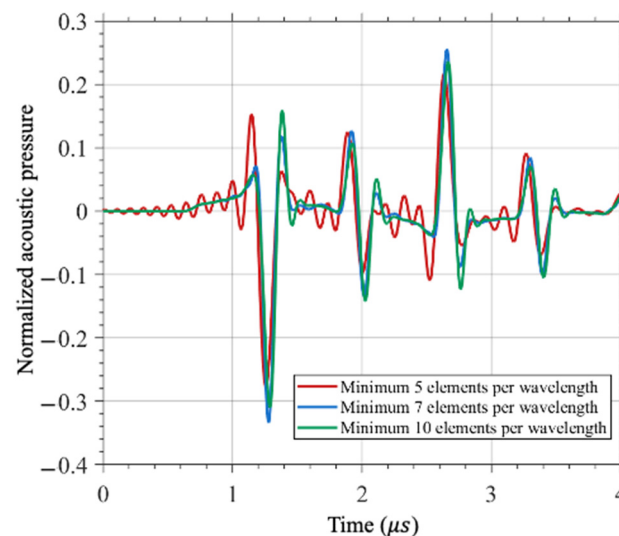


Figure 7. Average transducer acoustic pressure as a function of mesh size highlighting that a maximum element mesh size of $\lambda/7$ is sufficient.

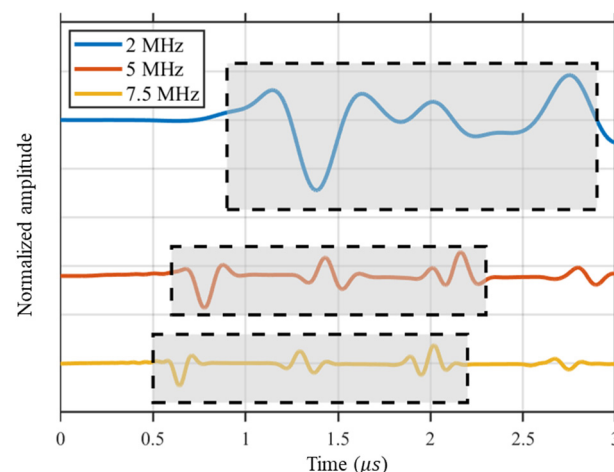


Figure 8. Normalized acoustic amplitude at transducer location for the model with 3 mm diameter of FOD in depth of 0.948 mm in CFRP.

3.3. Signal Detection from FOD

Figure 9 presents the acoustic pressure contours illustrating the wave propagation in the axisymmetric computational domain. This specific study is of a 3 mm diameter FOD placed 0.948 mm from the front wall of the CFRP. To represent the cylindrical geometry of

the spherically focused transducer and the circular shape of the FOD, the model is formulated in an axisymmetric domain. This approach ensures that the simulation environment closely replicates a single excitation cycle of the transducer when it is positioned directly above the FOD. In this study, ultrasonic waves emitted by the transducer first propagate through the fluid domain before reaching the top surface of the CFRP, as seen in Figure 9a. After interacting with the interface between the water and the CFRP, termed the front wall, a portion of the wave is reflected into the fluid domain, while the remaining energy refracts into the CFRP. The component of the wave that transmits into the CFRP has a longer wavelength, which penetrates into the CFRP until it hits the top surface of the PTFE layer as shown in Figure 9b. As the wave reaches the middle layers of the CFRP, where the FOD is located, a second reflection occurs at the PTFE-CFRP interface. A portion of the wave reflects into the CFRP and travels back toward the transducer, while the remaining portion refracts into the PTFE. Upon reaching the bottom surface of the CFRP, another reflection occurs in the interface, and the remaining wave energy enters the water domain and is ultimately absorbed by the perfectly matched layer. This ensures that no reflections interfere with the simulation, thereby maintaining the accuracy of the results. Figure 9c highlights the reflected waves from each interface, which will later in time interact with the transducer.

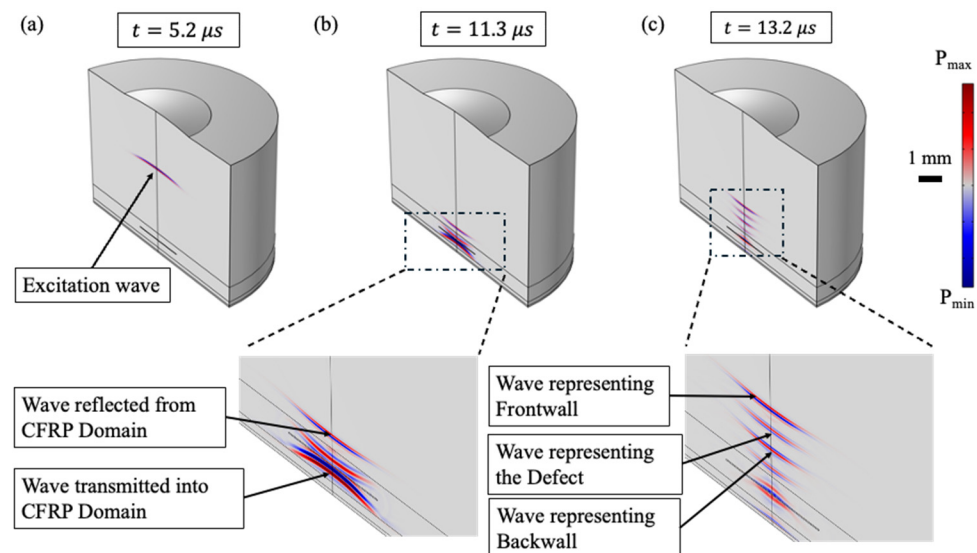


Figure 9. Acoustic pressure within the domain at (a) The time the wave is propagating toward CFRP domain (b) The time wave hits CFRP domain and reflection occurs at interface (c) The wavefronts reflected from CFRP features are propagating toward transducer (Note, the black scale bar shown by the caption is 1 mm in length).

Figure 10 depicts the entire time history of the normalized average acoustic pressure measured on the surface of the transducer. The normalized pressure is defined as the instantaneous average acoustic pressure on the surface of the transducer divided by the maximum value of the instantaneous average acoustic pressure on the surface of the transducer. The plot in Figure 10 highlights two distinct regions of the wave. The initial green excitation region corresponds to the wave transmitted from the transducer into the sample. The middle region with the white background there is a nominal pressure on the transducer as the wave is propagating into the water and CFRP domains. The final region, highlighted in red, represents the reflections from the solid domain, including those from internal FOD and the backwall. Exclusively analyzing the reflection wave region, the region highlighted in red, enables the identification and localization of FOD within the CFRP structure. In the following results, the time axis is reset to zero just before the

reflection wave interacts with the transducer surface, roughly $20\ \mu\text{s}$ after the initial acoustic pulse from the transducer firing.

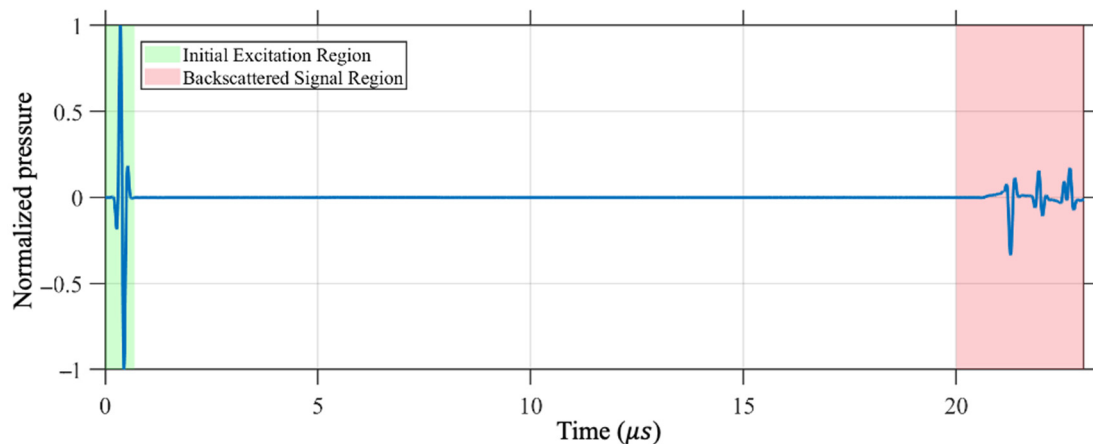


Figure 10. Normalized acoustic pressure plot for a total cycle of recording in transducer.

3.4. Comparison of FEM Results with Experimental Observations

To evaluate the results from the FEA simulation, the fabricated CFRP specimens discussed in Section 2.1 are tested using the ultrasound immersion tank system presented in Section 2.2. The A-scans are manually extracted from the raster scan at the location where the transducer was located directly over the centroid of the FOD. The results from the experimental scans represent the voltage amplitude in the piezoelectric transducer, which can be linearly correlated to the acoustic pressure [27]. Although generating B-scans from the FEM model would be beneficial for comparison with experimental results, the use of a 2D axisymmetric domain in this study limits the ability to position the transducer at multiple lateral locations across the CFRP domain. Consequently, the comparison between numerical and experimental results was performed using A-scan signals only, and a B-scan simulation is left for a future study.

Figure 11 shows the normalized acoustic pressure in the transducer location, comparing the results from the finite element analysis simulation with ultrasound scan measurements for specimens containing FOD of each of the 5 sizes; 3 mm, 5 mm, 7 mm, 10 mm, and 12 mm.

Each plot highlights three distinct amplitude variations corresponding to reflections from the CFRP top wall, the FOD, and the CFRP backwall. In the FEA results, the reflection from the top wall exhibits a lower ratio of positive to negative acoustic amplitude, whereas this ratio is higher in the experimental measurements. In ultrasonic scanning experiments, the acoustic amplitude reflected from the top wall (green region) remains nearly constant, as the top surface geometry does not vary across the specimen. In contrast, the amplitude of the wave reflected from the FOD shows noticeable variation based on the FOD size and manufacturing variability. The variability can be attributed to manufacturing imperfections such as trapped voids or imperfect bonding between the PTFE insert and the surrounding laminate. In the FEA results, where wave attenuation and imperfect interfacial bonding are not considered, the reflected amplitude from FOD with diameters larger than 3 mm remains approximately constant. One objective of this study is the detection of the FOD as well as the quantification of the FOD depth; the quantification between numerical and experimental results is therefore based on the time-of-flight differences between reflection features rather than absolute amplitude values. The time difference between features is defined as

$$\Delta t = t_{\text{Feature}} - t_{\text{Frontwall}} \quad (10)$$

where $t_{Feature}$ is the time when the FOD or the backwall echo is observed on the transducer surface, and $t_{Frontwall}$ is the time when the front wall echo reaches the transducer surface. An error metric to assess the FEA model is defined by comparing the time difference between the finite element results, labeled FEA, and the experimental ultrasonic testing (UT) results, labeled UT, as

$$\varepsilon_{feature} = \left| \frac{\Delta t_{FEA} - \Delta t_{UT}}{\Delta t_{UT}} \right| \times 100 \quad (11)$$

By analyzing the time-of-flight results from Figure 11, the error from Equation (11) is calculated to be less than 8% for all FOD sizes. Specifically, for the 3 mm diameter FOD, the error as defined in Equation (11) to detect the depth is 3.2%, while for the FOD diameters of 5 mm, 7 mm, 10 mm, and 12 mm, the error is, respectively, 8%, 4.9%, 4.7%, and 6.67%. The error for the backwall detection for the specimen with a 3 mm FOD is 0.29%, increasing to 0.5%, 1%, 4.33%, and 4.35% for FOD sizes of 5 mm, 7 mm, 10 mm, and 12 mm, respectively. It is possible this error could be further reduced by refinements of the manufacturing process. Regardless, the depth differences in the FOD and the backwall between the model and the physical system are less than 8% with a 2–3% difference being typical.

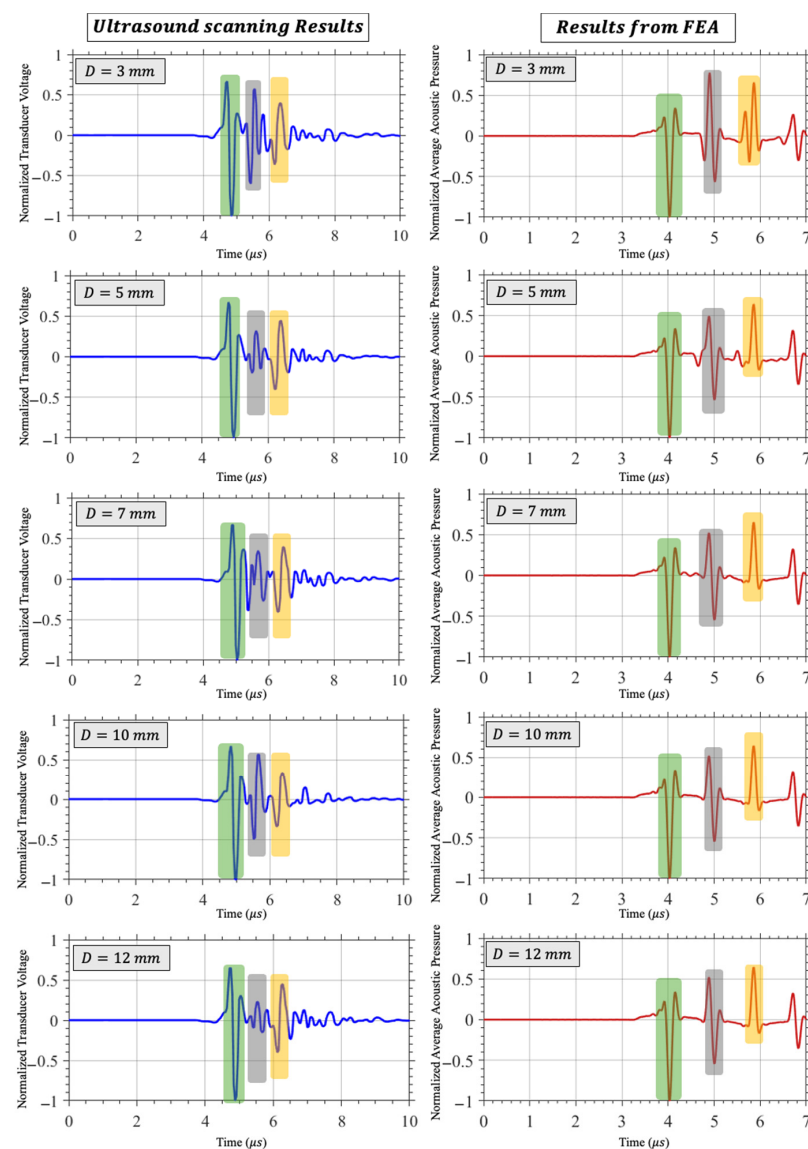


Figure 11. Normalized acoustic pressure from ultrasound scanning and FEA simulation at transducer location for FOD in different diameters.

3.5. Correlation Between FOD Depth and Size with Acoustic Signal

Figure 12a shows the spatial variation in the instantaneous pressure state at the moment the incident pressure wave impacts the FOD for three different depths of a 4.5 mm diameter FOD with a thickness of 0.06 mm. In Figure 12a, the pressure distribution is shown at the moment in time that the pressure wave first interacts with the FOD. The three scenarios, labeled D_1 for the 1.36 mm deep FOD, D_2 for the 0.948 mm deep FOD, and D_3 for the 0.435 mm deep FOD. Notice that the wave for the shallow FOD scenario, D_3 , has yet to come into full focus and has a larger diameter than the deeper FOD in scenario D_1 . This reflection surface area change directly correlates to the relative energy of the reflection wave that is returned and captured by the transducer.

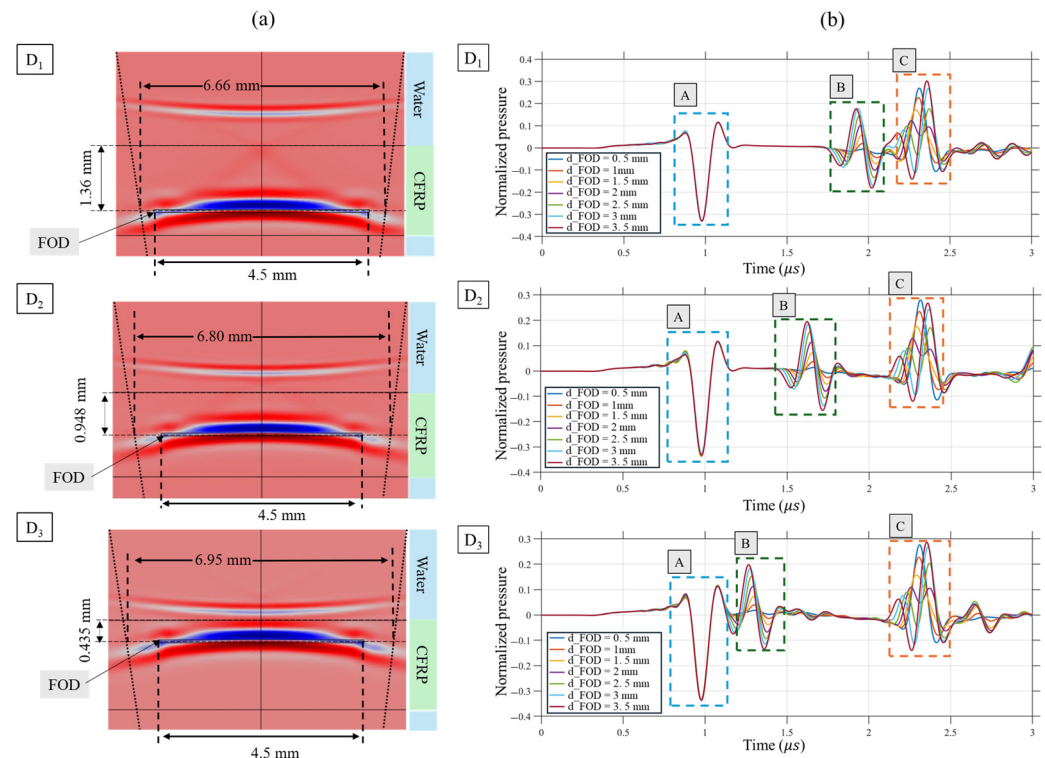


Figure 12. (a) Acoustic pressure when impacting the FOD at three different depths $D_1 = 1.36$ mm, $D_2 = 0.95$ mm, and $D_3 = 0.44$ mm. (b) Normalized acoustic pressure of the reflection wave at the transducer for each of the three depths.

Figure 12b illustrates the normalized acoustic pressure for the depth scenarios, D_1 , D_2 , and D_3 , but also includes the results from studies with variations in the FOD diameter from 0.5 mm to 3.5 mm. The plots highlight three distinct regions. Region A shows the reflection wave from the CFRP front wall signal, region B represents the reflection wave from the FOD, and region C shows the CFRP backwall reflection wave. The FOD reflection wave time is directly correlated to the depth of the FOD. The next observation is that, by increasing the diameter size of the PTFE FOD from 0.5 to 3.5 mm, a higher percentage of the wave energy is reflected and subsequently captured by the transducer. In addition, due to the curved shape of the excitation wave that has not yet come into focus, the FOD locations have a subtle shift earlier in time with increasing FOD diameter. By increasing the diameter of the FOD from 0.5 mm to 3.5 mm for the D_2 scenario, the onset of the reflection wave at the transducer occurs at 1.66 μs for the smaller diameter FOD, whereas it is at 1.62 μs for the larger FOD. Similarly, for the shallow FOD in scenario D_3 , the onset of the reflection wave for the small FOD is 1.31 μs, whereas for the larger FOD, it is 1.26 μs. Although the subtle shift in time may seem to be small, it is within the resolution of a 100 MHz digitizer.

(i.e., data collected every $0.01\ \mu\text{s}$) such as that used in the experimental study, although a higher digitizer frequency would be preferred. It was found that increasing the FOD diameter size from 0.5 to 3.5 mm has a significant change in the reflection wave intensity; from FOD diameters larger than 3.5 mm up to the largest FOD studied at 6 mm, the increase in the signal intensity was nominal. It is interesting to note that Figure 12b also highlights the relationship between the backwall peak time and amplitudes with that of the FOD size and depth. Given that the acoustic impedance and the speed of sound of the PTFE relative to that of the CFRP is, respectively, 60% and 40%, the wave scatter of the CFRP near the thin PTFE FOD becomes complex. Upon interaction with the PTFE layer, part of the wave slows down due to the reduced speed of sound, while the remaining part continues to propagate at the same speed within the CFRP domain. As a result, larger diameter FOD introduce delays in wave propagation within the CFRP, further emphasizing the role of FOD size in acoustic wave interactions. By increasing the diameter of the FOD from 0.5 mm to 3.5 mm in scenario D_2 , the backwall reflection time decreases from $2.31\ \mu\text{s}$ to $2.18\ \mu\text{s}$. As a result, when the FOD diameter is less than the diameter of the converging region of the wavefront, the resulting pressure of the reflection wave on the transducer can be used to estimate the FOD diameter and depth.

3.6. Evaluation of the Transducer's Ability to Detect FOD with Different Thicknesses

Unlike standard assumptions that FOD causes a hard reflection surface, such as one would expect with an air void, the PTFE that shares a mechanical bond with the laminate allows sound to both reflect and refract. Thus, variations in the thickness of the FOD can cause distortions in the acoustic reflection. This is observed in Figure 13 where the normalized acoustic pressure is shown for three different FOD thicknesses, 0.06 mm, 0.09 mm, and 0.12 mm, all modeled with a fixed FOD diameter of 3 mm. As the FOD thickness increases, the ultrasound wave travels a shorter distance before interacting with the top surface of the PTFE domain, leading to a shift in the pressure profile to an earlier time. But this is an artifact of the choice of modeling the geometry from the bottom up versus the top down. What is more striking is that, as the FOD thickness goes from a fourth of the wavelength to half of the wavelength of the acoustic wave, less energy is reflected. A secondary observation is that the specific depth of the FOD can be easily identified by the onset of the reflection wave, and even subtle changes as small as 0.06 mm can be captured.

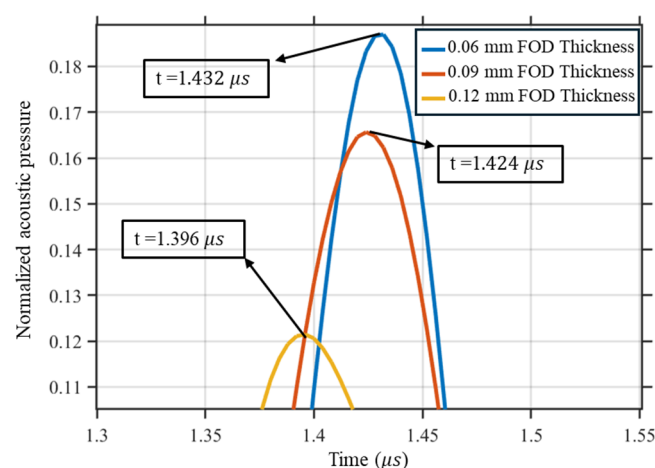


Figure 13. Normalized acoustic pressure for the CFRP laminate with different thickness of FOD.

3.7. Sound Pressure Amplitude Correlation

Figure 14 shows the normalized average acoustic pressure amplitudes of waves reflected from FOD and the backwall for the three different FOD depths, $D_1 = 1.36\ \text{mm}$,

$D_2 = 0.95$ mm, and $D_3 = 0.44$ mm. The amplitudes are normalized by dividing by the maximum observed acoustic pressure of either the FOD or the backwall reflection wave. The results indicate that an increase in the FOD diameter leads to a higher acoustic pressure amplitude from the FOD reflection wave, while simultaneously reducing the amplitude of the backwall reflection. Correspondingly, as the FOD diameter increases the reflection wave arrival time decreases for the FOD wave and the backwall wave.

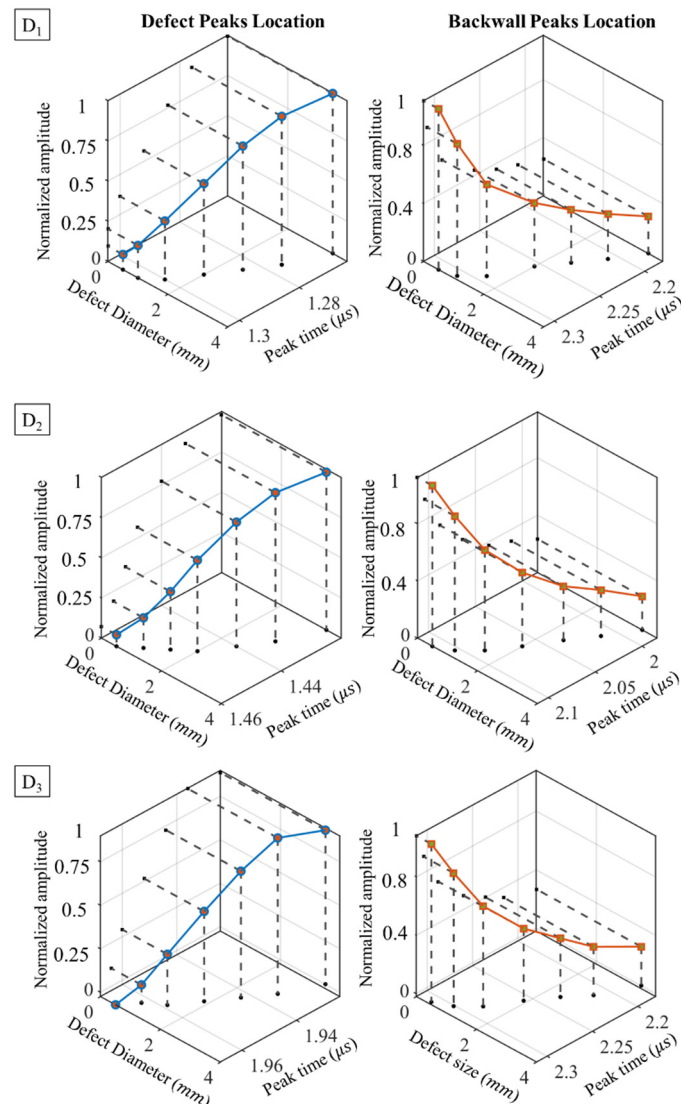


Figure 14. Normalized acoustic amplitude from FOD and CFRP backwall in varying diameter sizes for the FOD located in different depths of CFRP ($D_1 = 0.435$ mm, $D_2 = 0.948$ mm, $D_3 = 1.36$ mm).

For the deepest FOD, $D_3 = 1.36$ mm, increasing the FOD diameter from 0.5 mm to 1 mm results in a 131% increase in the reflection wave from the FOD, whereas the same doubling in diameter from 1 mm to 2 mm results in a 180% increase and a doubling from 1.5 mm to 3 mm results in a 149% increase. What is significant is that the increase in the acoustic energy of the reflected wave from the 3 mm to the 3.5 mm FOD is only 6%. For the FOD near the midplane of the CFRP, $D_2 = 0.95$ mm; increasing the FOD diameter from 0.5 mm to 3.5 mm produces similar conclusions as the deeper FOD with the doubling of the diameter from 1 mm to 2 mm, resulting in a 200% increase in reflected signal intensity. The change in the acoustic signal change is much more for the shallow FOD, where the increase from a FOD diameter of 0.5 mm to 1 mm results in a 525% intensity increase in the reflected signal, and a similar doubling from 1 mm to 2 mm results in a 400% increase and

a doubling from 1.5 mm to 3 mm results in a 205% increase. Increasing the FOD diameter from 3 mm to 3.5 mm for the shallow FOD simulation leads to only an increase of 1% of the reflection wave intensity. Overall, the results show a saturation effect, where the rate of increase in acoustic pressure amplitude decreases as the FOD size increases. This behavior is attributed to the FOD progressively covering a larger portion of the incident wavefront, thereby reflecting a greater fraction of the wave energy. Furthermore, for a given FOD size increment, the rate of increase in amplitude is higher for shallower FOD (from D_1 to D_3), which is attributed to the more focused wavefront at smaller depths. As FOD size increases, the backwall reflection amplitude decreases due to increased obstruction of the propagating wavefront.

3.8. Summary of Results

The results from the experimental study confirm the simulation's precision in locating the FOD depth using a single A-scan, achieving less than an 8% difference between simulation and experimentation in quantifying FOD depth for the FOD sized 3 mm (3.2% difference), 5 mm (8% difference), 7 mm (4.9% difference), 10 mm (4.7% difference), and 12 mm (6.7% difference). Comparative analysis of experimental immersion tank testing and simulation results reveals minor discrepancies primarily attributed to manufacturing variations and digitization limitations. These manufacturing variations affect the actual acoustic impedance mismatch at the material interfaces, contributing to amplitude differences.

The study shown in Figure 14 demonstrates the effect of FOD size on the acoustic pressure amplitude. Increasing the FOD diameter from 0.5 mm to 1 mm results in a 131% increase in acoustic pressure amplitude for a deep FOD and over a 500% increase for a shallow FOD. As the FOD diameter increase to a size similar to the focal spot size on the FOD plane itself, progressively smaller gains in acoustic pressure amplitude occur. This trend indicates a limit for practical ultrasonic inspections, where increases in FOD size beyond a certain threshold cannot be differentiated. In addition, the results of Figure 14 reveal a clear relationship between FOD size, reflected acoustic pressure amplitude, and peak arrival time. Analysis of the FOD depth reveals that FOD positioned deeper within the CFRP (e.g., 1.36 mm) exhibit a tighter wave convergence, resulting in stronger acoustic pressure reflections. Therefore, there may be reason to further optimize the transducer position relative to the surface, based on manufacturing expectations and sensitivity needs, to accommodate varying FOD depths effectively.

Frequency analysis shows that transducers with higher frequencies (7.5 MHz) yield improved FOD depth resolution, accurately localizing FOD peaks within margins below 0.8% compared to the lower frequencies. However, higher frequencies require significantly increased computational resources, making them less practical for routine investigations. A balanced frequency choice of 5 MHz was found acceptable for this research, offering efficient computational runtimes while maintaining accurate FOD detection within less than a 1% deviation compared to higher-frequency results.

The model's sensitivity to different FOD thicknesses was also investigated, highlighting its effectiveness in localizing FOD at sub-wavelength scales. Increasing FOD thickness from 0.06 mm to 0.12 mm shifted the pressure profile to earlier times, with measurable time intervals between reflected peaks similar in scale to the digitization frequency of many existing commercial ultrasonic systems.

4. Conclusions

In this study, a finite element model is presented to investigate ultrasonic wave propagation in carbon fiber reinforced polymer (CFRP) laminates containing foreign object debris (FOD). The purpose is to establish a novel fast and robust ultrasonic non-destructive

testing (NDT) method for FOD depth and size detection utilizing a single pulse from a transducer. It was found that a maximum element size of one-seventh of the acoustic wavelength was sufficient for stable simulations in the present study and features as thin as one-fourth the wavelength of the acoustic wave resulted in acoustic scatter. The presented method generates correlation plots for FOD size and depth with characteristic sizes smaller than 4 mm located at three different depths within the CFRP laminate. The results indicate a substantial increase in acoustic pressure amplitude as the FOD size increases from 0.5 mm to 1 mm. Specifically, the amplitude increases by 131% for a FOD located at a depth of 1.36 mm from the top surface, 200% for an FOD at a depth of 0.948 mm, and 525% for an FOD at a depth of 0.435 mm. A similar trend is observed for other incremental increases in FOD size across all three investigated depths. To confirm the simulation results in detecting the FOD depths, CFRP samples were fabricated in the laboratory and tested using an immersion tank ultrasonic NDT system. The simulation accurately predicted the depth of the FOD while also providing a clear visualization of the ultrasound wave behavior in both the fluid and solid domains. The study reveals that, when FOD diameters are smaller than the transducer converging area, the signal has a subtle shift in time in addition to the change in intensity.

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