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3D SIMULATIONS OF A PHASED ARRAY BASED ULTRASONIC POLAR SCAN SYSTEM

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ABSTRACT

The Ultrasonic Polar Scan (UPS) is a novel method to determine the viscoelastic properties of materials by insonifying a single material spot from various incidence angles $\Psi(\theta, \phi)$ *and analyzing the reflected or transmitted response. In order to create a portable UPS device, it is investigated whether a cylindrically focused transducer can be employed to activate many incident angles* θ *at once, together with a Circular Phased Array (C-PA) to capture the reflected field. A numerical model which is based on the decomposition of harmonic ultrasonic fields into its plane wave components is used together with an analytical model treating the plane wave-plate interaction in 3D. Afterwards, the complete reflected field can be reconstructed from the various reflected plane wave components. The reflected field data captured by the C-PA have been used in a post-processing procedure based on Fourier Transforms to determine plane wave reflection coefficients. The incident field produced by the proposed setup has been simulated, as well as its interaction with a unidirectional Carbon/Epoxy plate, after which the acquired data has been post-processed. In general, the plane wave reflection coefficient were retrieved with a high accuracy for a broad range of incident angles* θ *in a single measurement if the lateral width of the C-PA elements is large enough. However, for higher frequency ranges, aliasing effects disturb the result significantly. This problem can be circumvented using multiple emitters with a smaller angular coverage, properly treating the data related to these emitters separately, and subsequently merging the results of these individual emitters.*

Keywords: Ultrasonic Polar Scan, Phased Array, Composite materials, Simulation study

1. INTRODUCTION

The Ultrasonic Polar Scan (UPS) is a technique that was first developed during the 1980s [1] and is currently being optimized as a state-of-the-art technique to determine the viscoelastic properties of composite materials. In this technique, as seen in Figure 1, a sample is insonified by an ultrasonic signal directed towards a specific central spot from various oblique incidence angles $\Psi(\theta, \phi)$, covering a large part of a hemisphere. After interaction with the sample, the reflected or transmitted ultrasonic energy can be captured and analyzed, thereby producing plots with characteristic contours. These contours present a distinct fingerprint of the material under study and can be used in an inversion procedure to infer the full viscoelastic tensor characterizing the material [2,3].

Currently, an in-house built mechanical setup is used to rotate the position of the emitting and receiving transducer pair and perform the experiments. While excellent experimental results have been obtained in the past, some practical shortcomings have become apparent. First, due to the need to move mechanical parts, the system is slow, and measurement times are relatively long (15 minutes for 1 million incidence angles Ψ). Second, the system has to be fully water immersed in a water basin to ensure a good acoustic coupling, severely impeding the applicability of the technique in the field. Third, the finite sized transducers introduce bounded beam effects, such that the interpretation of the data becomes significantly harder.

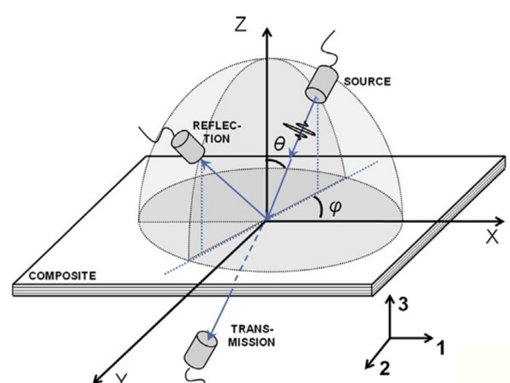

FIGURE 1: SCHEMATIC REPRESENTATION OF CURRENT UPS SETUP, TOGETHER WITH THE DEFINITIONS OF THE INCIDENT ANGLES θ AND ϕ.

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In order to create a device that can be used conveniently in an industrial setting, we propose to replace the mechanical setup by a combination of a cylindrically focused transducer with a large angular coverage to emit the ultrasonic signals, and a Circular Phased Array (C-PA) to capture the reflected signals. As seen in Figure 2, both components would be fixed in a single plane such that many incident angles θ can be activated at once, for a single specific incident angle ϕ. Via a single mechanical rotation around the z-axis, it would be possible to select a specific ϕ angle. As such the system would benefit from significantly faster measurement times and be considerably smaller, making it portable. Furthermore, the use of a large receiving aperture allows for the elimination of bounded beam effects.

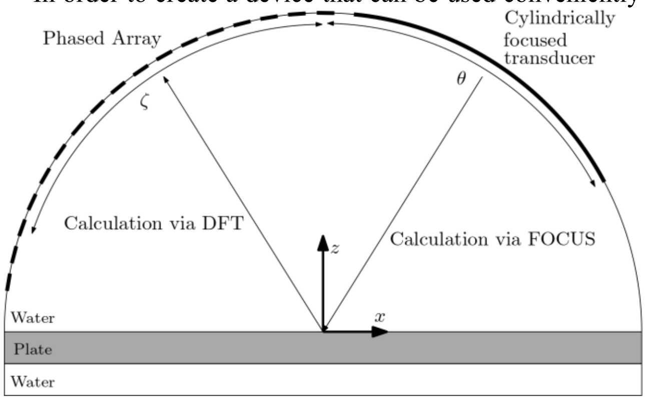

FIGURE 2: SCHEMATIC REPRESENTATION OF THE PROPOSED SETUP (SECTION WITH FIXED ϕ ANGLE). A CYLINDRICALLY FOCUSED TRANSDUCER IS USED TO CREATE THE INCIDENT BEAM, WHEREAS A PHASED ARRAY IS USED TO CAPTURE THE REFLECTED FIELD. THE Y-AXIS IS ASSUMED ORTHOGONAL TO THE X- AND Z- AXES.

In previous work, results based on a 2D simulation model confirmed that the use of a Phased Array system to both emit ultrasonic signals and receive the reflected field is a viable strategy in context of a UPS experiment for measurements along the material axes of the investigated sample [4]. Unfortunately, because of skewing effects due to the anisotropy, 2D simulations do not suffice along non-symmetry axes where out-of-plane components in the reflected field complicate the acquired data and its post-processing. In this contribution, an analytical bounded beam model is proposed that extends the previous results to 3D and allows to simulate Phased Array based UPS experiments along any incident angle ϕ.

2. MATERIALS AND METHODS

To test the proposed setup, simulations for a C-PA in reception consisting of 426 individual elements with a pitch of 0.35 mm, have been performed. The lateral width of the elements (along the y-axis in Figure 2) was either 1 mm or 10 mm, In addition, two cylindrically focused transducers for emission have been considered, either with an angular coverage of 60° or 30°. Both the emitter and the receiving C-PA are positioned at a radius of 100 mm.

2.1 Simulation of the incident beam and its interaction with an elastic medium

The first step in the simulation procedure is the calculation of the incident ultrasonic beam, i.e. a complex pressure field $P_i(x, y)$, at the location of the plate. Using FOCUS, we model the cylindrically focused transducer as multiple separate smaller transducers which are positioned along a cylinder surface [5].

Analytically, it is most convenient to calculate the reflected field of a given beam by convoluting the incident beam with the corresponding reflection characteristics for plane waves. Therefore, it was opted to decompose the harmonic incident bounded field $P_i(x, y)$ into its various plane wave components using a spatial Discrete Fourier Transform (FFT), i.e.

$$I(k_x, k_y) = \sum_{x,y} P_i(x, y) e^{i(k_x x + k_y y)}, \quad (1)$$

where k_x and k_y are the wave vector components in the x and y direction such that $k_z = \sqrt{|k|^2 - k_x^2 - k_y^2}$. Multiplying $I(k_x, k_y)$ by the theoretical plane wave reflection coefficients $R(k_x, k_y)$ of the considered material then results in the reflected field in k-space [6]. These reflected plane wave components can be used to build the reflected field in real space. More specifically, the reflected field measured by the C-PA elements can be expressed as a function of their angular position ζ with respect to the z-axis and across their lateral width (along the y-axis) by performing an Inverse Discrete Fourier Transform (IDFT) using appropriate phase shifts:

$$P_f(\zeta, y) = \sum_{k_x,k_y} I(k_x, k_y) R(k_x, k_y)\, e^{-i\alpha(k_x,k_y,\zeta,y)}, \quad (2)$$

where $\alpha(k_x, k_y, \zeta, y) = k_x r \sin(\zeta) + k_y y + k_z r \cos(\zeta)$. As a single array element is related to a single electric signal, a summation of the reflected field captured by the element across its lateral width is needed, i.e. $\tilde{P}_f(\zeta) = \sum P_f(\zeta, y)$, such that the final reflected field becomes a function of only the angular position of the elements. Note that using a similar procedure, a reference reflected field $\tilde{P}_{f,ref}(\zeta)$ corresponding to a perfect reflector can be found by setting $R(k_x, k_y)$ to unity in equation (2). The simulated fields $\tilde{P}_f(\zeta)$ and $\tilde{P}_{f,ref}(\zeta)$ should be considered as 'virtual data' that mimic the data which would be measured during a real experiment.

2.2 Calculation of the plane wave reflection coefficient

In this section, we start from the data of the (virtual or real experimental) reflection field captured at the discrete C-PA elements, and use this data as input for a procedure to back-calculate the plane wave reflection coefficients as a function of the incident angle θ. To do so, the procedure as presented in Section 2.1 is reused, but in reverse order. Via a DFT, the plane wave components of the actual (and reference) reflected field at the location of the plate can be calculated as

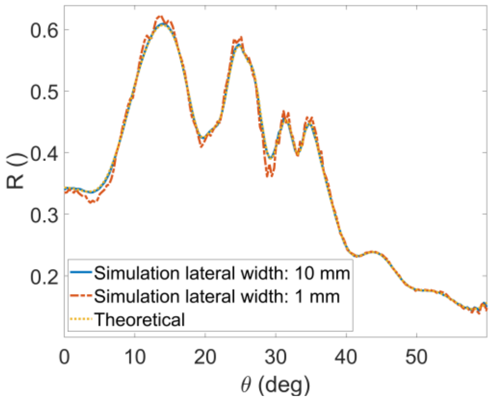

FIGURE 3: SIMULATED REFLECTION COEFFICIENT AMPLITUDE FOR THE UNIDIRECTIONAL C/E PLATE AT 2 MHZ AND $\phi = 75°$, AND ITS COMPARISON TO THEORY.

$$G_{(ref)}(\theta) = \sum_{\zeta} \tilde{P}_{f,(ref)}(\zeta) e^{i\tilde{\alpha}(\zeta,\theta)}, \tag{3}$$

with $\tilde{\alpha}(\zeta,\theta) = r|k|(\sin(\zeta)\sin(\theta) - \cos(\zeta)\cos(\theta))$. Using these results, the angle dependent reflection coefficient is determined as

$$\tilde{R}(\theta) = \frac{G(\theta)}{G_{ref}(\theta)}. \tag{4}$$

Note that while in principle $\tilde{R}(\theta)$ should be equal to the theoretical reflection coefficient used in equation (2), this is not necessarily the case. Indeed, as a result of the DFT, the final result will heavily depend on the discretization of the array elements, as this may generate aliasing effects. Moreover, the lateral size of the elements will also directly impact to what extend the non-specular contributions of the reflected field can be captured.

3. RESULTS AND DISCUSSION

Based on the procedure described in Section 2, simulations have been performed to retrieve the θ-dependent reflection coefficient via the proposed phased array based UPS system evaluated along various non-symmetry axes for an anisotropic material. In this paper, an illustration is given for a 3 mm thick unidirectional Carbon/Epoxy composite plate characterized by a complex-valued C-tensor with realistic viscoelastic properties. In a first exemplary case, a cylindrically focused transducer with an angular coverage of 60° was simulated with FOCUS. This transducer was positioned at 30° with respect to the z-axis such that the activated set of θ angles spans between 0° and 60°. Figure 3 shows the retrieved reflection coefficient after application of the forward and inversion procedure explained in Section 2.1 and 2.2 at a polar angle $\phi = 75°$ (= a non-symmetry axis of the UD C/E) and a harmonic signal at 2 MHz. For a lateral element width of 10 mm, an excellent match is found between the simulated results and the theoretical plane wave results, even though considerably strong out-of-plane components, due to energy skewing in the plate, were present at this polar angle. If the lateral width is reduced to 1 mm, the result remains relatively good, but a loss in accuracy can be noticed, most notably at the local minima and maxima. This suggests that the lateral width has to be appropriately selected with respect to the used frequency to appropriately capture the non-specular reflected field components.

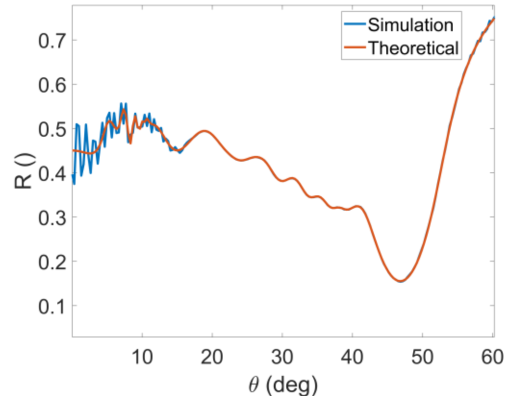

FIGURE 4: SIMULATED REFLECTION COEFFICIENT AMPLITUDE FOR THE UNIDIRECTIONAL C/E PLATEAT 4 MHZ AND $\phi = 30°$, AND ITS COMPARISON TO THEORY.

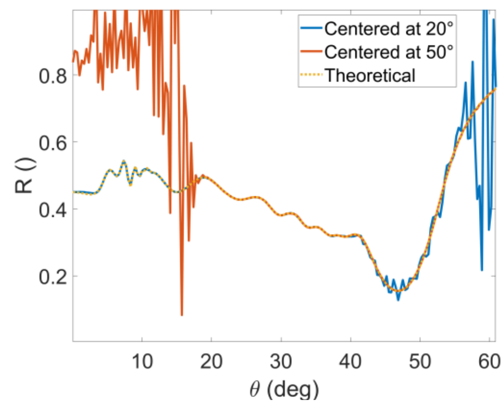

FIGURE 5: SIMULATED REFLECTION COEFFICIENT AMPLITUDE FOR THE UNIDIRECTIONAL C/E PLATE AT 4 MHZ AND $\phi = 30°$, AND ITS COMPARISON TO THEORY. TWO SMALLER TRANSDUCERS HAVE BEEN USED TO FULLY DETERMINE THE REFLECTION COEFFICIENT.

Figure 4 shows a similar result, but now for a harmonic signal of 4 MHz at a polar angle $\phi = 30°$ and a lateral width of 10 mm. While the retrieved result is in excellent agreement with theory for a considerable range of incident angles θ, discrepancies appear for the smaller angles up to approximately 20°. It was observed that this discrepancy disappears if the array elements were artificially halved in size and doubled in number, suggesting that aliasing effects are the problem, especially since the severity of the problem increases with frequency. As most problems arose for the smaller values of θ we decided to repeat the procedure using 2 smaller cylindrically focused emitters with only 30° angular coverage centered at 20° and 50° with respect to the z-axis. The reflected fields of each separate emitter were treated individually and the retrieved results for both parts in this alternative setup can be seen in Figure 5. The result for the transducer positioned at 20° shows an excellent agreement between the simulated and theoretical results up to about 40°. For larger angles, the emitted field does no longer contain plane wave components of considerable amplitude to resolve the plane wave reflection coefficients. On the other hand, when the emitter is centered at 50°, the retrieved result is an excellent representation of the theoretical values over a large angular range starting from approximately 20°. By merging these two results and selecting specific θ ranges for which a sensible result is found while disregarding the other data, it is possible to obtain a single angle dependent estimate for the plane wave reflection coefficients.

4. CONCLUSION

In this contribution a 3D model has been presented to simulate phased array based Ultrasonic Polar Scan experiments. It has been shown that an excellent agreement between the simulated and theoretically expected plane wave reflection coefficients can be found in ideal cases. However, depending on the used frequency range, adaptations to the proposed setup by means of multiple emitters rather than a single one are needed to attain credible results. Furthermore, the size of the lateral width of the elements has a clear influence on the accuracy of the results.

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