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Title: Recent Advances in the Ultrasonic Polar Scan Method for Characterizing (Degraded) Fiber Reinforced Plastics

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ABSTRACT

The ultrasonic polar scan (UPS) technique originated in the 1980's as a sophisticated method for inspecting composites. However, it is only in recent times that the true capabilities and strengths of the UPS methodology have been evidenced through experiment and simulation. Nowadays, the UPS method exists in different versions which led to several novel applications in the field of material inspection and characterization. This contribution gives an overview of our recent advances.

INTRODUCTION

In the early 1980's, the pulsed ultrasonic polar scan (P-UPS) technique was introduced by Van Dreumel and Speijer as an innovative means to nondestructively assess the fiber orientation of composites [1]. The P-UPS insonifies a specific material spot with ultrasound pulses from as many oblique incidence angles $\psi(\varphi,\theta)$ as possible (see the schematic in Figure 1a). By recording the transmission (or reflection) pulse amplitudes and mapping them in polar coordinates, a P-UPS image is obtained. Figure 1b shows a state-of-the-art P-UPS recording for a unidirectional $[0°]_8$ carbon/epoxy (C/E) laminate. The vertical incident angle θ is put on the radial axis, the in-plane polar angle φ is represented along the angular axis, while the assigned color pigment is a measure for the transmitted (or reflected) pulse amplitude. Within a P-UPS image characteristic contours emerge which relate to the stiffness of the insonified sample. In the example of Figure 1b, one can easily identify the unidirectional character of the $[0°]_8$ C/E laminate in the stretched view of the P-UPS image.

More than fifteen years after the pioneering work of Van Dreumel and Speijer, the P-UPS technique has been investigated again through the work of Degrieck. He used it for detecting fatigue damage in composites and determining the fiber volume fraction [2-3]. The UPS research has been further extended by Declercq who implemented a simulation model on the basis of a global matrix method [4-6].

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He also experimented with a time-of-flight (TOF) version of the P-UPS method, and commented on the superior sensitivity (compared with amplitude recording) to the presence of damage [7].

Until now however, the ultrasonic polar scan research has mainly been applied for qualitative purposes; simply because the gap between experiment and simulation has never been bridged. In view of bringing the technique to the next level, we have reexamined the experimental and numerical procedures. This has led to a revival of the technique, and to the demonstration of several quantitative applications for a wide range of (fiber reinforced) materials. The following gives a short overview of our recent progress in the ultrasonic polar scan research. All the shown experiments have been obtained with standard immersion transducers at low MHz frequencies.

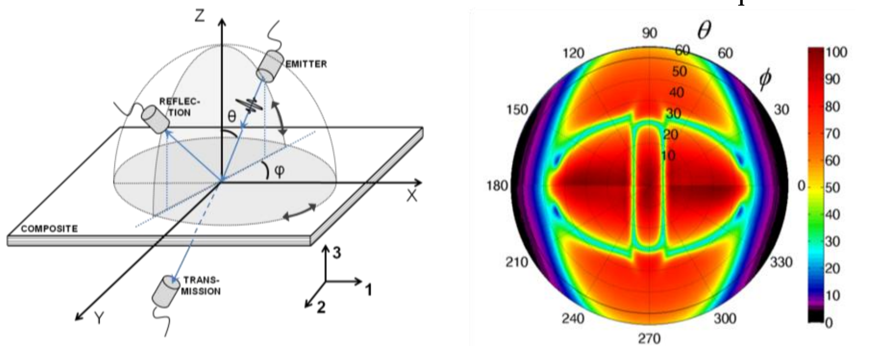


Figure 1: Schematic of P-UPS method (a) and P-UPS recording for $[0°]_8$ C/E (b).

REVISITING THE ULTRASONIC POLAR SCAN

In a first stage, we have built a fully automated 5-axis scanner which insonifies more than 1,000,000 incidence angles $\psi(\varphi,\theta)$ in less than 15 minutes. In this way, we obtain high-quality experiments which has led to the identification of several experimental pitfalls which basically prevented the further advancement of the UPS research [8]. The exceptional quality of our experimental recordings may be seen in Figure 2a-c for aluminum, $[0°]_8$ C/E laminate and $[0°,90°]_S$ C/E laminate.

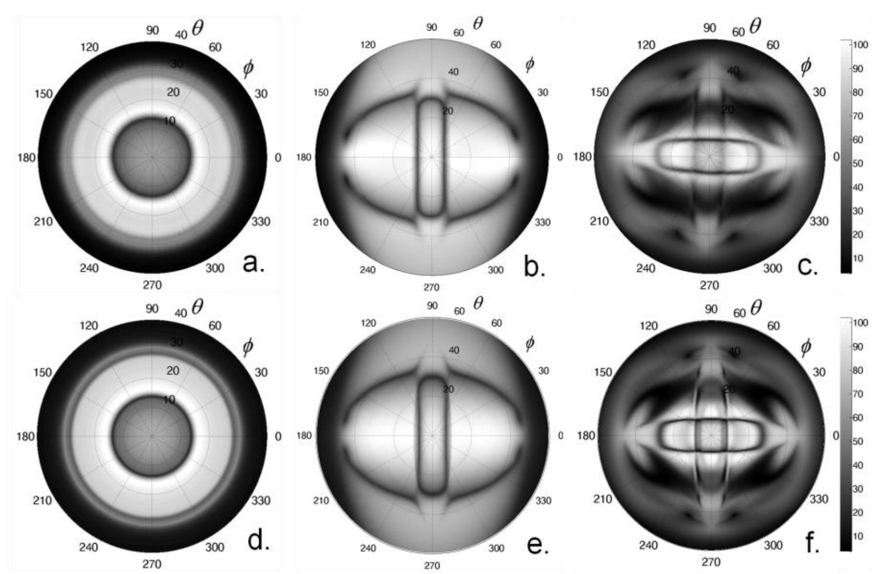


Figure 2: UPS experiments (a-c) and UPS simulations (d-f) for aluminum (left column), $[0°]_8$ C/E (middle column) and $[0°,90°]_S$ C/E (right column).

Secondly, we implemented a simulation technique to support experimental observations [9]. The simulation model is founded on a cascade matrix technique [10], and is fully applicable to simulate UPS of immersed layered viscoelastic anisotropic media. Compared to existing simulation models [5-6], we were able to significantly reduce the computational time. Figure 2d-f shows our simulations for aluminum, $[0°]_8$ and $[0°,90°]_S$ C/E laminate, showing good agreement with our experimental UPS recordings (Figure 2a-c).

The next step we took was the implementation of an inverse procedure to couple experiment to simulation, in view of identifying composite parameters. Basically, the simulated UPS image is fitted to the recorded UPS image while updating the composite material properties by means of a genetic algorithm [11-12]. A schematic of the optimization procedure is shown in Figure 3. In this way, we successfully identified (visco)elastic properties for a range of thin (composite) materials, and we obtained good correspondence with alternative identification techniques.

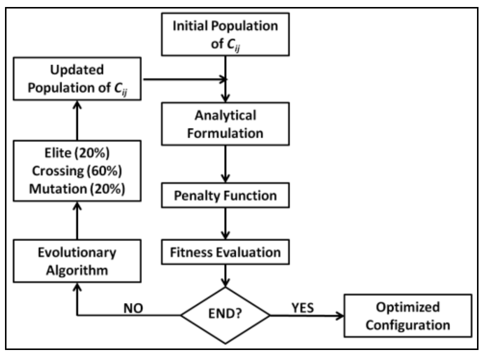


Figure 3: Schematic of inversion process to identify (visco-)elastic properties [11].

EXTENSIONS OF THE ULTRASONIC POLAR SCAN

Harmonic ultrasonic polar scan (H-UPS)

Our numerical simulations indicate that the global view of a UPS image is not only function of material parameters, but also strongly depends on the (temporal) shape of the employed ultrasound wave. This has led us to the experimental and numerical investigation of harmonic ultrasonic polar scans (H-UPS) in which quasi-harmonic bursts are employed [9]. In Figure 4a, the H-UPS recording of a $[0°]_8$ C/E laminate is shown. Compared to the corresponding P-UPS recording (see Figure 2b), a change in the characteristic contours can be seen. This is easily understood considering that the H-UPS image puts on view the stimulation conditions of dispersive Lamb waves, while the P-UPS image is mainly governed by bulk wave characteristics [13]. This immediately reveals the potential of the H-UPS for assessing frequency dependent properties such as attenuation. For the H-UPS it also meaningful to analyze the phase information (instead of amplitude) of the transmitted wave (see Figure 4b). Our results indicate a good sensitivity of the phase signal to several material features. However, the true potential of phase recorded H-UPS for composite inspection and/or characterization has not yet fully been investigated in depth.

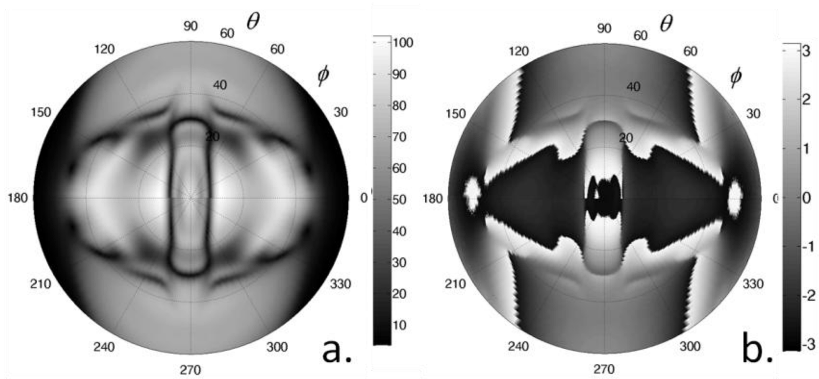


Figure 4: H-UPS experiment of $[0°]_8$ C/E: amplitude (a) and phase (b) analysis.

Ultrasonic backscatter polar scan (UBPS)

During our UPS investigations, we persistently observed a small amount of ultrasonic energy being backscattered to the emitter, even for large incidence angles θ. Recording of the backscattered amplitude according to the UPS principle, i.e. as a function of the incidence angle $\psi(\varphi,\theta)$, then results in the ultrasonic backscatter polar scan (UBPS). We speak of P-UBPS [14] or H-UBPS [15] when employing a pulsed or a quasi-harmonic wave respectively. A schematic of the UBPS method, together with the H-UBPS recording for a $[0°]_8$ C/E laminate is presented in Figure 5.

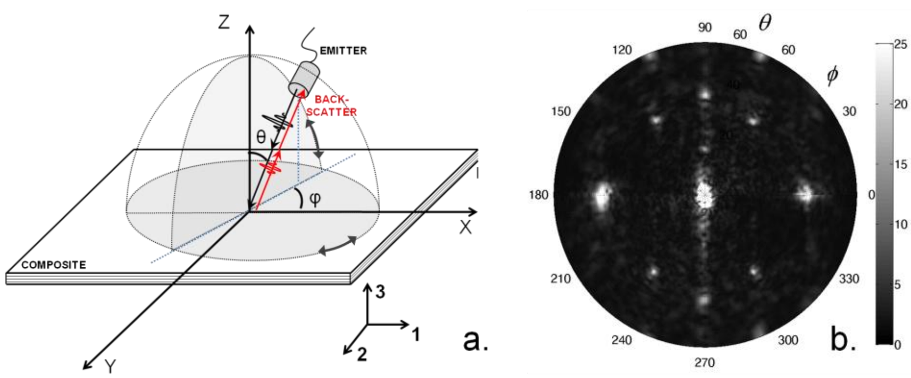


Figure 5: Schematic of UBPS method (a) and H-UBPS recording for $[0°]_8$ C/E (b).

A H-UBPS image is typically characterized by well-defined high amplitude spikes, and we found that these spikes expose geometrical characteristics of (sub)surface structures. For the $[0°]_8$ C/E laminate, the imprint left by a peel-ply cloth (used during manufacturing of the laminate) was identified as the origin of the observed backscatter spikes.

APPLICATIONS OF UPS AND UBPS

The UPS and the UBPS, both in pulsed and harmonic version, have been applied for a range of NDT applications involving ceramic, metallic and fiber reinforced materials.

Static damage

Various fiber reinforced plastics have been statically loaded to induce material degradation. In Figure 6, UPS images are shown of $[-45°,+45°]_S$ C/E laminate before and after applying a (quasi-)static shear load. The indicated overlap angle ζ provides a measure for the actual fiber orientation. Initially $\zeta = 91.5°$ indicating that the stacking of the laminate was not done correctly (see Figure 6a). After loading in shear, the overlap angle reduced to $\zeta = 81.5°$ (see Figure 6b), which thus reveals a distortion of the fiber orientation of 10°. The evolution of the overlap angle ζ has been monitored for a range of shear load levels, and we found a clear relation between the applied shear load level and the observed fiber distortion [16].

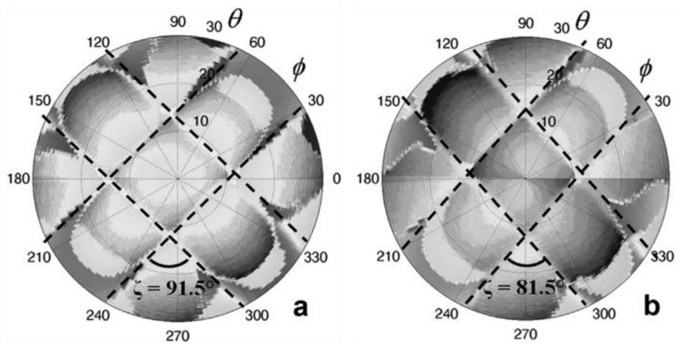


Figure 6: UPS image of $[-45°,+45°]_S$ C/E laminate: before (a) and after (b) applying a quasi-static shear load.

(Multi-)delamination

As the patterns in a H-UPS image are governed by stimulation conditions of Lamb waves, these patterns will shift position in the presence of a delamination. This is easily understood considering that a delamination divides the original laminate in two sub-laminates which have different boundary conditions, and as a consequence imposes different Lamb wave stimulation conditions [17]. This is demonstrated in Figure 7 for a cross-ply C/E laminate (thickness of 1.1 mm) which is provided with a water-filled (multi-)delamination (thickness of 50 μm). We have found both experimentally and numerically that delamination characteristics, e.g. depth position, thickness and fluid/air filled, are fully represented in a H-UPS image.

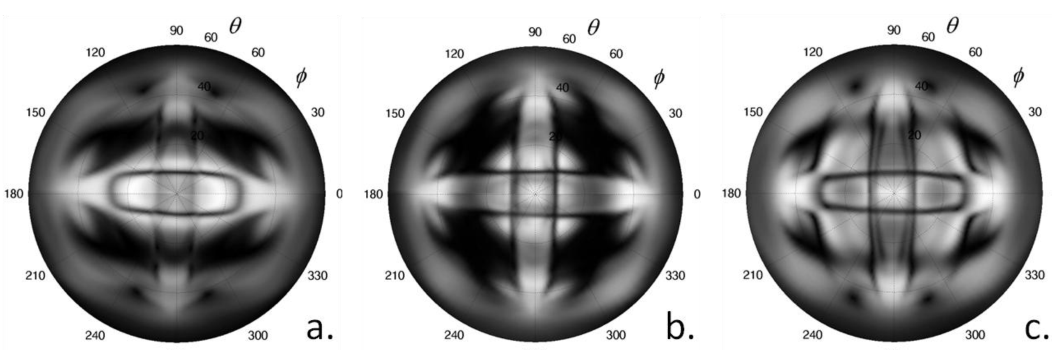


Figure 7: H-UPS recordings of a cross-ply C/E laminate: $[0,90]_S$ (a), [0,90,D,90,0] (b) and [0,D,90,90,D,0] (c). 'D' stands for the depth position of the delamination.

Note that such types of delaminations are difficult to assess in thin composites using conventional normal incidence techniques.

Tension-tension fatigue damage

The UPS method was also applied to composites which have been fatigued in a tension-tension setup. Such fatigue loading typically leads to the initiation, progression and accumulation of micro defects. At the macroscopic level, these defects manifest themselves in a directional reduction of the stiffness properties along the loading direction. As a consequence, this stiffness reduction should be visible as a stretching (along the direction of loading) of the UPS contours. This is explicitly demonstrated in Figure 8 for a woven C/E laminate which was fatigued along φ = 0°. The UPS experiment yields a stiffness reduction of 12.8% along the loading direction, which agrees well with extensometer data giving a reduction of 11% [18].

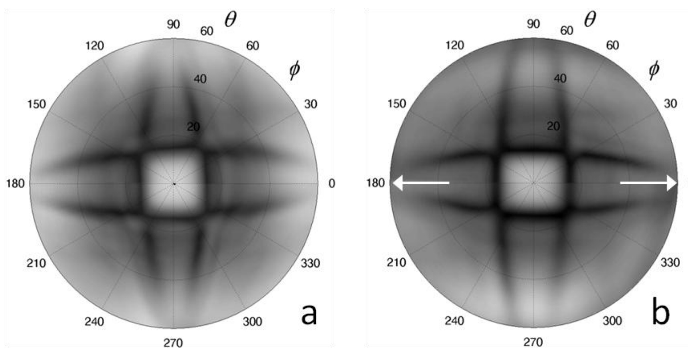
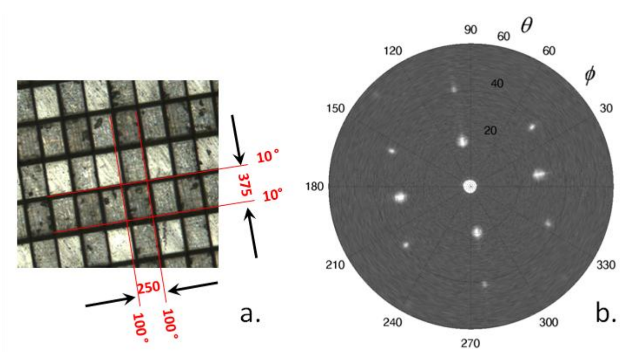


Figure 8: P-UPS recording before (a) and after (b) applying tension fatigue.

2D subsurface structure

As the characteristics of a periodic (sub)surface structure determine the position of the observed backscatter spikes in a H-UBPS experiment (see Figure 5b), we may also reverse this, i.e. analyze a H-UBPS experiment to reconstruct a (sub)surface structure. This has been successfully demonstrated for a 2D subsurface corrugation (see Figure 9). The ultrasonic reconstruction of the corrugation parameters shows excellent agreement with both the design parameters and optical measurements (see Figure 9c). The reconstruction procedure was also successfully applied to periodic subsurface structures having a certain degree of geometrical randomness [19].



Design parameters	Ultrasonic reconstruction	Optical measurement
250 µm	249.8 µm	250.1 µm
100°	99.3°	99.2°
375 µm	375.3 µm	374.8 µm
10°	9°	9.1°

c.

Figure 9: Optical microscopy of 2D subsurface corrugation (a), H-UBPS recording (b) and reconstruction results (c).

3D strain measurement

As we succeed to ultrasonically reconstruct a (sub)surface structure with excellent accuracy, we should also be able to detect any changes in surface parameters due to applied strain. Analysis of the transformed surface structure then yields a representation for the applied in-plane strain field [20]. Instead of machining a periodic surface structure, which would mechanically weaken the sample, we simply exploit residual surface roughness features. The ultrasonic strain measurement technique has been successfully demonstrated on cold-rolled DC06 steel coupons which were strained at different levels. One can clearly observe the shifting of the backscatter spikes when strained (see Figure 10). This shifting is then used to reconstruct the applied in-plane strain field.

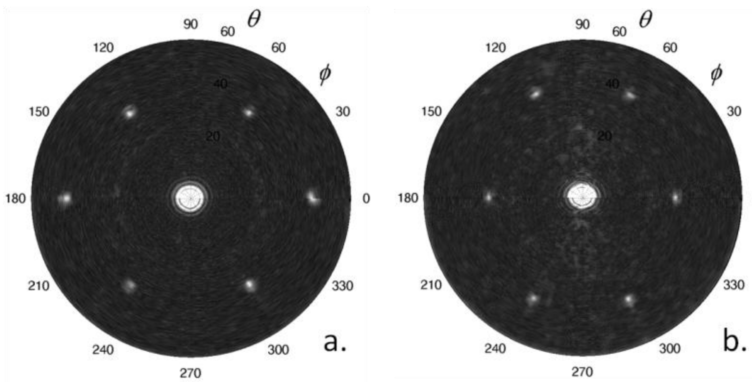


Figure 10: H-UBPS for unstrained (a) and strained (b) DC06 steel coupon.

In concurrence, we also analyze the response of normally incident ultrasound pulses in order to detect changes in the stimulation condition of thickness resonances. From these changes, we reconstruct the out-of-plane normal strain component. The ultrasonically reconstructed 3D strain field has been confronted with the results of conventional strain measurements techniques (e.g. 3D DIC), showing excellent agreement for a wide range of applied strain values (up to 35%) [20]. Interestingly, the developed ultrasonic strain gauge is the only method which effectively determines the local 3D strain field in a single-sided and contactless manner.

CONCLUSIONS

This paper provides a short review of recent advances in the ultrasonic (backscatter) polar scan research for composite characterization and NDT. We have illustrated our recent progress with several state-of-the-art research results for a range of different applications, e.g. composite characterization, 3D strain field reconstruction, assessment of fatigue damage ... At present, we are extending the U(B)PS technique with several innovative approaches, e.g. nonlinear ultrasound and spectroscopic analysis, in order to expand its applicability to a broader range of (degraded) composites and to increase its sensitivity to incipient damage features.

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