THE QUASI-HARMONIC ULTRASONIC POLAR SCAN FOR MATERIAL CHARACTERIZATION: EXPERIMENT AND NUMERICAL MODELING

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ABSTRACT

The conventional ultrasonic polar scan (UPS) records the transmitted amplitude of an acoustic pulse for a certain solid angle, resulting into a unique fingerprint of the local critical bulk wave angles, which relate to the local elasticity tensor at the insonified material spot. Numerical plane wave computations reveal that the use of harmonic sound, instead of sound pulses, provides a picture that exposes the leaky Lamb wave angles. For the first time, UPS experiments have been obtained with the use of quasi-harmonic pulses to check this premise. To achieve good correspondence with the experimental recordings, a more advanced numerical model (based on the partial wave technique and the stiffness matrix method) has been implemented. Both temporal and spatial beam dependency is accounted for by application of the Fourier transform. Besides a traditional amplitude measurement, the analysis has also been extended, both numerically and experimentally, to the phase of the transmitted sound, hence introducing the concept of a ‘phase ultrasonic polar scan’. The results clearly indicate that a phase UPS offers very defined and detailed results, with high sensitivity to small disturbances. Even more, combination of both the amplitude and phase UPS yields complete knowledge about the complex transmission coefficient.

To demonstrate the potential of the quasi-harmonic UPS for NDT and material characterization, it has been applied to a unidirectional (UD) carbon/epoxy laminate which contains an artificially generated delamination. It is demonstrated that, contrary to the pulsed UPS, the quasi-harmonic UPS show great sensitivity to the presence of the delamination.

Key words: Ultrasonic polar scan, quasi-harmonic sound, amplitude & phase analysis, composites, delamination.
1. Introduction

Already in the early 1980's, the UPS was introduced and presented as a sophisticated means for non-destructive testing (NDT) of fiber-reinforced materials [1]. Contrary to the classical C-scan, the UPS records the transmitted amplitude of an ultrasonic wave for a wide range of liquid-solid interface incidence angles $\psi(\phi, \theta)$. Till now, ultrasound pulses were employed for the recording of an UPS, resulting into a fingerprint which is dominated by bulk wave phenomena (see Figure 1) [2-3]. Very recently, the potential of the technique was demonstrated by combining the pulsed UPS experiment with an inverse procedure to characterize the local mechanical elasticity of orthotropic composite materials [4-5].

Plane wave numerical computations, based on the direct matrix technique, reveal that the use of mono-frequency ultrasound (also called continuous waves) rather generates a fingerprint which is related to the stimulation of Lamb waves [3, 6]. In section 2 and 3, we report on the first ever conducted UPS experiments with the use of quasi-harmonic sound pulses (i.e. bursts of periodic cycles) in order to check this premise. Because of the poor agreement between the experimental recordings and existing plane wave simulations, we implemented a more robust numerical model, based on the partial wave technique and stiffness matrix method [7], which has been further extended in order to account for the angular frequency spectrum of the experimentally employed sound beam. With this, satisfying agreement is obtained between experimental recording and numerical modeling.

Additionally, since a quasi-harmonic wave can be fully described by the combination of its amplitude and its phase, we also extended the analysis, both numerically and experimentally, to the phase of the transmitted wave, hence introducing the concept of the ‘phase UPS’ in section 4. Such kind of phase results are unique and unprecedented.

Finally, in section 5, we investigated the sensitivity of the pulsed UPS as well as the quasi-harmonic UPS to samples containing an artificial delamination. In contrast with the pulsed UPS results, the quasi-harmonic UPS results (both amplitude and phase recording) show great sensitivity to the presence of a delamination.

![Figure 1: Recorded pulsed UPS for (a) aluminum and (b) [0]_8 carbon/epoxy laminate. The characteristic contours correspond to the different bulk waves: the (quasi-)longitudinal (QL), the (quasi-)shear horizontal (QSH) and the (quasi-)shear vertical (QSV) polarized waves.](image)

2. General approach and background

Due to space limitations, we restrict ourselves to a brief introduction of the experimental conditions. A full description of the experimental setup and of the numerical scheme to simulate the UPS can be found elsewhere [8].

The signal emission and recording in this study have been performed by means of general shock wave transducers, operated in a quasi-harmonic burst mode. In Figure 2(a-b), the temporal characteristics at frequency $f = 5$MHz are shown. Each quasi-harmonic pulse consists of at least 10 periods, in which the outer 2 periods are ignored in the experimental analysis, in order to
avoid possible transient effects. In Figure 2(c-e), the spatial radiation field, together with a cross-section of the amplitude and phase distribution of the sound beam at the measurement plane \((z = 130\text{mm})\), are presented. It is clear that the sound beam differs considerably from a plane wave (as most often assumed in literature [3, 6]), and rather resembles a 2D Bessel distribution. Therefore, a more robust and unconditionally stable numerical model has been implemented, which accounts for both the temporal and spatial profile of the sound beam. Instead of the 2D Bessel distribution, the sound beam was first fitted to an anisotropic 2D Gaussian distribution by means of the Levenberg-Marquardt algorithm. This approximation is mainly motivated by numerical considerations and by the fact that the angular frequency content of both distributions can be considered to be very alike [9]. Finally, the fitted 2D Gaussian surface is decomposed by application of the 2D spatial FFT, hence it is written as a superposition of harmonic plane waves, each propagating in a specific angular direction. Note that for large incident angles \(\theta\), such kind of Fourier decomposition leads to an unrealistic description since the possibility exists that plane waves are incorporated, having their wave vector \(\mathbf{k}\) pointing upwards, i.e. as if the plate is insonified from the bottom. However, because of mechanical considerations during the experiment, the incident angle \(\theta\) is anyway limited to \(70^\circ\) which makes the above concern of no importance.

![Figure 2: Quasi-harmonic signal at \(f = 5\text{MHz}\) in time domain (a) and in frequency domain (b). Measured radiated amplitude field in the yz-plane of the transducer (c), cross-section at \(z = 130\text{mm}\) of the amplitude (d) and phase distribution (e).]

3. Results

For simplicity, we first consider an immersed homogeneous and isotropic aluminum plate for which no influence on the polar direction is expected. The associated dispersion curves \(\theta(\omega d)\), which prescribe the condition for efficient Lamb wave stimulation under plane wave insonification, are shown in Figure 3. A longitudinal wave velocity \(c_L = 6300\text{ m/s}\), a shear wave velocity \(c_S = 3300\text{ m/s}\) and density \(\rho = 2700\text{ kg/m}^3\) have been considered for the aluminum, while the water is characterized by a wave speed \(c_{\text{Fluid}} = 1480\text{m/s}\) and a density \(\rho = 1000\text{kg/m}^3\).
Figure 3: Dispersion curves $\theta(f_d)$ for an immersed aluminum plate. The black vertical arrows indicate the $f_d$-values at which results have been obtained. The black circles indicate the possible Lamb wave stimulations.

Experimental as well as numerical results for the transmission coefficient as a function of the incident angle $\theta$ are presented in Figure 4 at three different $f_d$ values. At $f_d = 1.5\text{MHz} \cdot \text{mm}$ (Figure 4a) shows that 2 peaks are present, namely at $\theta \approx 17^\circ$ ($S_0$ mode) and $\theta \approx 35^\circ$ ($A_0$ mode), which is in correspondence with the dispersion curves. Note that the location of the bounded beam transmission peaks (experimental and simulated) are slightly shifted compared to the numerical results of the plane wave approach. Furthermore, the superiority of the bounded beam simulation, with respect to the plane wave simulation, to model the transmission amplitude can be clearly seen. Basically, the bounded beam approach lowers the transmission amplitude profile while the transmission peaks are widened, as could have been expected from a physics point of view. According to the dispersion curves, surpassing the first cut-off frequency-thickness $f_d = 1.65\text{MHz} \cdot \text{mm}$ should give rise to the excitation of higher order Lamb modes. Indeed, the results obtained at $f_d = 3\text{MHz} \cdot \text{mm}$ (Figure 4b) show several additional transmission peaks, which belong to the stimulation of the $S_1, S_1, A_1$ Lamb modes. Similar observations and conclusions can be formulated concerning the agreement of both computational approaches with the experimental recording. Investigation of the results for a further increase of the frequency-thickness to $f_d = 4.5\text{MHz} \cdot \text{mm}$ points out some additional concerns (see Figure 4c). First of all, whereas the dispersion curves predict the stimulation of 5 Lamb waves, this is not the case for the numerical nor the experimental results. Part of it can be attributed to the convergent nature of the fundamental $A_0$ and $S_0$ mode, which implies that both modes cannot be resolved anymore, and thus merge into one single transmission peak. Secondly, making abstraction of the $A_0$ and $S_0$ mode, it can be observed that the number of higher order Lamb mode transmission peaks differ: 3 for the plane wave simulation, 2 for the bounded beam approach and 2 for the experimental recording. Indeed, the transmission peak at $\theta \approx 15^\circ$, which corresponds to the stimulation of the $S_1$ mode, is not at all represented in the bounded beam simulation nor in the experimental recording. The present results thus reveal that a quasi-harmonic UPS experiment cannot be regarded as if it were a pure fingerprint of the Lamb wave angles because of the integrating effect of a realistic bounded beam. These observations are of utmost importance for the correct interpretation of a quasi-harmonic UPS experiment, and for the use of the UPS method to infer the elasticity properties of the insonified material spot.

Although the bounded beam simulations correspond quite well to the experimental recordings, still some deviations are seen in the exact shape of the transmission coefficient. This can be mainly attributed to two causes. First, the approximation of the experimental bounded beam by a 2D Gaussian distribution. Second, the lack of knowledge of the imaginary parts of the elasticity tensor which prevents us to correctly account for the viscoelastic nature of the insonified solid, and thus for the damping of the ultrasonic waves in the solid. The latter becomes especially important for increasing $f_d$-value because of the nature of material damping.
Figure 4: Normalized amplitude of the transmitted sound for an aluminum sample at: $f_d = 1.5$ MHz.mm, $f_d = 3$ MHz.mm and $f_d = 4.5$ MHz.mm: plane wave computation (solid line), bounded beam computation (dashed line) and experimental recording (dotted line).

In Figure 5, a comparison is shown between the bounded beam simulation and the recorded UPS experiment for different types of materials at a specific $f_d$-value. Comparison with the pulsed UPS recordings (see Figure 1) clearly shows an altered fingerprint. Since neither the real nor the imaginary parts of the elasticity tensor for the carbon laminates were available, representative values for the mechanical properties have been estimated (see Table 1). The resemblance of the contours in the experiment and the simulation suggests that the estimated real C-tensor may be fairly close to the actual mechanical properties of the carbon laminates. Nevertheless, the recorded and simulated transmitted amplitudes differ quite significantly for the carbon/epoxy composites, indicating the rather poor estimation of the imaginary C-tensor.

Figure 5: Experimentally recorded and numerically computed UPS of (a-b) aluminum at $f_d = 3$ MHz.mm, (c-d) [0]_8 carbon/epoxy laminate at $f_d = 6.6$ MHz.mm and (e-f) cross-ply [0_2,90_2]_S carbon/epoxy laminate at $f_d = 3.3$ MHz.mm.

Table 1: Estimated viscoelastic properties of a carbon/epoxy lamina.

<table>
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<tr>
<th>$E_1$ [MPa]</th>
<th>$E_2$ [MPa]</th>
<th>$E_3$ [MPa]</th>
<th>$v_{12}$ [-]</th>
<th>$v_{13}$ [-]</th>
<th>$v_{23}$ [-]</th>
<th>$G_{12}$ [MPa]</th>
<th>$G_{13}$ [MPa]</th>
<th>$G_{23}$ [MPa]</th>
<th>$\rho$ [kg/m$^3$]</th>
</tr>
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<tr>
<td>119.13 (1-0.0025i)</td>
<td>8.85 (1-0.03i)</td>
<td>10 (1-0.03i)</td>
<td>0.306 (1-0.01i)</td>
<td>0.275 (1-0.01i)</td>
<td>0.475 (1-0.01i)</td>
<td>5.5 (1-0.03i)</td>
<td>5 (1-0.02i)</td>
<td>3 (1-0.05i)</td>
<td>1733</td>
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4. Phase UPS

Since a quasi-harmonic wave can be fully described by the combination of its amplitude and its phase, it is possible to extend conventional amplitude UPS analysis to the phase of the transmitted wave. Whereas it is relatively easy to extend the numerical model to incorporate the computation of the phase of the transmitted waves, experimentally this becomes much more difficult as phase measurements are known to be highly sensitive to minor experimental errors. On the other hand, for material research, phase measurements could turn out to be very useful, precisely because of its sensitivity to small perturbations.

The experimentally recorded and numerically computed phase results for an aluminum sample, insonified at $f_d = 3$ MHz.mm, are shown in Figure 6. Overall, a good correspondence is obtained between both curves. For large incident angles $\theta$ however, the experimentally recorded phase becomes unsteady and highly oscillatory, and a deviation with respect to the numerical values can be observed. This unsteady behavior should be attributed to the small amplitude level of the transmitted wave at large incident angles $\theta$ (see Figure 4b), which obviously complicates the accurate recording of the phase information of the transmitted sound.

Similarly as for the amplitude analysis discussed in the previous section, the recorded and computed phase UPS for several materials are presented in Figure 7 at fixed $f_d$-values. The phase results for the aluminum sample show satisfying agreement. For the carbon/epoxy materials, a relatively large difference is noticeable between the recorded and computed phase map, potentially again cause by the unknown imaginary elasticity tensor. Indeed, numerical simulations indicate that the phase UPS is sensitive to the viscoelastic nature of the sample. Despite the particular details, it can be stated that the qualitative agreement between experiment and numerical model is acceptable. In comparison with the amplitude recording, the detail and sharpness of the characteristic phase patterns is much more outspoken and defined. Hence, these results suggest that the phase UPS has the potential to become a valuable means for NDT and material characterization in general. In fact, by combining the amplitude UPS with the phase UPS, one obtains full knowledge about the complex transmission coefficient. Current research focuses on a better understanding of the formation of the patterns in a phase UPS, and eventually to extract hidden information.

Figure 6: Recorded and computed phase of the transmitted wave for an aluminum sample insonified at $f_d = 3$ MHz.mm.
Figure 7: Experimentally recorded and numerically computed phase UPS of (a-b) aluminum at $f_d = 3$ MHz.mm, (c-d) $[0]_8$ carbon/epoxy laminate at $f_d = 6.6$ MHz.mm and (e-f) cross-ply $[0_2,90_2]_3$ carbon/epoxy laminate at $f_d = 6.6$ MHz.mm.

5. Effect of a delamination

Till now, the discussion has been limited to the investigation of intact or virgin material samples. However, the UPS technique can also be applied to detect and characterize a damaged material zone, due to impact, fatigue, etcetera. Here we investigate an often encountered failure mechanism in several industrial applications, namely the presence of a delamination. Several carbon/epoxy samples have been autoclave manufactured, in which an artificial delamination has been added by the use of a kapton insert with thickness $d = 50 \mu m$. After the manufacturing cycle, the kapton foil has been carefully removed, in order to obtain a representative edge delamination. In Figure 8, the experimentally recorded pulsed UPS results are shown for a virgin and a delaminated $[0]_8$ carbon/epoxy laminate. Besides a general transmission amplitude drop, no substantial change in the characteristic contours can be observed. Taking into account that a pulsed UPS is basically dominated by non-dispersive bulk wave phenomena, this could have been expected.

Figure 8: Pulsed UPS of a UD carbon/epoxy laminate recorded at $f_d = 5.5$ MHz.mm: (a) $[0]_8$ and (b) $[0]_8$ with a delamination between layer 4 and layer 5.
In Figure 9, the experimentally recorded quasi-harmonic UPS results (amplitude and phase) are presented for the UD carbon/epoxy laminates. Contrary to the pulsed UPS results, a considerable shift in the characteristic contours can be observed for both the amplitude and the phase recording. This can be readily understood by considering the fact that the delamination basically divides the laminate into two separate layers, with each layer having half of the original thickness \( d \). Since Lamb waves are dispersive of nature, i.e., they are dependent upon the frequency-thickness \( f_d \) (see Figure 3), the thinning effect of the delamination induces a change in the conditions for efficient Lamb wave stimulation, and thus results in a shifted characteristic fingerprint. Similar observations hold when performing the measurement in reflection. Further, as the investigated sample has a thickness \( d \) comparable to the applied acoustic wavelength \( \lambda \), the use of the ultrasonic C-scan becomes rather cumbersome for the detection of the delamination because of overlapping echoes. The quasi-harmonic UPS does not suffer from this limitation, since it relies on the stimulation of Lamb modes, instead of capturing an echo directly originating from the delaminated interface.

Figure 9: Quasi-harmonic UPS of a UD carbon/epoxy laminate recorded at \( f_d = 5.5 \text{ MHz.mm} \); amplitude (left) and phase (right): (a-b) [0]_8 and (c-d) delaminated [0]_8.

6. Conclusions

For the first time, UPS experiments have been obtained using quasi-harmonic pulses. To obtain acceptable agreement with the simulation, the plane wave model has been extended in order to incorporate the angular frequency content of the experimental sound beam. The results show a link between the UPS contours and the stimulation of Lamb waves. Nevertheless, it is clear that the obtained quasi-harmonic UPS image cannot be conceived as a pure lamb wave angle fingerprint, precisely because of the bounded nature of a realistic sound beam.

In addition, we extended both the numerical model and the experimental setup to the analysis of the phase of the transmitted wave, thus introducing the concept of the phase UPS. The phase UPS show even more intriguing and detailed patterns than the traditional amplitude UPS. Knowledge of both the amplitude and phase map yield complete knowledge of the complex
transmission coefficient. Future work will focus on the determination of the frequency dependent complex elasticity tensor from a quasi-harmonic UPS experiment through inverse modeling. Finally, the superiority of the quasi-harmonic UPS, with respect to the pulsed UPS, has been demonstrated for the detection of a delamination. It has been shown that the quasi-harmonic UPS fingerprint shows great sensitivity to the presence of a delamination. Currently, an investigation is performed on cross-ply carbon/epoxy samples with an artificial delamination. First experimental results are very promising.

7. References


