ANISOTROPY OF PLATE WAVES IN COMPOSITES: EFFECTS AND NDE IMPLICATIONS

(ELASTIC ANISOTROPY OF CFRP: A HURDLE FOR SHM-APPLICATIONS?)

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Introduction: Ultrasonic waves & Elastic anisotropy

Christoffel equations:

\[(c_{ijkl} n_j n_l - \rho v^2 \delta_{ik}) u_k = 0\]
\[\det \left| c_{ijkl} n_j n_l - \rho v^2 \delta_{ik} \right| = 0 \quad \text{Bulk wave velocities}\]

Velocity anisotropy for **bulk** and **surface** waves is an intrinsic material property
Questions to be answered:

- Is plate wave anisotropy frequency dependent? (Dispersion of velocity anisotropy?)
- If yes: What are the implications for applications (SHM-)?
Outline

- Velocity anisotropy for plate waves in CFRP:
  - Numerical analysis of frequency dependence
  - Experimental results

- Implications for plate wave application in composites:
  - Dispersion of beam steering
  - Phonon focusing in composites
Numerical analysis of plate wave anisotropy

Calculations of in-plane velocity anisotropy (a₀-mode) in UD-CFRP (T300/914)

\[(f \cdot D) \rightarrow 4000, 3000, 500, 250, 175, 50, \text{and } 5.\]

Anisotropy depends on frequency: Maximum a₀-mode anisotropy for low \((f \cdot D)\)
Quantification of dispersion of velocity anisotropy

Parameters of anisotropy: \( A_{a_0,s_0} = \frac{v^{0\degree}_{a_0,s_0}}{v^{90\degree}_{a_0,s_0}} \)

\[ A_{a_0} (f \cdot D) \]

\[ A_{s_0} (f \cdot D) \]
Dispersion of anisotropy: Why?

Anisotropy at a certain frequency corresponds to different wave structures

Contribution of frequency-dependent wave structure provides dispersion of anisotropy
Dispersion of velocity anisotropy: $a_0$-interpretation

$$\lim(f \to 0): \quad (v_{a_0})_i \approx (\pi D f)^{1/2} (E_i / 3 \rho)^{1/4}$$

$$A_{a_0}^{static} \approx (E_0 / E_{90})^{1/4} \approx 1.95$$

Fast transition to shear

Slow transition to shear

$$A_{a_0} = v_{a_0}^{0\circ} / v_{a_0}^{90\circ}$$

Fast decrease of $a_0$-anisotropy parameter
Dispersion of velocity anisotropy: $s_0$-interpretation

$$f \to 0: (\nu_{s_0}(\alpha))_{x_i} \approx (E_i(\alpha) / \rho)^{1/2}$$

$$A_{s_0}^{static} \approx (E_0 / E_{90})^{1/2} \approx 3.81$$

$$A_{s_0} = \nu_{s_0}^{0^\circ} / \nu_{s_0}^{90^\circ}$$

Fast increase of $s_0$-anisotropy parameter
Dispersion of velocity anisotropy: asymptotic behaviour \( f \to \infty \)

Transition to shear (out-of-plane) for \( a_0 \)- and \( s_0 \)-waves

\[ a_0^\infty = a_0^\infty \approx 1.2 \]
Dispersion of velocity anisotropy: Experimental study

Air-Coupled Ultrasound (ACU)
- Broadband ACU transducer
- Frequency range 40 – 100 kHz
- Phase velocity derived from phase matching condition

Wave Front Imaging (WIM)
- Wide-band L-wave transducer
- Frequency range 15 – 250 kHz

34x24x0.25 cm³, 20 ply UD-CFRP specimen

Laser vibrometer

2D-scan

Point-like transducer

\[ \theta_c = \sin \frac{\theta_{1/2, \text{air}}}{v_p} \]
Phase velocity anisotropy: Overall pattern ($a_0$-wave)

WIM: Conversion from group ($v_g$) to phase velocity ($v_p$)

$$v_p(\alpha) = v_g(\theta) \cos \psi$$

Beam steering angle: $\psi = \alpha - \theta$

- Velocity anisotropy is frequency-dependent
- Anisotropy increases at low $f \cdot D$
- Excellent fit to numerical data
Dispersion of velocity anisotropy: Experimental evaluation

\[ A_{a_0} = \frac{v_{a_0}^0}{v_{a_0}^{90\degree}} \]

\[ A_{s_0} = \frac{v_{s_0}^0}{v_{s_0}^{90\degree}} \]
Implications for applications: Dispersion of beam steering \((a_0\text{-modes})\)

Beam steering angle: \(\tan(\psi(\theta)) = (1/v_p)dv_p/d\alpha\)

- Energy steering depends on frequency
- Strong beam steering at low \((f \cdot D)\)
- Similar behaviour to \(A_{a_0}(f \cdot D)\)
Beam steering of $a_0$-wave: Experimental evidence

- ACU excitation of 50 kHz $a_0$-wave ($f \cdot D = 125$)
- (315°) propagation direction
- Wave field visualization with laser vibrometer

$\psi \approx 32^\circ \pm 2^\circ$
Implications: dispersion of phonon focusing

Focusing factor:

\[ F = \left| \frac{d\theta}{d\alpha} \right|^{-1} \]

Dispersion of phonon focusing

Phonon focusing in UD-CFRP
Conclusions

- Unlike bulk ultrasound, elastic anisotropy of plate waves strongly depends on frequency (dispersion of anisotropy)

- Dispersion of beam steering and phonon focusing affect configurations of ultrasonic sensors in SHM-applications

- Effects of anisotropy can be controlled by proper choice of operation frequency
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