Numerical Study of a Phased Array Based Ultrasonic Polar Scan to Determine Plane Wave Reflection Coefficients of Plates

Jannes Daemen, Arvid Martens, Mathias Kersemans, Erik Verboven, Steven Delrue, Wim Van Paepegem, Koen Van Den Abeele

Abstract—Numerical finite elements simulations and post-processing analysis methods are presented for Ultrasonic Polar Scan (UPS) measurements involving a Circular Phased Array (C-PA) to determine the plane wave reflection coefficient of plates. Apodization weights for the C-PA elements are determined in order to assure the generation of a quasi-plane wave upon excitation at the plate surface and to mitigate bounded beam effects on the assessed reflection coefficient. In addition, post-processing of the reflection signals is performed via the synthetic plane wave technique to further filter out any bounded beam effects. Reflection coefficients for three test cases are presented, namely for an aluminum, a unidirectional Carbon Epoxy and a cross-ply Carbon Epoxy plate. For all three cases, the comparison with analytical plane wave theory shows an excellent agreement with the reflection coefficients obtained by the C-PA and the additional post-processing steps for both pulsed and harmonic signals. It is also shown that the agreement becomes considerably worse if the non-specular reflection field is disregarded in the post-processing treatment, thus enforcing the need to capture the full reflected field via the Phased Array whenever plane wave reflection coefficients are needed.

Index Terms—Ultrasonic Polar Scan, Phased Array, Composite materials, Nondestructive testing, Finite Elements Analysis

I. INTRODUCTION

FIRST introduced in the 1980s, the Ultrasonic Polar Scan (UPS) has recently regained interest as a promising technique to both determine the viscoelastic properties [1], [2] and assess damage [3], [4], [5] in composite materials. A schematic representation of a UPS measurement can be seen in Fig. 1a. In practice, a predefined material spot is sequentially insonified from several oblique incidence angles $\Psi(\theta, \phi)$ by a broadband signal. After the emitted pulse activates the admissible waves within the plate, an appropriately positioned (i.e. above or below the plate) receiving transducer records the reflected or transmitted signal. The amplitude level, i.e. the maximal amplitude of the recorded time signals, or Time-of-Flight (TOF) can be extracted from these signals and visualized in polar plots. Fig. 1b shows an experimental transmission amplitude

polar plot for a 1.2 mm thick unidirectional carbon/epoxy laminate. Distinct, characteristic contours can be observed which offer a local fingerprint of the anisotropic stiffness properties of the material. Indeed, a particular C-tensor can be related to a specific set of Christoffel equations, which are essentially a set of eigenvalue problems and result in a unique set of phase velocities and polarizations related to multiple propagating waves. Using the partial wave technique, these solutions can be used to calculate the reflection or transmission coefficients, or the TOF [6], which can be fitted to the experimental data. Therefore, an inversion algorithm based on this theory has been developed to uniquely determine the elastic C-tensor of the material from the polar plot data [2], [7], [8]. Based on numerically simulated experiments, it was shown that the (visco-)elastic C-tensor of a carbon/epoxy plate could be found with relative errors of maximum 1.63% [7]. Similarly, based on experimental data, it was shown for a similar type of plate that a reliable estimation of the C-tensor can be found through this inversion algorithm [8]. As an alternative to using broadband (pulsed) excitation and considering UPS data in the bulk wave regime, the data can also be collected and analyzed in the harmonic regime, thereby focusing on Lamb wave excitation at different frequencies [9], [10]. This spectroscopic approach can provide meaningful insight into the frequency dependent damping behavior of plates.

Despite the excellent quality of the experimental data and the promising outcome of the inversion results, the UPS setup as illustrated in Fig. 1a is not convenient to be used in an industrial setting, and this involves several reasons. First, the 2D angular scanning over out-of-plane and in-plane angles of the emitting and receiving transducers is performed mechanically using a robotic arm, resulting in a relatively long measurement duration of approximately 15 minutes. Second, to ensure an adequate acoustic coupling between the test sample and the transducers, the setup must be immersed in a large water basin, severely limiting the applicability of the measurement technique. Third, transducers with a finite aperture create bounded beams as well as diffraction effects rather than plane waves. This implies that no pure bulk or Lamb modes can be excited and leads to a broadening of the contours observed in the polar plots [9]. In addition, when Lamb waves are excited, the reflected field is typically

Manuscript received March 20, 2019; accepted July 25, 2019

Support from the Fund for Scientific Research-Flanders (FWO Vlaanderen, grant G0B9515N, 1S45216N and 12T5418N), and the NVIDIA corporation is gratefully acknowledged.

J. Daemen, A. Martens, S. Delrue and K. Van Den Abeele are with the Department of Physics, KU Leuven Kulak, Belgium, e-mail: jannes.daemen@kuleuven.be.

M. Kersemans, E. Verboven and W. Van Paepegem are with the Department of Materials, Textiles and Chemical Engineering, Ghent University, Belgium.

Fig. 1. Conceptual image of the current UPS device (a). A couple of emitting and receiving transducers are employed to scan the plate at multiple incidence angles using rotational movements. An example of an experimental polar plot showing the maximum of the recorded time signals for a 1.2 mm thick unidirectional carbon/epoxy laminate is shown in (b). The measurement was performed in transmission mode using a broadband pulse with a center frequency $f_c = 4$ MHz.

Fig. 2. In contrast to the original UPS system shown in Fig. 1a, the phased array based UPS system uses a subset of emitting elements and collects the reflected pressure with the full array without having to deal with mechanical interventions.

composed of a direct or specular reflection, and a non-specular component which is due to a leakage of energy from the plate arising from internal reflections. If the latter component cannot be captured within the finite aperture of the transducers, this results in a loss of information.

To avoid the aforementioned limitations, the authors propose to replace the bulky, mechanical design by a Circular Phased Array (C-PA) consisting of small piezoelectric elements [11], [12], as shown in Fig. 2. The use of a Phased Array (PA) drastically reduces the dependence on mechanical movements and allows to control the pulse and its incidence angle electronically, resulting in faster measurement times in the order

of a few seconds, thereby relieving the first drawback of the present set-up. To address the acoustic coupling and create a portable device at the same time, the C-PA can be placed in dome-shaped structure which is filled with water. By using a rubber membrane at the bottom of the structure, the water can be kept within, similar to using a water bag to provide the acoustic coupling [13], and thus removing the immersion issues and drastically downscaling the system. The extended dimensions of a PA compared to a single element transducer also effectively increases the receiving aperture of the device. As such, the leaky field can be fully captured over its full length, as long as it is emitted in the same plane as the circular array. The circular arrangement of the PA is specifically chosen such that the same incident beam will be generated and directed to the same local material spot for any predetermined subset of neighboring elements, equal in number and using the same element dependent phase shifts and apodization weights [14], [15]. Moreover, a circular design allows for a larger range of incident angles compared to a linear arrangement. The C-PA design significantly improves the treatment and interpretation of the recorded data as a function of the incident angle and ensures the envisioned locality of the method. Furthermore, tailored apodization weights can be applied to the active elements both to reduce the presence of side lobes and to create a beam profile with a central constant phase, i.e. maximally resembling a plane wave. The incident beam created in that way will be referred to as a quasi-plane wave in the present article.

The aim of this paper is to validate the working principle of the proposed C-PA in view of future UPS measurements. To do so, FEM simulations have been performed in which the interaction of a pulse emitted by the C-PA with either isotropic aluminum or anisotropic carbon-epoxy laminates is modelled, and the angle-dependent plane wave reflection coefficients are

evaluated from the post-processing of the recorded signals at the individual array elements. The reflection coefficients will be analyzed and discussed for the case of pulsed as well as harmonic signals, and their relationship to the determination of the dispersion curves for characterizing the material will be reviewed.

II. SIMULATION MODEL AND DATA ANALYSIS

A. Simulation Model

Although several analytical platforms exist to simulate wave propagation by phased arrays (e.g. FOCUS [16], Field II [17], k-Wave [18], etc.), as well as theoretical formulations to calculate the angle-dependent reflection coefficients of fluid-loaded plates [7], [6], the present work is based on the 2D Finite Element Modelling (FEM) offered by COMSOL Multiphysics. The multiphysics framework of COMSOL has the advantage that the developed simulation procedure, which in this work relies on idealized phased array elements, can be more easily extended to treat the full piezoelectric interaction of the C-PA.

The simulation is performed in the frequency domain, and to keep the computational cost of the complete model as low as possible, the simulation is divided in several steps (I to V), allowing to partially omit the water domain enclosed by the C-PA. A schematic representation of the complete simulation model can be seen in Fig. 3. Via steps I and II the emitted beam profiles close to the plate are determined, while steps III to V simulate the interaction with the plate and the propagation of the reflected field towards C-PA elements. The five steps are discussed in more detail below. Step I considers a small water domain next to the active, emitting part of the C-PA, after choosing a certain incident angle θ_s . The domain is discretized by a triangular mesh with a maximal element size of $\lambda/6$, where λ is the wavelength, which offers an appropriate trade-off between accuracy and computation time to resolve the ultrasonic waves in the model [19]. The upper boundary in the model represents the C-PA and is subdivided in discrete pressure boundaries of 0.3 mm representing the active elements of the PA, while perfectly reflecting boundary conditions are set in between the elements. The other boundaries of the simulation domain are coupled to a Perfectly Matched Layer (PML) to reduce the effect of non-physical reflections. Via step I, the pressure field created by a subset of activated array elements is calculated within the domain. In step II, the values found on the lower boundary can be used in a Far Field calculation, based on the Helmholtz-Kirchoff equation (as implemented in COMSOL Multiphysics), to determine the pressure on an evaluation line near the plate's position. Note that for any incident angle, the field calculated in step I will not change, provided that the number of active array elements remains the same, and they are operated similarly. Thus, rather than computing this field for every incident angle, it is computationally equivalent to compute the field in the small water domain only once under normal incidence, and then to proceed through step II for every incident angle θ_s to evaluate the pressure on an evaluation line which is rotated by angle $-\theta_s$.

Fig. 3. Schematic representation of the simulation model which consists of five separate steps (I to V) to reduce the computational requirements. First the beam profile at incident angle θ_s is calculated through FEM and further propagated towards the plate via a Far Field calculation (I and II). In step III, the beam profile is used to calculate the pressure field right above the plate. Step IV simulates the interaction of the incident field with the plate and the resulting reflected pressure field, before propagating the field towards the C-PA elements in step V.

To treat the interaction of the incident beam with the plate (steps III and IV), three stacked rectangular domains are considered. In this stack, the upper layer represents the water filled coupling bag and the central layer the solid material to be studied. The medium of the lower layer depends on the specific plate loading condition in which the component or sample is inspected. In the present study, a second water domain is considered in order to more easily interpret the results in view of the experimental studies performed with the current setup. A mapped mesh is used with a maximal element size of $\lambda/6$, and the outer boundaries are coupled to PML layers above and below the water domains. In step III, the beam profiles computed in step II are used as pressure boundary conditions applied to the surface of the upper water domain. This way, the pressure field in the uppermost water layer can be calculated, without immediately taking into account the interaction with the plate. In step IV, the pressure boundary condition is removed and the field computed in step III is used as a pressure load which can interact with the plate such that the reflected field can be calculated. This sequential strategy is used to avoid additional reflections between the plate and the pressure boundary condition used in step III. Finally, in step V, the reflected field found in the water domain right above the plate is used in a Far Field calculation to propagate the reflected field found in step IV towards the array elements of the C-PA.

In order to get meaningful reflection coefficients, it is essential to compare the raw data to reference values. This can be simply achieved by repeating the previous procedure in which one omits the lower two layers and replaces them by a hard sound boundary wall at the bottom of the uppermost layer. As such a perfectly reflected field is found which serves as the reference.

Note that, despite the fact that actual UPS experiments employ short, broadband pulses, it was chosen to perform the FEM simulations in the frequency domain as transient simulations proved to be too time consuming. For all results in this paper, 371 different frequencies between 0 and 2 MHz

have been simulated for 151 incident angles ranging from 0° to 60° . Higher frequencies were not considered due to limited computational resources. Using a hardware setup with an Intel® Xenon® E5-2620 v4 processor (32 logical cores, clock speed of 2.1 GHz), a total available RAM of 132 GB, and heavily parallelizing the computations, the simulation time via the frequency domain approach is approximately 82 hours. In contrast, if a broadband pulse is simulated in the time domain, the simulation time increases to approximately 182 hours. The longer simulation time of the latter approach can mainly be attributed to the fact that all time steps have to be calculated using a mesh density which can resolve the highest frequency of the pulse. This leads to a higher RAM usage, and consequently a lower parallelization efficiency. Moreover, in order to perform the Far Field Calculations via the Helmholtz-Kirchoff integral, the transient result must be transformed to the frequency domain. It should also be noted that from the frequency domain results, any arbitrary broadband pulse with components up to 2 MHz can be reconstructed via an Inverse Fast Fourier Transform (IFFT), further justifying the use of the frequency domain approach compared to the transient simulations.

B. Creation of a Quasi-plane Beam Profile

To excite pure Lamb and bulk modes, defined by single plane wave interactions, it is necessary to eliminate the bounded beam contributions as much as possible. A first important step in this regard is the creation of a quasi-plane wave for which the phase remains more or less constant over a predefined region around the beam center, and for which the side lobe amplitudes are significantly diminished.

Using the elements in the C-PA, a roughly constant phase for the generated beam profile at the location of the plate can be achieved by applying the following relative phase shifts:

$$\Delta\varphi_{j,1} = \frac{2\pi R(1 - \cos \tilde{\theta}_j)}{\lambda} \quad (1)$$

where R is the radius of the circular phased array and $\tilde{\theta}_j$ the angular position of the j th element with respect to the central element, as indicated on Fig. 3. The phase shifts ensure that the array elements operate as if they are located on a straight line. In order to reduce side lobes in the beam profile, it is common practice to use apodization windows [15]. However, by introducing intensity differences between the emitted elements, their respective phase contributions to the final profile will also alter, potentially nullifying the efforts made via the phase shifts of (1). In the present study, an optimization of the apodization weights has been performed while conforming the constant phase in the center. To do so, the beam profile under normal incidence is considered in the spatial Fourier space, or k -space, rather than in real space, and optimized by increasing the amplitude of the k -vector components for which $k_x = 0$ while lowering the amplitude if $k_x \neq 0$. This will establish beam profiles with a central lobe in k -space which is both as small as possible and has an increased amplitude, ensuring that plane wave characteristics are favored as a plane wave is defined by a single k -vector.

Fig. 4. Plot showing the element-specific apodization weights as calculated by the optimization procedure. The red line corresponds the Hanning apodization window with the same number of active elements.

Simultaneously the amplitudes of the side lobes in k -space will be decreased, which directly impacts the amplitude of the side lobes in real space as these are directed towards nonzero incidence angles, and hence represented by nonzero k_x values. To further enforce that a constant phase is found in a specified region around the central beam axis, the mean phase, shifted to be centered around zero, is evaluated and taken into account during the optimization.

In practice, the optimization of the quasi-plane beam to be used in the Finite Element model is performed as follows. First, steps I to III of the model presented in Fig. 3 are reused to generate the individual beam profiles of each of the activated array elements at the location of the plate. These profiles are saved and used in the particle swarm optimizer provided by Matlab. Every particle in the swarm represents a vector of apodization weights $\vec{A}$ and is multiplied by the corresponding single element beam profiles. Next, the addition of all weighted profiles together yields a single beam profile which results from the complete set of apodized array elements in the C-PA. This profile is then evaluated by the following fitness function which has to be minimized:

$$f(\vec{A}, l) = a \left(\int_{k_x=-|\vec{k}|}^{k_x=|\vec{k}|} \bar{Y}(\vec{A}, k_x) dk_x - \bar{Y}(\vec{A}, k_x = 0) \right) + \langle |\varphi(\vec{A}, l)| \rangle \quad (2)$$

where $\bar{Y}(\vec{A}, k_x)$ is the amplitude of the beam in k -space as a function of k_x and of the apodization weight vector $\vec{A}$, whereas $\varphi(\vec{A}, l)$ is the phase in real space where l defines the range $x \in [-l, l]$ for which the phase should be constant. The first two terms in the fitness function (between brackets) promote a strong main component while discouraging the presence of other components related to the side lobes. The second term in the function evaluates the mean phase difference (relative to the beam center) within a fixed interval to additionally enforce a constant phase in this region. a is a scaling factor that can

Fig. 5. Plots (a) and (b) show the effect of the different optimization steps with respect to the amplitude and the phase respectively. It is clear that the with the last step included, the best result is achieved, even though a reasonable approximation can be achieved by using a simple Hanning window.

Fig. 6. Plots of the excitation signal used for the simulation in the time domain (a) and in the frequency domain (b). During the simulation only frequency components up to 2 MHz were considered to reduce the computation time, while retaining a good representation of the incident pulse.

be chosen by the user to weigh the importance of the first set of terms with respect to the last one.

Even though only frequencies below 2 MHz are considered in this work, the final design of the C-PA is envisioned to operate up to 5 MHz. Therefore a C-PA is considered with an element width of 0.3 mm and a pitch of 0.35 mm to create the incident beams. In order to create plane waves, it may seem beneficial to use as many C-PA elements as possible, creating a large emitting aperture. Additionally, using apodization functions, this better limits the influence of side lobes in the beam pattern. However, three important issues arise when a large aperture is used. First, due to the fact that a curved array is used, elements located far from the center of the beam introduce noise to the signal due to their directivity, rather than be beneficial to the construction of the plane wave. Second, even though the result should resemble a plane wave,

the beam still has to be reasonably localized in space to ensure the locality of the method, limiting the appropriate aperture size. Third, a large aperture limits the angular range of the incident angle, which is determined by the position of the central C-PA element. Indeed, there may not be enough array elements available to guarantee a beam which is exactly the same for all incident angles. Taking into account these issues, it is found that the use of 119 elements, corresponding to an emitting aperture 41.6 mm provides a good compromise.

Following the optimization procedure, using the Hanning apodization profile as an initial guess for $\bar{A}$, and setting a and l to 50 and 10 mm respectively, an optimal beam with a center frequency f_c of 1 MHz can be created if the apodization weights as seen in Fig. 4 are used. These weights follow a non-trivial pattern resembling a Hanning apodization window, indicated in red, for which several weights are significantly

decreased in value, most notably near the center elements. Fig. 5a and 5b show the absolute amplitude and phase of the resulting beam profile at the location of the plate. As expected, the non-optimized result shows a focused beam pattern which is due to the circular arrangement of the array elements. Using appropriate phases improves the phase profile, but results in a beam which does not have a well-defined central lobe. Once the apodization window is optimized, a Gaussian-like beam pattern with greatly reduced sidelobe levels is found with a nearly constant phase near the center of the beam. This result can also be compared to the beam created by using a Hanning apodization. Whereas the amplitude of the beam remains roughly the same, differences can be observed in the phase profile. Even though, the use of a Hanning apodization leads to a reasonably flat central phase, it is clear that improvements can still be achieved by optimizing the apodization weights further as described.

Once the beam profile is optimized, the multiple-step simulation model as discussed earlier can be used to propagate the incident beam, to predict the reflected beam after interaction with the plate, and to find the complex pressure values at the location of the array elements.

C. Post-processing of the Data

To further enhance results that resemble true plane wave behavior, the synthetic plane wave technique, first introduced in transmission experiments [20], [21] and later adapted for the reflection regime [22], can be used. The idea of this technique for a linear phased array is to simply add up all time signals measured by the individual receiving elements, effectively using the full aperture of the array. Based on the principle of reciprocity of ultrasonic waves, bounded beam effects can then be filtered out and plane wave behavior can be retrieved [22]. Note that this principle holds in the frequency domain due to the linearity of (inverse) Fourier Transforms. In the case of a curved array, however, this strategy cannot be used straightforwardly as this would lead to a focused beam. Similar to the use of phase shifts in the creation of the incident beam, phase shifts need to be applied to the raw data such that a planar configuration can be approximated. Therefore, (1) can be reused, with $\tilde{\theta}_j$ now being the angular position of the j th receiving element with respect to the center of the specularly reflected beam. Once the raw data for each receiving element are properly phase shifted, they are multiplied by the frequency content of a typical excitation pulse used in UPS experiments of which an example is shown in Fig. 6a and 6b. As such, after applying an Inverse Fourier Transform, signals representative for a real experiment would be found. However, for the current study it is adequate to remain in the frequency domain and analyze the data in this manner.

Based on the frequency domain data, the bulk wave reflection coefficient is calculated by considering the energy content of the signal and dividing it by the energy content of the reference, i.e.

$$R_{bulk}(\theta_s, \phi_s) = \frac{\int |R_{meas}(fd, \theta_s, \phi_s)|^2 d(fd)}{\int |R_{ref}(fd, \theta_s, \phi_s)|^2 d(fd)}, \quad (3)$$

Fig. 7. Figure comparing the bulk wave reflection coefficients of a 3 mm thick aluminum plate for the full-size synthetic plane wave technique, a subset in which only the specular reflection is considered and the analytical plane wave results.

where f and d are the frequency and thickness of the solid plate respectively, and θ_s and ϕ_s represent the incident azimuthal and polar angles, respectively. Alternatively, the harmonic reflection coefficient can be calculated directly by omitting the integral in (3) and treating a single fd slice:

$$R_{harm}(fd, \theta_s, \phi_s) = \frac{R_{meas}(fd, \theta_s, \phi_s)}{R_{ref}(fd, \theta_s, \phi_s)}. \quad (4)$$

In this case, the reflection coefficients for all frequencies and incident angles θ_s can be considered together to produce $fd-\theta_s$ reflection landscapes.

III. RESULTS AND DISCUSSION

To assess the quality of the data measured by the proposed C-PA UPS system, three different plates with a thickness of 3 mm have been simulated and the obtained results have further been post-processed. The first case considers an aluminum plate, characterized by a Young's modulus $E = 70$ GPa and a shear modulus $G = 26$ GPa, and provides a first simple test case to check the validity of the simulation procedure due to its isotropic material structure and the extensive knowledge available about its dispersion curves [23]. The second case deals with a unidirectional carbon epoxy plate, characterized by the complex stiffness tensor given in Table I. As this material is anisotropic, the reflective behavior will depend on the polar angle ϕ_s . Here, only two values of ϕ_s are considered, namely 0° and 90° which are the directions parallel and perpendicular to the fiber orientations respectively. Insonification along other incident polar angles will generally lead to non-specular contributions which are skewed in out-of-plane directions and cannot be covered by the 2D model [6]. The third case again considers a carbon epoxy plate, but this time in a cross-ply configuration with a symmetric layup $[0_2 90_2]_{2S}$. In this case, the model of Fig. 3 is slightly adapted to properly accommodate this type of layered system by dividing the plate in n horizontally aligned subdomains of the same thickness,

Fig. 8. $fd - \theta_s$ landscape of the reflection coefficient based on the full-size synthetic plane wave procedure using data from the C-PA UPS (a). The black stars correspond to the theoretically predicted Lamb wave dispersion curves. (b) shows the absolute difference of the results shown in (a) with the theoretical plane wave reflection results. (c) and (d) reconsider the $fd - \theta_s$ landscape and its difference with theory for the case when only the information in the specular field is considered in the post-processing procedure.

where n is the number of lamina in the cross-ply configuration, namely 16. The partitioning of the plate in multiple layers requires a higher meshing density to accurately resolve the physics in the model, leading to significantly longer simulation times. For this reason, the discussion of the results concerning this type of laminate is restricted to a polar angle $\phi_s = 90^\circ$. As mentioned before, frequencies ranging between 0 and 2 MHz are considered such that a broadband incident pulse with a center frequency $f_c = 1$ MHz can be simulated.

All case studies will be discussed following a similar structure. First, confirm the treatment of the measured data in the current UPS setup, the results will be assessed for a pulsed signal by looking at the bulk wave reflection coefficient. Next, the same data will be reconsidered in the frequency domain to analyze the harmonic reflection coefficient of the plates by looking at the characteristic $fd - \theta_s$ landscapes and by studying specific frequency slices in more detail. Both analysis strategies, further referred to as the synthetic plane wave results, will be compared to the theoretical plane wave reflection coefficients, which can be calculated through the

plane wave theory provided by Nayfeh [6] and (3) and (4). Additionally, the effect of omitting essential information stored in the non-specular field will be discussed by limiting the number of receiving elements such that only the reflected field is recorded where the specular contribution is expected to be found.

A. Case Study I: Aluminum

Fig. 7 shows the bulk wave reflection coefficient $R_{bulk}(\theta_s, \phi_s = 0^\circ)$ as calculated by (3) using (i) the synthetic plane wave procedure considering the full array information, (ii) the synthetic plane wave procedure limited to only the specular reflection data, and (iii) the theoretical plane wave result. The reflection coefficient based on the full-size synthetic plane wave results is found to be in excellent agreement with the theoretical result. Once the data contained in the non-specular field is disregarded, the overall shape of $R_{bulk}(\theta_s, \phi_s = 0^\circ)$ curve is maintained, albeit with a decreased absolute value, especially at low angles. This decrease suggests that the non-specular field is much more prominent

TABLE I
VISCOELASTIC PARAMETERS OF THE UNIDIRECTIONAL CARBON EPOXY LAYERS USED IN THIS STUDY. THE C -TENSOR IS IN GENERAL COMPLEX AND DENOTED AS $C_{ij} = \mathcal{R}(C_{ij}) - i\mathcal{I}(C_{ij})$, WHERE i IS THE COMPLEX NUMBER.

	Viscoelastic Parameters (GPa)								
	C_{11}	C_{12}	C_{13}	C_{22}	C_{23}	C_{33}	C_{44}	C_{55}	C_{66}
$\mathcal{R}(C)$	122.73	6.5664	6.5664	13.465	6.5542	13.465	3.3980	5.8600	6.2500
$\mathcal{I}(C)$	8.5909	0.4596	0.4596	0.9426	0.4588	0.9426	0.2379	0.4102	0.4375

Fig. 9. The bulk reflection coefficients for Carbon Epoxy characterized by the C -tensor represented in Table 1. The incident polar angles were $\phi_s = 0^\circ$ (a) and $\phi_s = 90^\circ$ (b).

at lower incident angles and shows the importance of the large receiving aperture.

Fig. 8a displays the $fd - \theta_s$ landscapes as calculated by (4). A smooth landscape is found with distinct minima which are in excellent agreement with the expected dispersion curves of aluminum, revealing the conditions for efficient lamb mode stimulation within the plate [6]. Fig. 8b shows the absolute difference between the synthetic plane wave results and the theoretically expected results, based on plane wave theory. There is a good agreement between the results, with absolute errors that do not exceed 0.005 for most regions in the landscape. It should be remarked that the errors become larger in three instances. First, below fd values of 1 MHz.mm, the absolute error increases drastically, up to 0.25, which may be related to the fact that for those frequencies the wavelength becomes much larger than both the thickness of the plate and the dimensions of the array. Second, the error increases slightly, up to 0.03 in the vicinity of the minima, which is related to high gradients near these minima. These gradients cannot be fully resolved by the FE model due to the chosen mesh density, but it was checked that these errors decrease if a denser mesh is used, suggesting that these type of discrepancies are numerical in nature. Third, strong oscillations appear around the S_0 mode, and to a lesser extent also around the A_1 mode at lower fd values. These oscillations can be attributed to a loss of information contained in the non-specular field. Indeed, due to the long wavelengths involved, the effective travel distance of the wave inside the plate becomes longer than the radius

of the used array. Consequently, the non-specular field cannot be fully captured and the efficacy of the synthetic plane wave technique breaks down. Therefore, it is advisable to design the diameter of the C-PA in function of the fd bands of interest. Fig. 8c and 8d show the $fd - \theta_s$ landscape and its difference with the theoretical plane wave results, respectively, calculated when only the data in the specular reflection field is considered in the post-processing steps. Comparing Fig. 8a and 8c reveals no clear influence on the location of the minima, and thus on their predictive strength to find the dispersion curves of aluminum, even though the valleys appear to have broadened slightly. However, when comparing Fig. 8b and 8d, it becomes clear that even though the absolute error remains low in regions far from the valleys, the errors near the minima increase considerably. This means that the valleys have become much more shallow and that the loss of the information contained in the non-specular field results in an incorrect estimation of the reflection coefficients. Notably, the oscillations seen in Fig. 8a and 8b are smoothed out if the non-specular field is omitted, further reinforcing that this issue is related to this particular part of the reflected field.

B. Case Study II: Unidirectional Carbon Epoxy

Fig. 9a and 9b show the $R_{bulk}(\theta_s, \phi_s)$ curves for the polar angles $\phi_s = 0^\circ$ and $\phi_s = 90^\circ$ respectively and it can be seen that the agreement between the full-size synthetic plane wave result and plane wave theory is excellent. Compared to the specular reflection data, it is clear that the effect of omitting the

Fig. 10. $fd - \theta_s$ landscapes of the reflection coefficient for Carbon Epoxy characterized by the C -tensor represented in Table I for an incident polar angle $\phi_s = 0^\circ$. (a) and (c) show the landscapes for respectively the full-size synthetic plane wave procedure and the results when only the specular field is considered in the post-processing procedure. The black dots indicate the theoretically expected dispersion curves under fluid loading. These results can be compared to the theoretical plane wave reflection results by considering the absolute error (b & d).

information of the non-specular field is considerably smaller than in the aluminum case. This can be attributed to the fact that the density of the composite material ($\rho = 1528 \text{ kg/m}^3$) is relatively low such that heavy water loading is experienced by the plate. As a result, the beam-plate interaction bears a high energy leakage and a small displacement of the leaky field along the water-solid interface with respect to the specular field [6]. Consequently, it is more difficult to separate the specular and non-specular contributions, and thus less information contained in the non-specular field is lost if the effective receiving aperture is limited to the area where the specular field is expected to be found. However, as can be seen on the figures, there are still some specific incident angles where the displacement of the non-specular field becomes considerable. For these angles the use of all receiving elements remains very important to retrieve plane wave results.

Fig. 10a shows the $fd - \theta_s$ landscape for $\phi_s = 0^\circ$. The multiple sharp minima observed around 7.5° account for the presence of a strong non-specular component which was also apparent in the discussion of Fig. 9a. At angles below 20°

and below $fd = 2 \text{ MHz.mm}$, there is some evidence of oscillations in the results which is again due to the inability to fully reconstruct the plane wave behavior, similar as in the aluminum case. In contrast to the results of the aluminum plate, the observed minima in the reflection coefficient do no longer exhibit a one-to-one correspondence with the predicted dispersion curves. This discrepancy is again due to the heavy water loading of the plate, which furthermore implies that the true Lamb modes are associated with wave vectors with considerable imaginary parts. However, during the simulation – and this would also be the case during a real-life experiment with this type of device – real wave vectors are used for which minima in the reflection spectrum can still be found, leading to a mismatch between these minima and the theoretical dispersion curves [6], [23], [24], [25]. Fig. 10b shows the absolute error with respect to the theoretical plane wave result. Overall, it is clear that there is a good agreement between the synthetic plane wave approach and the analytical results, with errors that do not exceed 0.03 except in specific areas. For instance, the errors are higher for low fd values around

Fig. 11. $fd - \theta_s$ landscapes of the reflection coefficient for Carbon Epoxy characterized by the C -tensor represented in Table I for an incident polar angle $\phi_s = 90^\circ$. (a) and (c) show the landscapes for respectively the full-size synthetic plane wave procedure and the results when only the specular field is considered in the post-processing procedure. The black dots indicate the theoretically expected dispersion curves under fluid loading. These results can be compared to the theoretical plane wave reflection results by considering the absolute error (b & d).

Fig. 12. The bulk reflection coefficient of a $[0_2 90_2]_{2S}$ C/E laminate for which each layer is characterized by the C -tensor represented in Table I. The incident polar angle is $\phi_s = 90^\circ$.

7.5° , evidently due to the oscillatory behavior linked to the finite dimensions of the array. Similar as in case I, the error is also higher near strong gradients as a function of the angle, which is merely a numerical artefact. Fig. 10c and 10d allow to assess the importance of including the non-specular field in the synthetic plane wave treatment. These figures respectively show the $fd - \theta_s$ landscape for the specular field only and its difference with plane wave theory, and should be compared with Fig. 10a and 10b. Once again, the main characteristics of the landscape remain mostly the same, but the error with respect to the analytical result increases, especially around the multiple minima at $\theta_s = 7.5^\circ$. The latter suggests that an inclusion of the non-specular field in the data treatment is preferred as it is not always easy to predict the spatial extent of the non-specular field.

Fig. 11a to 11d show the $fd - \theta_s$ landscapes (a & c), together with their absolute errors with respect to plane wave theory (b & d), for an incident polar angle of $\phi_s = 90^\circ$. Similar as before, it is clear that while the minima in the landscape might give a rough indication of the location of the dispersion

Fig. 13. $fd - \theta_s$ landscapes of the reflection coefficient for a cross-ply C/E laminate with a symmetric $[0_2 90_2]_{2S}$ structure, calculated for an incident polar angle $\phi_s = 90^\circ$. Each layer is characterized by the C -tensor represented in Table I. (a) and (c) respectively display the landscapes for the full-size synthetic plane wave procedure and the results when only the specular field is considered during post-processing. The black dots represent the theoretically expected dispersion curves under fluid loading. These results can be compared to the theoretical plane wave reflection results by considering the absolute error (b & d).

curves, a direct one-to-one correspondence is not valid. There is an excellent agreement between the full-size synthetic plane wave and theoretical results with an error that does not exceed 0.03, except for the lowest fd values. Using only the specular data in the post-processing step does not significantly alter the overall appearance of the landscape and the location of its minima, but the errors with respect to the analytical result do increase slightly to values ranging between 0.05 and 0.1. While this is only a slight increase, it again confirms the fact that essential information is contained in the non-specular field which is needed to accurately reconstruct the reflection coefficients. Hence, its contribution should not be neglected to accurately reconstruct the properties of the material.

C. Case Study III: Carbon Epoxy Cross-ply Plate

In case of cross-ply laminates, part of the incident pulse entering the plate may not reach the backside of plate as the multi-layered structure constitutes interfaces from which the incident pulse partially reflects. This leads to more complex reflection signals, which additionally may contain progres-

sively less information about the deeper lying layers. This increased level of complexity warrants an investigation as to whether or not the simulation model and the reconstruction of the plane wave behavior still holds. Fig. 12 shows the calculated bulk reflection coefficient. Once again, we observe an excellent agreement between the full-size synthetic and analytical plane wave results, validating the plane wave reconstruction procedure for laminates. If only the specular field is taken into account, some discrepancies are apparent between approximately 7° and 25° , suggesting that capturing the full reflected field remains important to ensure an accurate extraction of the material properties. Fig. 13a shows the $fd - \theta_s$ reflection coefficient landscapes based on the full-size synthetic plane wave approach for the $[0_2 90_2]_{2S}$ C/E plate. Similar as before, multiple minima can be observed in the landscape. In this case of a cross-ply plate, they appear more complex as can be observed from the multiple intersections between the valleys. Again, these minima provide a rough first indication of the location of the dispersion curves, but they cannot be regarded as accurate predictors. Indeed, at certain

angles some dispersion curves deviate slightly from the valleys in the landscape, while in other regions they do not correspond to minima at all. Nevertheless, the increased complexity of the system does not impact the quality of the simulation and post-processing procedure as can be seen in the difference plot in Fig. 13b. Overall, the absolute error does not exceed 0.02, except at low frequencies where oscillations similar to those observed in the previous results appear. Interestingly, the strong gradients near the minima do not lead to higher errors as was the case in the previous results. This is due to the fact that a higher meshing density was employed to fully resolve the physics in the individual layers. This adaptation also resolves the numerical errors observed in the previous results. Fig. 13c shows the $fd - \theta_s$ landscape once the non-specular field is omitted, and Fig. 13d its error with respect to the analytical result. Equivalent to the conclusions for the previous cases, the omission of the data does not impact the general features of the landscape. Again, due to the fact that the minima become more shallow, the error increases significantly. Thus, even though the energy might penetrate less deep into the laminate due to various multiple reflections, the non-specular field still contains a significant amount of information, which requires to be treated properly in order to find accurate reflection coefficients.

IV. CONCLUSION

This paper presented a novel UPS device based on a circular phased array as a portable alternative to the current bulky measurement setup. Such a device guarantees that the same beam can be emitted at various incident angles, covering a broad angular range. Via numerical experiments it has been shown that it is possible to create a quasi-plane wave profile at the surface of the plate by choosing a proper set of phase shifts for each individual array element and by optimizing their apodization weights via a Particle Swarm optimization scheme. Via Finite Element Modelling the bulk wave and harmonic reflection coefficients for both isotropic aluminum and anisotropic (cross-ply) carbon epoxy plates have been calculated. However, to attain good results, the acquired data had to be post-processed via the synthetic plane wave technique to treat the full reflected field. The found reflection coefficients were in excellent agreement with plane wave theory for all three cases except in certain regions of the $fd - \theta_s$ landscape. These deviations were mostly numerical in nature, except for low fd values near specific Lamb modes. These deviations were found to be due to a loss of information as the reflected field was partially emitted out of the boundaries of the array, indicating that a proper choice of array size and used frequency range is mandatory to attain reliable results, without significantly impacting the envisioned portability of the system. It was also shown that once the receiving aperture was limited to the specular reflection region, the observed minima became more shallow and the overall error in both the $fd - \theta_s$ landscapes and the bulk wave reflection coefficient increased. This shows the need to capture the full reflected field such that the information in the non-specular field is not dismissed, especially if little information is known about the sample under study.

REFERENCES

- [1] M. Van Dreumel, "Nondestructive composite laminate characterization by means of ultrasonic polar-scan," *Materials Evaluation*, vol. 39, pp. 922–925, 1981.
- [2] M. Kersemans, A. Martens, J. Degrieck, K. Van Den Abeele, S. Delrue, L. Pyl, F. Zastavnik, H. Sol, and W. Van Paepegem, "The Ultrasonic Polar Scan for Composite Characterization and Damage Assessment: Past, Present and Future," *Applied Sciences*, vol. 6, no. 2, p. 58, Feb. 2016.
- [3] M. Kersemans, I. De Baere, J. Degrieck, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, and W. Van Paepegem, "Nondestructive damage assessment in fiber reinforced composites with the pulsed ultrasonic polar scan," *Polymer Testing*, vol. 34, pp. 85–96, Apr. 2014.
- [4] M. Kersemans, A. Martens, K. Van Den Abeele, J. Degrieck, F. Zastavnik, L. Pyl, H. Sol, and W. V. Paepegem, "Detection and Localization of Delaminations in Thin Carbon Fiber Reinforced Composites with the Ultrasonic Polar Scan," *Journal of Nondestructive Evaluation*, vol. 33, no. 4, pp. 522–534, Jul. 2014.
- [5] M. Kersemans, I. D. Baere, J. Degrieck, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, and W. V. Paepegem, "Damage Signature of Fatigued Fabric Reinforced Plastics in the Pulsed Ultrasonic Polar Scan," *Experimental Mechanics*, vol. 54, no. 8, pp. 1467–1477, Oct. 2014.
- [6] A. H. Nayfeh, *Wave Propagation in Layered Anisotropic Media: with Application to Composites*. Elsevier, 1995, pp. 153–201.
- [7] A. Martens, M. Kersemans, J. Daemen, E. Verboven, W. Van Paepegem, J. Degrieck, S. Delrue, and K. Van Den Abeele, "Numerical study of the Time-of-Flight Pulsed Ultrasonic Polar Scan for the determination of the full elasticity tensor of orthotropic plates," *Composite Structures*, vol. 180, pp. 29–40, Nov. 2017.
- [8] M. Kersemans, A. Martens, N. Lammens, K. Van Den Abeele, J. Degrieck, F. Zastavnik, L. Pyl, H. Sol, and W. V. Paepegem, "Identification of the Elastic Properties of Isotropic and Orthotropic Thin-Plate Materials with the Pulsed Ultrasonic Polar Scan," *Experimental Mechanics*, vol. 54, no. 6, pp. 1121–1132, Jul. 2014.
- [9] M. Kersemans, W. Van Paepegem, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, and J. Degrieck, "Pitfalls in the experimental recording of ultrasonic (backscatter) polar scans for material characterization," *Ultrasonics*, vol. 54, no. 6, pp. 1509–1521, Aug. 2014.
- [10] E. Verboven, M. Kersemans, A. Martens, J. Daemen, S. Delrue, K. Van Den Abeele, and W. Van Paepegem, "Matching spectroscopy with the ultrasonic polar scan for advanced ndt of composites," in *Proceedings of the 18th International Conference on Experimental Mechanics*, vol. 2, no. 8. MDPI AG, 2018. [Online]. Available: <http://dx.doi.org/10.3390/icem18-05458>
- [11] B. W. Drinkwater and P. D. Wilcox, "Ultrasonic arrays for non-destructive evaluation: A review," *NDT & E International*, vol. 39, no. 7, pp. 525–541, Oct. 2006.
- [12] C. Holmes, B. W. Drinkwater, and P. D. Wilcox, "Post-processing of the full matrix of ultrasonic transmit–receive array data for non-destructive evaluation," *NDT & E International*, vol. 38, no. 8, pp. 701–711, Dec. 2005.
- [13] R. Long, J. Russell, and P. Cawley, "Non-destructive inspection of components with irregular surfaces using a conformable ultrasonic phased array," 2007, pp. 1–9.
- [14] S.-C. Wooh and Y. Shi, "Influence of phased array element size on beam steering behavior," *Ultrasonics*, vol. 36, no. 6, pp. 737–749, Apr. 1998.
- [15] L. W. Schmerr Jr., *Fundamentals of Ultrasonic Phased Arrays*. Springer, Aug. 2014.
- [16] R. J. McGough, "Rapid calculations of time-harmonic nearfield pressures produced by rectangular pistons," *The Journal of the Acoustical Society of America*, vol. 115, no. 5, pp. 1934–1941, May 2004.
- [17] J. A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 2, pp. 262–267, Mar. 1992.
- [18] B. E. Treeby, J. Jaros, D. Rohrbach, and B. T. Cox, "Modelling elastic wave propagation using the k-Wave MATLAB Toolbox," in *2014 IEEE International Ultrasonics Symposium*, Sep. 2014, pp. 146–149.
- [19] "COMSOL Multiphysics v5.3., Acoustics User Guide," Stockholm, Sweden.
- [20] B. Hosten and M. Castaings, "Transfer matrix of multilayered absorbing and anisotropic media. Measurements and simulations of ultrasonic wave propagation through composite materials," *The Journal of the Acoustical Society of America*, vol. 94, no. 3, pp. 1488–1495, Sep. 1993.

- [21] A. Safaeinili, O. I. Lobkis, and D. E. Chimenti, "Quantitative materials characterization using air-coupled leaky Lamb waves," *Ultrasonics*, vol. 34, no. 2, pp. 393–396, Jun. 1996.
- [22] J. Jocker and D. Smeulders, "Minimization of finite beam effects in the determination of reflection and transmission coefficients of an elastic layer," *Ultrasonics*, vol. 46, no. 1, pp. 42–50, Mar. 2007.
- [23] D. E. Chimenti and S. I. Rokhlin, "Relationship between leaky Lamb modes and reflection coefficient zeroes for a fluid-coupled elastic layer," *The Journal of the Acoustical Society of America*, vol. 88, no. 3, pp. 1603–1611, Sep. 1990.
- [24] S. I. Rokhlin, D. E. Chimenti, and A. H. Nayfeh, "On the topology of the complex wave spectrum in a fluid-coupled elastic layer," *The Journal of the Acoustical Society of America*, vol. 85, no. 3, pp. 1074–1080, Mar. 1989.
- [25] A. H. Nayfeh and D. E. Chimenti, "Propagation of guided waves in fluid-coupled plates of fiber-reinforced composite," *The Journal of the Acoustical Society of America*, vol. 83, no. 5, pp. 1736–1743, May 1988.

Jannes Daemen was born in Kortrijk, Belgium, in 1993. He received the M.Sc. degree in Nuclear Physics from KU Leuven, Leuven, Belgium, in 2016. He is currently active as a Ph.D. student in the Wave Propagation and Signal Processing research group at KU Leuven Campus Kulak. His Ph.D. research focuses on the development of a phased array system to be used for the Ultrasonic Polar Scan, a non-destructive measurement tool to characterize composite materials.

Arvid Martens was born in Ronse, Belgium, in 1992. He received the M.Sc. degree in Soft Matter Physics from KU Leuven, Leuven, Belgium, in 2015. He is currently active as a Ph.D. student in the Wave Propagation and Signal Processing research group at KU Leuven Campus Kulak, for which received an FWO-SB research grant. During his PhD research he was also awarded an FWO travel grant and an Nvidia Seeding grant. His Ph.D. research focuses on the inverse characterization of anisotropic viscoelastic materials by means of the Ultrasonic

Polar Scan, a novel non-destructive measurement tool.

Mathias Kersemans was born in 1982 in Lommel, Belgium. He has an Engineering degree in Electromechanics and in Physics. In 2014, he obtained a PhD in Applied Physics on the subject 'Ultrasonic inspection of fiber reinforced polymers'. Currently he is Professor at Ghent University, and is leading the research on non-destructive testing and evaluation of materials. His research team focuses on the development of novel inspection approaches, which includes the use of ultrasound, guided waves, active thermography, vibrometry and luminescence.

Erik Verboven was born in 1988 in Diest, Belgium. He studied Physics at KU Leuven and obtained a M.Sc. degree in 2011 and a PhD degree in 2017. The focus of his PhD research was a numerical and experimental study into the potential of using ultrasonic contrast agents for dosimetry in radiotherapy. Currently he is a postdoctoral researcher at the Department of Materials, Textiles and Chemical Engineering at Ghent University working on novel ultrasonic inspection techniques for non-destructive testing of materials.

Steven Delrue was born in Kortrijk, Belgium, in 1985. He received the M.Sc. degree in mathematics from KU Leuven, Belgium, in 2007, and the Ph.D. degree in mathematical physics and applied mathematics from KU Leuven Campus Kulak, Kortrijk, Belgium, in 2011. His Ph.D. research focused on the development of numerical models to support and optimize experimental techniques for ultrasonic non-destructive testing. Since 2011, he worked as a postdoctoral lecturer in the Wave Propagation and Signal Processing research group at KU Leuven Campus Kulak, Kortrijk, Belgium. His current research interests include the numerical modelling of contact defects and their interaction with ultrasonic waves, nonlinear signal processing techniques, ultrasonic thermography, and ultrasonic imaging using phased arrays.

Wim Van Paeppegem was born in Ninove, Belgium, in 1975. He received his MSc. degree in Civil Engineering from Ghent University, Belgium in 1998. In 2002, he obtained a PhD on the subject of fatigue modelling of fibre-reinforced composites. Currently he is full professor and head of the research group Mechanics of Materials and Structures at Ghent University. His research area is focussed on experimental and computational mechanics of fibre-reinforced composites, polymers and additively manufactured materials. He is member of the Editorial Board of the journals *Composites Science and Technology* and *Polymer Testing*. He also received 5 personal awards for his scientific achievements.

Koen Van Den Abeele was born in 1965, in Lokeren, Belgium. He has a M.Sc. degree in applied mathematics from KU Leuven, Belgium, in 1987, and obtained a Ph.D. degree in mathematical physics and applied mathematics from KU Leuven, in 1992 on the subject "Alternative Fundamental Theoretical Descriptions for Acousto-optic and Acoustic Investigation of Pulsed and Profiled Ultrasound in View of Nondestructive Testing of Layered Structures". Currently he is Full Professor at the KU Leuven, head of the Wave Propagation and Signal Processing research group at KU Leuven Campus Kulak, Kortrijk, Belgium, and chair of the group Science Engineering and Technology at KU Leuven Campus Kulak, Kortrijk, Belgium. His research team focuses on theoretical modeling and experimental verification of linear and nonlinear wave propagation phenomena in liquid and solid media, and its application to non-destructive evaluation (NDE), damage detection, quality control in industrial materials, monitoring of bio(techno)logical processes, and ultrasound based dosimetry.