Dataset: Polar group velocity representations for fiber-reinforced polymer composites using stiffness matrix method

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ABSTRACT

Material property identification in composite materials is necessary for material degradation as well as non-destructive characterization. The inverse problem needs a forward simulator. Ultrasonic-guided waves are sensitive to material properties and can be used for the purpose. The stiffness matrix method and group velocity calculation routine are used as the forward solver. The solver outputs polar group velocity curves of two fundamental Lamb wave modes for different material properties and ply layup sequences. The curves can be converted into binary images (black and white) named polar representations for image processing algorithms. The datasets contain polar representations corresponding to different material properties and ply layup sequences of a transversely isotropic laminate.

Background & Summary

Composite materials have revolutionized different industries due to their high strength-to-weight ratio and improved manufacturing techniques at lower costs. However, due to uncertainties involved at different stages, beginning from the design phase to the end of the material's service life, accurate determination of material properties presents unprecedented challenges. Therefore, the characterization of composite materials is necessary not only for non-destructive property measurements but also for real-time material degradation aspects. Ultrasonic guided waves (UGW) based technique has gained a tremendous amount of attention in recent years for non-destructive evaluation (NDE), and structural health monitoring (SHM) of composite structures[1,2].

Methods

Ultrasonic lamb waves are the superposition of bulk waves in waveguides. Due to the presence of boundaries and interfaces, phase velocity and group velocity of the wave becomes frequency-dependent (dispersion)[3]. Along with this, the velocities also depend on the propagation direction for anisotropic composites. In acoustic field theory, the Christoffel equation is a combination of three equations. These equations are strain-displacement relation, equation of motion and elastic constitutive equation, combining them gives Eq. (1)[4].

$$\rho \frac{\partial^2 u_i}{\partial t^2} = c_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k}. \tag{1}$$

where ρ is the density of the solid, u is the displacement field and c_{ijkl} is the stiffness tensor. To solve the above equation, u_i can be written in terms of bulk wave amplitudes U_i as shown in Eq. (2).

$$(u_1, u_2, u_3) = (U_1, U_2, U_3)\mathrm{e}^{\mathrm{i}\xi(x_1+\alpha x_3 - c_\mathrm{p} t)}, \tag{2}$$

In the above equation, c_p is the phase velocity component along x_1, ξ $(= \omega/c_\mathrm{p})$ is the wavenumber along x_1, and α is the ratio of the wavenumber of bulk waves along the x_3 and x_1-directions ($\alpha = \zeta_3/\zeta_1 = \zeta_3/\xi$). Eq. (2) can be substituted into the Eq. (1) to obtain the Christoffel matrix

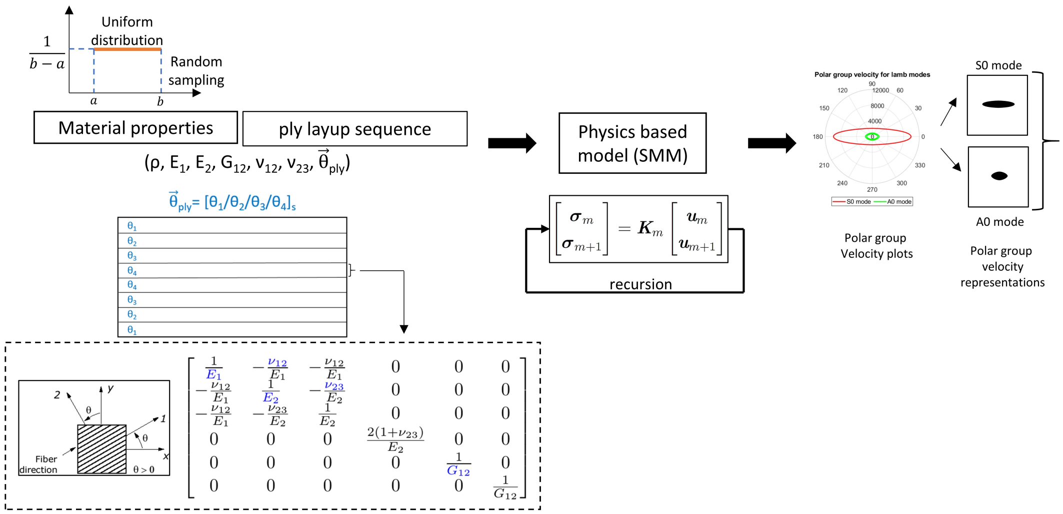

Figure 1. Detailed schematic of forward physics-based model: Material properties (ρ,E_1,E_2,G_{12},μ_{12},μ_{23}) and ply-layup sequence (constant) are the inputs to the model and polar representations are the outputs[5]

$$\begin{bmatrix} C_{11}-\rho c_p^2+C_{55}\alpha^2 & C_{16}+C_{45}\alpha^2 & (C_{13}+C_{55})\alpha \\ & C_{66}-\rho c_p^2+C_{44}\alpha^2 & (C_{36}+C_{45})\alpha \\ \text{sym} & & C_{55}-\rho c_p^2+C_{33}\alpha^2 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = 0, \tag{3}$$

The matrix contains stiffness matrix coefficients C_{ij}, wavenumber ratio α, phase velocity c_p and density ρ. In order to obtain non-trivial solutions for U_1, U_2, and U_3, the determinant of the matrix vanishes. This yields a sixth-degree polynomial equation, which needs to be solved for α. SMM is used extensively in the popular Dispersion Calculator to simulate wave propagation behavior in materials[4]. The detailed mathematical formulation of SMM is presented in Ref.[5].

Data Records

The entire approach of using SMM and the group velocity calculation routine as the forward model is presented schematically in Fig. 1.

Table 1. Material properties of commercially available CFRP composite materials

Commerical CFRP composite materials	ρ (kg/m^3)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ν_{23}
AS4M3502[6]	1550	144.6	9.6	6	0.3	0.28
GraphiteEpoxy_Rokhlin_2011[7]	1610	150.95	12.8	8	0.47	0.45
SAERTEX7006919RIMR135[8]	1454	119.9	7.25	6	0.32	0.45
SigrafilCE125023039[6]	1500	128.6	6.87	6.1	0.33	0.37
T300M914[9]	1560	139.92	10.05	5.7	0.31	0.48
T700M21[10]	1571	125.5	8.7	4.1	0.37	0.45
T700PPS[6]	1600	149.96	9.98	4.5	0.29	0.37
T800M913[6]	1550	152.14	6.64	20	0.25	0.54
T800M924[11]	1500	161	9.25	6	0.34	0.41
T800_Michel[12]	1510	178.96	9.17	5.5	0.36	0.53

Two material sets (Matsets) containing six material properties (density, Young's modulus in 1 and 2 directions, shear modulus in 1-2 plane, Poisson's ratio in 1-2 and 2-3 plane) are generated for this study. Matset-1 is a set of material properties containing commercial CFRP materials (Table-1). For Matset-2, the six material properties are varied in a range (ρ = [1304 1760] kg/m^3, E_1 = [115 184] GPa, E_2 = [6 14] GPa, G_{12} = [3 9] GPa, ν_{12} = [0.2 0.52], ν_{23} = [0.23 0.59]). A vector of six elements that corresponds to the six material properties is randomly selected from a uniform distribution with the abovementioned bounds. Each material (Matset-1 & 2) is fed into the forward model (See Fig. 1), which provides polar group velocities at different excitation frequencies ranging from 20 kHz to 200 kHz in increments of 20 kHz. Both the fundamental lamb modes are dispersive in this frequency range. This range is considered suitable for Lamb-wave propagation-based experiments because the selected range with the given thickness eliminates higher lamb wave modes which may complicate the study[13]. This process is performed for 16-layered symmetric laminate with 2 mm thickness. Further, the polar group velocities are transformed into binary images (black & white images) called polar representations.

Dataset-1 contains samples corresponding to 10 materials with 10 different frequencies for each Lamb mode and three different ply-layup sequences, i.e., unidirectional, cross-ply, and quasi-isotropic. Dataset-2 contains samples corresponding to 987 materials with 10 different frequencies for each Lamb mode and a unidirectional laminate. Dataset-1 contains 600 samples, whereas Dataset-2 includes 19,740 samples.

Technical Validation

The datasets are collected using the backend Matlab code of Dispersion calculator[8]. Both the code as well as the user interface product are open sourced.

Usage Notes

The datasets are uploaded at `doi.org/10.5281/zenodo.7301863`. The folder contains two subfolders with the name *'Dataset-1_COMM'* and *'Dataset-1_GEN'* containing polar group velocity representations corresponding to commercial materials and generated materials, respectively. The folder *'Dataset-1_COMM'* has labels and images for cross-ply, quasi-isotropic and unidirectional laminate for both A0 and S0 modes. The folder *'Dataset-1_GEN'* has labels and images for unidirectional laminate for both A0 and S0 modes.

Code availability

The backend Matlab code is taken from open-sourced Dispersion calculator[8] to generate the above dataset.

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