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# On the influence of fatigue on ultrasonic polar scans of fiber reinforced composites

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**Abstract**

Ultrasonic polar scans have already proved to be well-suited as a practical means of characterizing fiber reinforced composite plates. The method consists of registering the reflected or transmitted sound amplitude as a function of each possible angle of incidence. It is hence an amplitude measurement by which it differs from more common 'time of flight' measurements. Ultrasonic polar scans are actually a fingerprint of a composite laminate. One of the many promising applications of the ultrasonic polar scan is the monitoring of fiber reinforced composites in service. Especially the progress of fatigue damage can be monitored easily and nondestructively. This paper presents numerical simulations of the influence of fatigue on ultrasonic polar scans as well as some experimental results.


*Keywords:* Ultrasonic polar scans; Fiber reinforced composites; Fatigue

## 1. Experimental procedure and results

### 1.1. Causing fatigue damage

A FR4 composite laminate is a fabric glass fiber reinforced epoxy composite that is often used in electronic devices. The present paper reports experiments on such a FR4 sample. The use of the polar scan method to study the sample is discussed below. In between each polar scan, the sample has been subjected to applied dynamic (sinusoidal) strain in one direction. It is well-known that this results in degradation of the material after a large number of cycles. This is called fatigue. Contrary to degradation in metals, in composites degradation always occurs in a relatively large zone (bulk degradation) and is accompanied by a diminishing stiffness in many directions. The dynamic strain is caused by clasping the sample in a system of two grabs that are connected to a machine that generates controlled displacements of the grabs relative to each other. The dimensions of the laminate inside the grabs system are shown in Fig. 1. The amplitude of the applied dynamic strain is 0.8% which for this material ($E$ modulus is approximately 22 GPa) corresponds to a maximal applied stress of 181 MPa, i.e. 60% of the strength of the laminate. The dynamic stress is applied at a pace of 2.5 Hz. Below, we will study the effect of this applied stress on an experimental polar scan before fatigue and after 39,060 dynamic deformations.

### 1.2. The principle of ultrasonic polar scans in a nutshell

Just like for example the well-known time of flight techniques, an ultrasonic polar scan is performed on a plate immersed in water and investigates anisotropic mechanical properties of the laminate exploiting its influence on obliquely incident sound. Frequently in nondestructive characterization of fiber reinforced composite plates, time of flight measurements are used, which are relatively difficult to perform. The ultrasonic polar scan on the other hand applies the amplitude of transmitted (or if necessary reflected) sound, which results from sound impinging the plate from every direction above the plate and is relatively easy to measure. Furthermore, a polar scan is able to investigate sound amplitudes on a small area, whence it can present a local fingerprint of the laminate under investigation. The

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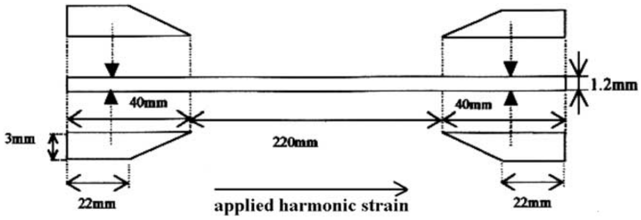


Fig. 1. A schematic view of the laminate inside the grabs during cyclic deformations. The dimensions of the sample are 300 mm (length) by 1.2 mm (thickness).

characteristic pattern of such a 'fingerprint' consists in fact of a set of rings, showing considerably less intensity than elsewhere on the registered polar scan. The rings are physically connected to generated critical waves in the plate, such as leaky Rayleigh waves, leaky Lamb waves or even lateral waves. Therefore, they almost directly elucidate the mechanical anisotropy and the stiffness of the investigated area.

Ultrasonic polar scans have first been developed by Van Dreumel and Speijer [1] who used them to determine the fiber orientation in composite laminates, and have been further developed by Degrieck and coworkers [2–6], who utilized them for additional applications such as the determination of the anisotropic (nonorthotropic) stiffness, fiber and resin fraction and more. Contrary to classical *C*-scans, in polar scans the transducer is not directed invariably normal to the surface, scanning a whole area, but is constantly directed towards a particular targeted zone on the surface, occupying successively all possible directions of incidence from the upper half space, and maintaining a constant distance to the target, as shown in Fig. 2. The measured amplitude is then plotted in a polar diagram where the radius corresponds to $\varphi$ and the polar angle to $\theta$.

### 1.3. Experimental results

The ultrasonic polar scans were experimentally performed using a Krautkrämer USIP20 ultrasonic apparatus and a Krautkrämer H5M shock wave probe with a nominal frequency of 5 MHz. The pulse had a shape that is given in Fig. 3. Since a shock wave probe generates sound that contains a large frequency range, the existence of Lamb wave angles is not directly visible in the overall reflected or transmitted amplitude. One would need to perform a frequency analysis of the received sound if the individual Lamb modes have to be detected. However the positive consequence of applying a shock wave transducer is that patterns appear at angles that almost coincide with bulk critical angles. That is because all frequency dependent Lamb modes phase cancel each other, which is not the case for the effects at the frequency independent bulk critical angles. Therefore the reflected sound resulting from an impinging shock wave will show maximum amplitude at bulk critical angles, while the corresponding transmitted sound will show a strong amplitude dip. Now, since bulk critical angles are relatively simply connected to the stiffness of the material through Snell's law and Christoffel's equation, they form an ideal fingerprint to visualize stiffness changes due to fatigue damage. In the experiments performed here, the maximum transmitted amplitude is measured for each angle of incidence, whence critical amplitude dip patterns will appear due to the bulk critical angles. The results for the ultrasonic polar scan in transmission is shown before fatigue (Fig. 4) and after fatigue caused by 39,060 cycles of dynamic deformation as discussed above (Fig. 5). The 'omitted' parts in the polar scans of Figs. 4 and 5 correspond to angles where no measurements have been performed. Since there are large areas where the amplitude changes very little, a plot where the brightness corresponds linearly to the intensity results in very ambiguous figures. Therefore we have opted to make plots in color and transform them to black and white pictures similar to a black and white copier. This results in figures where the brightness does not correspond one to one to a certain

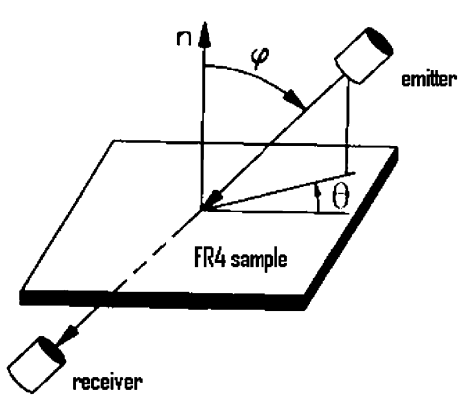


Fig. 2. In a polar scan, a spot is impinged at constant distance form all possible angles.

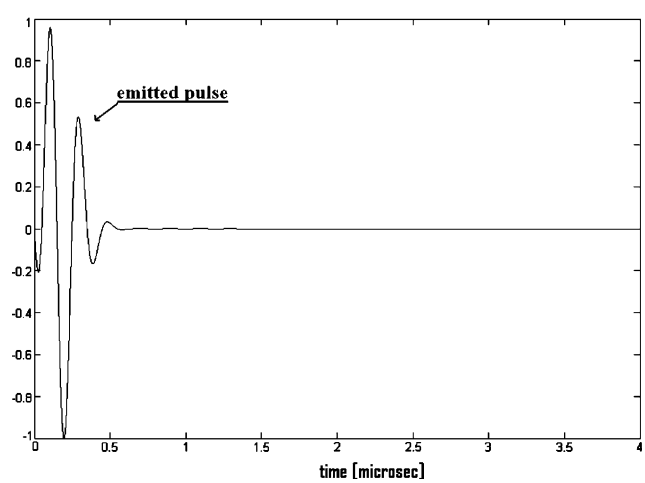


Fig. 3. The amplitude versus time profile of the impinging sound pulse.

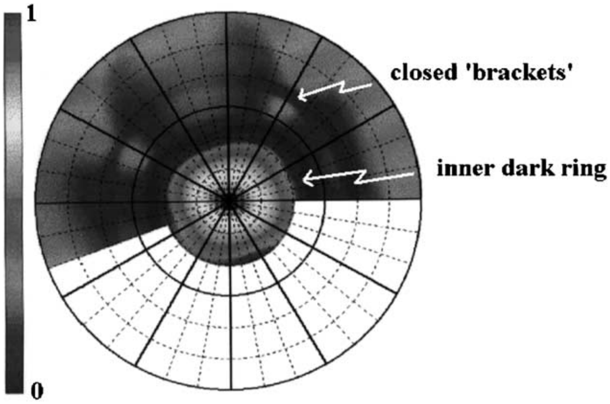


Fig. 4. Experimental ultrasonic polar scan on a FR4 plate before fatigue damage. The dotted circles of the diagram correspond to steps of 10°. The amplitude is normalized.

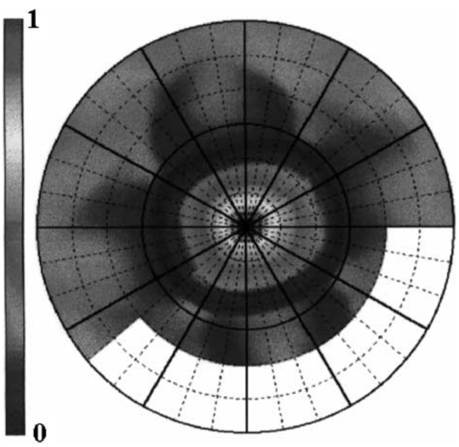


Fig. 5. Experimental ultrasonic polar scan on a FR4 plate after fatigue damage. It is noticed that the inner dark ring has moved outward if compared with Fig. 4 and also that the closed brackets of Fig. 4 have opened. The amplitude is normalized.

intensity. However, it is so that the dark center in the presented ultrasonic polar scans corresponds to maximum intensity. All other dark regions exceeding $\varphi = 10°$ correspond to low intensities. The gray regions are more or less linearly related to medium intensities as can be noticed from the 'color bar' next to each polar scan. It is seen that the dark ring in between 20° and 30° has moved slightly (approximately 1°–2°) outwards after the fatigue damage has occurred. This ring is caused by the critical angle corresponding to quasi-longitudinal waves. Hence ultrasonic polar scans enable us to monitor fatigue damage.

## 2. Numerical simulations

When sound is incident on a fiber reinforced laminate, there will be some scattering on the individual fibers. In some cases this is dramatic, especially when thick fibers or high frequencies are involved. For a FR4 composite, 5 MHz is more or less the limit before this scattering becomes very important. At 5 MHz the scattering is not dramatic and does not change the influence of the overall stiffness parameters that determine the position of the 'dark rings' in polar scans. As can be seen in Ref. [6], scattering on individual fibers mainly causes some deviations in the amplitude at normal incidence. These considerations result in a justification to apply an approach where the material properties are considered to be homogeneous throughout the plate. The theory that deals with this situation can be found for example to a large extend in the work of Nayfeh [7]. It is based on the plane wave solution of the equation of motion, the stress–strain relation for orthotropic materials, Snell's law combined with Christoffel's equation for revealing the possible values of the wave vector and the continuity conditions for normal stress and normal displacement along the water/solid interface. The sound field in the solid is then written as a linear combination of each possible plane wave inside the plate (6 in number), while the sound field in each liquid side is just one single plane wave solution. The continuity conditions are then represented by a linear matrix equation that can be solved by means of matrix inversion in order to find the complex amplitude of each plane wave that constitutes the sound field. Besides the thickness, we do not know the exact values of the material parameters of the FR4 laminate that is investigated here. Therefore we have applied numbers that are generally accepted as being reasonable numbers for this material. The values are found in Table 1, where symbols $E$ denote Young's moduli, $v$ indicate the Poisson coefficients and $G$ represent shear moduli. The numerical simulation of an ultrasonic polar scan before fatigue damage is shown in Fig. 6. There is of course no perfect similarity between Figs. 6 and 4, however the basic structure is the same and so is approximately the position of the dark ring that is caused by quasi longitudinal waves. In order to perform a simulation after fatigue damage, we have applied general features of fatigue damage that have recently been published [8–15]. These papers indicate that the $E$ and $G$ moduli tend to $k = 60\%$ and that the Poisson coefficients tend to $m = 25\%$ of their original values at the time that fracture occurs due to fatigue damage. Since the polar scan of Fig. 5 corresponds to severe fatigue damage, but not to the amount that causes fracture, we have entered $k = 75\%$ and $m = 35\%$ in the simulation that is shown in Fig. 7. Analysis of Figs. 6 and 7 reveals that the dark ring moves from 23.25° to 24.88°, which is in qualitative and more or less quantitative agreement with the experiments. It is also seen that the other patterns that are similar to brackets, tend to 'open' after fatigue damage. This is also in agreement with the experiments, where it is seen that before damage (Fig. 4), the

Table 1
Material properties used in the numerical simulations

| | | |
|---|---|---|
| $\rho = 1925$, kg/m$^3$ | | |
| $E_{11} = 20030(k - 0.15i)$ MPa | $E_{22} = 22630(k - 0.15i)$ MPa | $E_{33} = 8628(k - 0.005i)$ MPa |
| $\nu_{23} = 0.5(m - 0.005i)$ | $\nu_{13} = 0.5(m - 0.005i)$ | $\nu_{12} = 0.1793(m - 0.08i)$ |
| $G_{23} = 3930(k - 0.04i)$ MPa | $G_{13} = 3930(k - 0.04i)$ MPa | $G_{12} = 4781(k - 0.15i)$ MPa |
| Before fatigue: $k = 1$, $m = 1$ | | |
| After fatigue: $k = 0.75$, $m = 0.35$ | | |

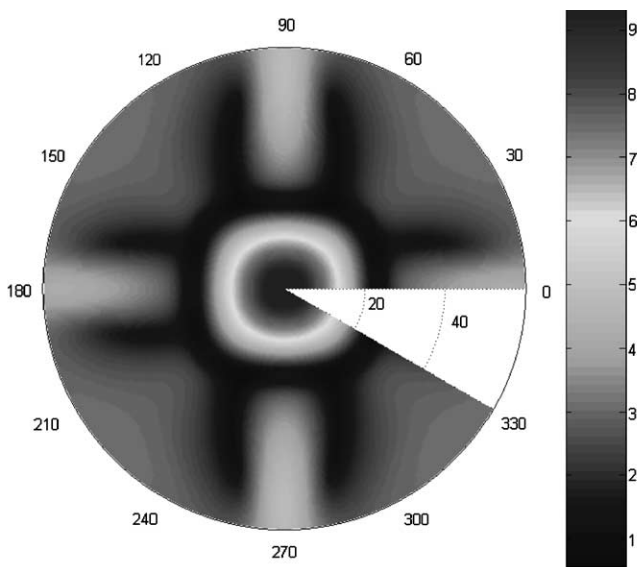


Fig. 6. Simulation of ultrasonic polar scan on a FR4 plate before fatigue damage. The amplitude is given in exact numbers.

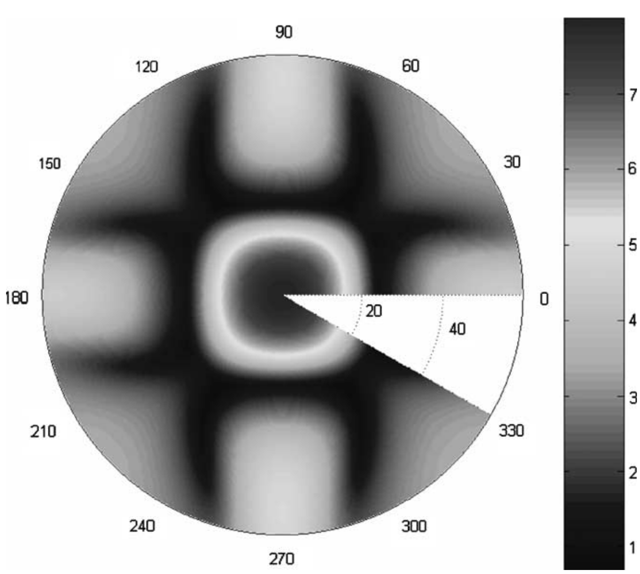


Fig. 7. Simulation of ultrasonic polar scan on a FR4 plate after fatigue damage. The amplitude is given in exact numbers. It is seen that the inner dark ring has been shifted outward from 23.25° to 24.88° if compared with Fig. 6 and that the 'brackets-patterns' of Fig. 6 have opened more.

'brackets' are so closely situated to each other that they appear as closed circles, a phenomenon that disappears after fatigue damage (Fig. 5).

## 3. Conclusions

It is shown by means of experiments and numerical simulations that ultrasonic polar scans are a possible tool to reveal fatigue damage. The simulations are in reasonable agreement with the experiments, and so is the evolution of the patterns in a polar scan due to fatigue damage. In the science and technology of composites, it is often desirable to measure the stiffness degradation of composites due to fatigue in order to verify physical micro-models for this phenomenon. Most often destructive methods are used for that purpose and frequently it is impossible to measure the out of plane properties. Ultrasonic polar scans may be an excellent tool for that purpose with the extra advantage that it is a nondestructive technique whence each measured sample (or part of a construction) might continue its life without destructive interruption.

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