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Guided ultrasonic waves for determining effective orthotropic material parameters of continuous-fiber reinforced thermoplastic plates

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ABSTRACT

Ultrasonic methods are widely established in the NDE/NDT community, where they are mostly used for the detection of flaws and structural damage in various components. A different goal, despite the similar technological approach, is non-destructive material characterization, i.e. the determination of parameters like Young's modulus. Only few works on this topic have considered materials with high damping and strong anisotropy, such as continuous-fiber reinforced plastics, but due to the increasing demand in the industry, appropriate methods are needed. In this contribution, we demonstrate the application of laser-induced ultrasonic Lamb waves for the characterization of fiber-reinforced plastic plates, providing effective parameters for a homogeneous, orthotropic material model.

1. Introduction

Ultrasonic measurement methods are well-established in non-destructive evaluation and testing (NDE/NDT) applications, where they are used for detecting material defects like cracks. The results are usually presented as images to be interpreted by a human operator or analyzed computationally to find dimensions or orientation of the defect (qualitative and quantitative NDE [1]). Different kinds of ultrasonic approaches can be found along with examples of applications in mechanical [2–4], civil [5] and biomedical [6] engineering.

However, ultrasonic techniques can also be used for material characterization, i.e. the process of determining specific properties of a material, like Young's modulus [7]. In contrast to defect characterization, where the region of interest is sampled locally (scanned), the goal in material characterization is to provide "global" information that is valid for the given material, independent of the specific sample's geometry or structure. One possible use case relevant in the industry is the continuous monitoring of components, especially in safety-critical applications. Here, ultrasonic material characterization can be used to detect material degradation even before significant structural damage occurs [8,9].

For both NDE and material characterization purposes, modern materials, such as polymers and fiber-reinforced plastics (FRPs), pose additional challenges because of significant absorption and – especially for continuous fiber reinforcement – strong anisotropy [10]. This increases the number of unknowns and, consequently, the complexity of the required mathematical models.

Different approaches for ultrasonic material characterization have been developed over the years. Some have been applied to small-scale anisotropy, e.g. material crystallinity [11] or stacked-plate structures [12], while a few works also consider large-scale anisotropy as can be found in continuous-fiber reinforced plastics [13]. A common method also applied to FRPs is the immersion technique [13–15], which requires the measurements to be carried out in water. However, water resorption can lead to drastic changes in the elastic behaviour of the material, even for short exposition times [9,8]. One example is polyamide 6 (PA6), commonly used as the matrix material for FRPs, which is particularly susceptible to this effect.

In this paper, we demonstrate the inverse identification of effective material parameters, based on laser-induced ultrasonic Lamb waves. The general approach is adapted and applied to three different sample types, covering different degrees of isotropy. Results are compared to values obtained with the traditional approach of tensile testing as per ISO 527–4/5.

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2. Experimental investigation

2.1. Material samples

In this investigation, three different kinds of samples were used, which all share a square plate geometry with approx. 250 mm sides. The first sample (type I) is included as a reference with simpler properties compared to the other two. It is made from plain polyamide 6 and can, in good approximation, be considered isotropic. The other samples (type II and III) are continuous-fiber reinforced plastic plates (FRPs) with a polyamide 6 matrix and orthogonally oriented glass fibers. These materials can be considered orthotropic.

The two FRP variants differ in the fiber distribution ratio along the two in-plane directions: While type II features a traditional symmetric canvas weaving with an identical amount of fibers oriented in either direction (50:50), type III has a distribution ratio of 80:20. Consequently, type II can be considered transversely isotropic, a special case of orthotropy.

Table 1 shows the relevant properties for all three sample types. The displayed values for the thickness were determined via direct measurements using a digital caliper, while the other properties are taken from the respective datasheet or product description.

Table 1
Properties of material samples used in the experimental investigation.

Type	Material	Fiber distr.[a]	Thickness d/mm	Density $\rho/\frac{kg}{m^3}$
I	PA 6	–	8.8	1156
II	PA 6/ Glass	50:50	3	1800
III	PA 6/ Glass	80:20	0.5	1800

[a] Distribution ratio of the fibers along the two orthogonal in-plane axes.

2.2. Measurement setup

The experimental setup used for the following measurements is designed for plate-shaped specimens [16,17], which fits the commonly produced shape of FRPs, and is generally similar to the setups used in [18,19]. For ultrasonic wave excitation, high-power laser[1] pulses are focused onto a thin 15 mm long line on the specimen's surface, using a mirror and a cylinder lens. This quickly heats up a small portion of the specimen, causing rapid material expansion and therefore the excitation of ultrasonic Lamb waves [20] – a result of the photo-acoustic effect [21,22]. Due to the short pulse duration (3 ns full duration at half maximum), this provides wide-band, multi-modal excitation. After propagating through the specimen, the ultrasonic wave is received by a purpose-built piezoceramic strip transducer [16], which is placed on the specimen's surface with a thin layer of couplant[2] being applied. The transducer has an active area of approx. 1 mm × 12 mm and a bandwidth of approx. 8 MHz [23].

The line-shaped laser focusing is chosen instead of a traditional dot shape for two reasons: First, this increases the affected surface area, decreasing the energy density and thus preventing ablation. Secondly, the received signal would otherwise be distorted because of using a line-shaped receiver to detect circular wave fronts.

The received signal is recorded with a USB oscilloscope[3] for digital storage and further processing. A signal generator is used to simultaneously trigger both the data acquisition and the laser pulse, allowing repeated, synchronized measurements. The results are then averaged to increase the signal-to-noise ratio [23].

Furthermore, the optical focusing assembly (cylinder lens and mirror) is mounted on a linear actuator[4], so that the point of excitation and, consequently, the wave propagation distance to the receiver can be varied. Performing multiple measurements at – usually equidistantly placed – positions then provides spatial resolution in addition to temporal resolution that is generally provided by a time series measurement.

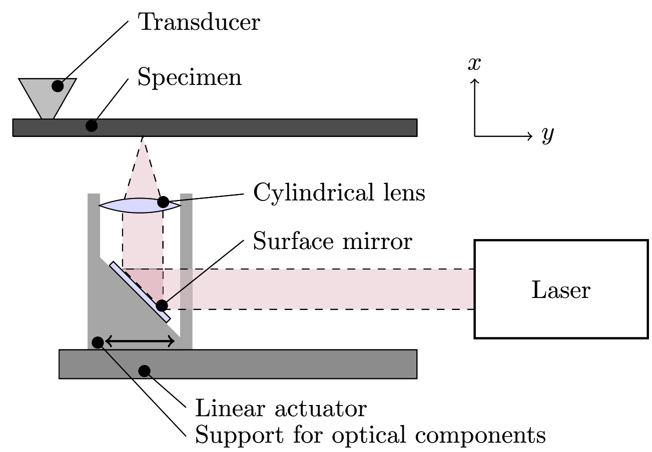

Fig. 1. Experimental setup (schematic) (adapted from [23]).

Fig. 1 schematically displays the experimental setup, which has already been used in the characterization of approximately isotropic materials like metals [16] and plain polymers [23].

It should be noted that, instead of the contact transducer, a vibrometer could be used for contactless detection. However, since these devices are not abundantly available (especially in the required frequency range), the contact transducer is chosen for this investigation. The results (see Section 4) underline that this setup is sufficiently sensitive and nonreactive. In fact, the authors expect the method to work with a variety of setups, including contact and contactless approaches for both excitation and detection of the ultrasonic waves.

2.3. Signal preprocessing

The measurement results for a single sample consist of a time-series result for every excitation position y. Those can be combined into a single two-dimensional matrix[5] $\mathbf{u}(y,t)$, where the dimensions correspond to space and time, respectively.

Taking advantage of the multi-modal excitation and the combination of temporal and spatial resolution, dispersion information can be extracted from the received signal. For this, the two-dimensional Fourier transform of the result matrix is calculated, yielding the *dispersion map* $\mathbf{U}$ [17]. In the Fourier domain, the independent variables can be interpreted as the temporal frequency f and the angular wavenumber (i.e. spatial frequency) k, so that

$$\mathbf{U}(k,f) = \mathcal{F}\{\mathbf{u}(y,t)\} \tag{1}$$

[24–26]. The dispersion map shows distinctive ridges of large values at all points (k,f) where mode propagation takes place. Consequently, the shapes of these ridges closely resemble the well-known dispersion curves [23]. This relation serves as the starting point for the subsequent material characterization.

[1] LTB Lasertechnik Berlin, model MNL 103-PD High Power, pulse energy 225 µJ
[2] GE multi-range coupling paste ZGT.
[3] TiePie Handyscope HS5-540.
[4] Zaber Technologies Inc., model T-LSM, positioning accuracy 8 µm

[5] Despite the fact that all signal processing is performed in MATLAB, i.e. with discrete signals, the following equations use continuous notation for the sake of readability.