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The influence of temperature variations on ultrasonic guided waves in anisotropic CFRP plates

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ABSTRACT

Carbon Fibre Reinforced Polymer (CFRP) materials are lightweight and corrosion-resistant and therefore are increasingly used in aerospace, automotive and construction industries. In Structural Health Monitoring (SHM) applications of CFRP materials, ultrasonic guided waves potentially offer large area inspection or inspection from a remote location. This paper addresses the effect of temperature variation on guided wave propagation in highly anisotropic CFRP materials. Temperature variations cause changes in guided wave velocity that can in turn compromise the baseline subtraction procedures employed by many SHM systems for damage detection. A simple model that describes the dependence of elastic properties of the CFRP plates on temperature is presented in this paper. The model can be used to predict anisotropic velocity changes and baseline subtraction performance under varying thermal conditions. The results produced by the model for unidirectional and 0/90 CFRP plates are compared with experimental measurements.

1. Introduction

Ultrasonic guided waves can travel long distances in plate-like structures without significant attenuation and therefore potentially offer large area inspection, or inspection from a remote location, with a relatively small number of sensors in Structural Health Monitoring (SHM) applications [1–4]. Carbon fibre reinforced polymer (CFRP) materials are strong, lightweight and corrosion-resistant materials and therefore are increasingly used in the construction, automotive and aerospace industries [5]. There is a demand from industry to develop SHM techniques for CFRP materials and structures.

The quantification of propagation characteristics in CFRP materials is crucial when designing guided-wave-based SHM systems and it remains the focus of current research [6–10]. This paper examines the effect of temperature variation on guided wave propagation and its influence on the performance of baseline subtraction techniques used in SHM. Temperature response is well understood for guided waves in isotropic materials [2,11,12], however studies for CFRP materials concentrate on quasi-isotropic cases only [13,14].

The SHM paradigm is based on observation of the relative changes in a structure by means of permanently installed transducers. The baseline signal characterizing the structure, $I_0(t)$, is firstly recorded, when it is known to be in a damage-free condition. The baseline waveform contains guided wave scattered signals from all the structural features. $I_0(t)$ is then compared with a measurement, I(t), made during the monitoring and any deviation infers damage in the structure. One of the widely adopted methods of comparison is the baseline subtraction technique, where the baseline signal is subtracted from the waveform acquired during the monitoring stage: [15,2–4]

$$u(t) = I(t) - I_0(t) \qquad (1)$$

The resulting residual signal, $u(t)$, would ideally isolate any small signals corresponding to damage that could otherwise be masked by the signals associated with structural features, or give perfect subtraction when there is no damage. However, environmental changes like temperature variation affect guided wave propagation and result in elevated residual signal levels that can be mistaken for damage. The maximum amplitude in the residual signal, expressed as a fraction of the maximum amplitude in the original recorded signal, for isotropic materials can be expressed as: [2,3]

$$u_{max} = \frac{\omega r}{v_p}\left(\alpha - \frac{k_p}{v_p}\right)\delta T \qquad (2)$$

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where ω is the angular centre frequency of the signal, r is the propagation distance, v_p is the phase velocity, α is the coefficient of thermal expansion, δT is a temperature change and $k_p = \delta v_p/\delta T$ is a coefficient of velocity change with respect to temperature change. In anisotropic materials v_p is directionally dependent and so are the coefficients k_p and α, implying that the maximum residual is also a function of propagation direction. For CFRP plates α is smaller, by at least an order of magnitude, than k_p/v_p, determined later in the paper ignoring α, and hence it is excluded from calculations in this paper [16].

A model that predicts guided wave velocity response to temperature variations in CFRP plates, which in turn can determine the baseline subtraction performance using Eq. 2, is presented in Section 4. It is a relatively simple model with only two linear equations involved to describe the influence of temperature on the elastic moduli of CFRP plates. Firstly, a brief overview of guided wave propagation phenomenon in highly anisotropic plates is given in the next section. Following this, an experimental procedure used to investigate guided wave propagation under thermally varying conditions is described in Section 3. The experimental data was used to evaluate the subtraction performance predicted by the model discussed in Section 4. The overall anisotropic subtraction performance is also discussed for unidirectional and cross-ply plates and conclusions drawn in the last section.

2. Overview of anisotropic propagation

CFRP materials are anisotropic materials with directionally dependent physical properties leading to directionally dependent propagation of guided waves such as dispersion as shown in the example case of fundamental guided wave modes in unidirectional CFRP plate in Fig. 1. Not only dispersion becomes directionally dependent, phase and energy velocity vectors generally do not point in the same direction in anisotropic materials [8,10,9,6,7]. Direction of energy velocity vector is perpendicular to the tangent of the phase slowness (inverse of phase velocity) corresponding to a particular phase velocity direction (see Fig. 2). This phenomenon is known as steering [6,7] and the angle difference between the velocity directions of phase, θ_p, and energy, θ_e, is called the steering or skew angle, ψ. Since velocity vectors point in different directions, only a projection is observed of the phase velocity vector in the energy velocity direction and vice versa. Experimental

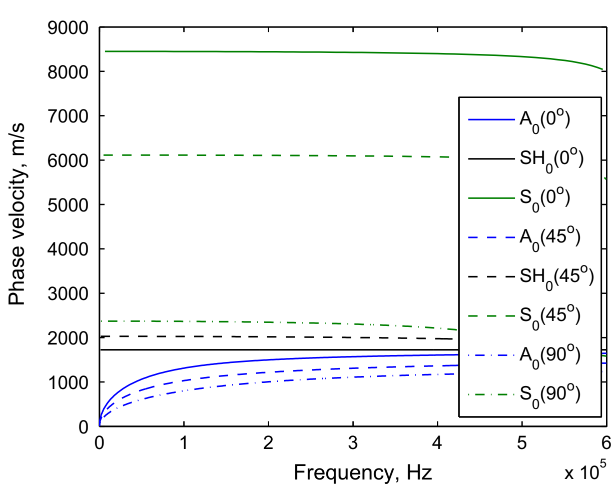

Fig. 1. Examples of dispersion curves of fundamental modes in unidirectional CFRP plate in different phase velocity directions. Curve corresponding to SH_0 mode in 90° is the same as in 0° and therefore is not shown. Plate is 2 mm thick, its elastic are constants given in Table 1.

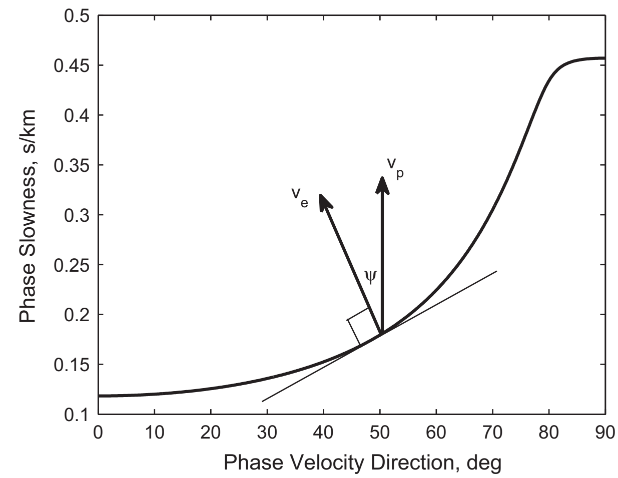

Fig. 2. A typical phase slowness curve for unidirectional (0°) CFRP plate for S_0 mode at low frequencies. Phase and energy velocity vectors point in the same direction only in principal directions, i.e. $\theta_p = 0$ and $\theta_p = 90$.

measurements are typically made in the θ_e direction and hence it is more convenient to consider $v_p(\theta_e)$ rather than $v_p(\theta_p)$, as shown in Fig. 3.

Steering also leads to energy focussing [17,18], which results in increased or decreased amplitude excitability in particular directions as shown in Fig. 4(a). It can be seen that there is a relatively large energy focussing for the A_0 and S_0 modes towards fibre direction, which makes excitation in non-fibre directions more difficult. In addition, steering can give rise to multiple energy velocity values in certain energy velocity directions, as in the example case for SH_0 mode shown in Fig. 4(a), which can result in guided wave mode signal travelling as multiple wavepackets in certain directions. Moreover, the distinction of different guided wave modes through their mode shapes is no longer obvious in anisotropic materials and, for example, the mode shapes of S_0 and SH_0 modes are very similar in certain directions. In this paper, Lamb's notation for the modes of an isotropic plate are employed for simplicity.

The Semi-analytical Finite Element (SAFE), also called spectral element, method [19,8,20,10] was used in this paper to calculate dispersion curves for anisotropic CFRP plates. In SAFE model the plate is discretized along the thickness of the plate with each element representing a single ply in the plate. The displacement along the propagation direction is assumed to be harmonic. Then, finite

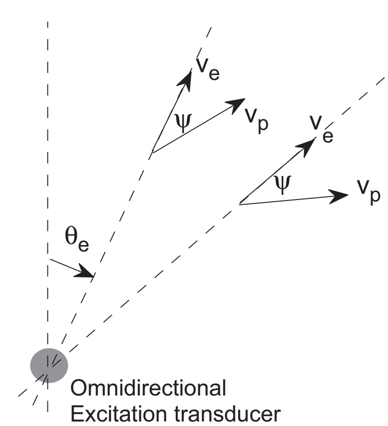

Fig. 3. A diagram indicating the meaning used for $v_p(\theta_e)$ in this paper: magnitude of phase velocity vector corresponding to energy velocity vector pointing in θ_e direction.