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A non-destructive material characterization framework for retrieving a stiffness matrix using bulk waves

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ABSTRACT

The accuracy of the stiffness matrix used as input in dispersion curve algorithm determine the accuracy of the predicted wave speeds. Common practice is to use standard mechanical testing procedures to determining the E_{11}, E_{22}, G_{12} and ν_{12}. The other engineering constants are then based on assumptions such as: $E_{33} = E_{22}$. The engineering constants are converted to the stiffness matrix and used as input. Due to this approach the dispersion curves can vary significantly from those obtained experimentally.

In this research the stiffness matrix components are determined non-destructively using a newly introduced ultrasonic immersion technique, the LAMSS approach. The LAMSS approach utilizes the symmetry planes within an orthotropic transversely isotropic material and the critical angle approach to divide the stiffness matrix retrieval process into several steps to reduce the complexity of the process and increase the accuracy of the solution.

As last, the predicted group velocity dispersion curves obtained using a stiffness matrix based on mechanical testing and the ultrasonic immersion technique are compared to experimentally obtained velocities.

1. Introduction/state-of-the-art

Dispersion curve algorithms require the user to provide the stiffness matrix as an input. For an anisotropic material, this requires a matrix such as

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \tag{1}$$

It is, however, uncommon to have a fully anisotropic material as shown in Eq. (1). In fact, the material most commonly used will be an orthotropic transversely isotropic material (hereafter referred to as unidirectional) with only 5 independent stiffness components instead of 36:

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{12} & C_{23} & C_{22} & 0 & 0 & 0 \\ & & & \frac{C_{22}-C_{23}}{2} & 0 & 0 \\ & & & & C_{55} & 0 \\ & & & & & C_{55} \end{bmatrix} \tag{2}$$

The most common way to determine the stiffness matrix components for unidirectional materials is to follow the ASTM standard D3039/D 3039M and D 3518/D 3518M for the tensile and in-plane shear properties respectively. The ASTM standards require destructive mechanical testing and at least five specimens for each material property that needs to be determined, this however is expensive both in time and cost. Methods to determine the stiffness matrix components non-destructively are therefore desired. In particular, focus has been set on techniques based on the analysis of the propagation of bulk waves due to the direct correlation between the material's stiffness matrix components and the characteristics of the bulk waves [1–4]. One specimen can be used to determine all the stiffness matrix components by orientating the specimen in different directions, measuring the time-of-flight (ToF) experimentally and deriving the phase velocities [5–7,4,8].

In 1970, Markham [5] introduced a method to determine the elastic constants for composite laminates using ultrasonics. By measuring the ultrasonic wave velocities in multiple directions Markham determined the elastic constants of the laminate. Smith [6] applied Markham's method and was able to determine five elastic constants for his measurements. The number of elastic constants determined by Markham's method was later increased to nine by Gieske and Allred in 1972 [8].

At the same time Gieske and Allred in 1972 [8] correctly observed that the ToF measurement used in Markham's method result in the

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group velocity of the ultrasonic wave, while for determining the elastic constant the phase velocity is required. Pearson and Murri [9], however, showed that for transversely isotropic material the group velocity and phase velocity can be interchanged, therefore obtaining the correct elastic properties.

Rokhlin and Wang [10] investigated Pearson and Murri [9] findings in more details and derived the following equation (valid for generally anisotropic materials) to obtain the phase velocity based on the ToF.

$$v_p(\theta_r) = \left[\frac{1}{v_f^2} - \frac{2\Delta t \cos\theta_i}{h v_f} + \frac{\Delta t^2}{h^2}\right]^{-\frac{1}{2}} \tag{3}$$

where

$$\Delta t = t_0 - t(\theta_i) \tag{4}$$

where t_0 is the ToF without the presence of a specimen, $t(\theta_i)$ is the ToF with the presence of a specimen at an incident angle of θ_i,v_f is the velocity of sound in the immersion fluid (water in this dissertation) and h is the thickness of the specimen. A more detailed derivation of the Eq. (3) the authors recommend reading [10].

Mal et al. [11] proposed an ultrasonic immersion technique based on the travel time of reflected wave between a transducer and receiver both aimed at an angle to a composite surface. The experiment was based on the pitch-catch method while the specimen was immersed in water. Mal et al. [11] reported all the five stiffness constants of a unidirectional fiber-reinforced composite laminate.

Hosten et al. [4] and Castaings et al. [7], described a through-transmission ultrasonic immersion technique to obtain the stiffness matrix components for composites non-destructively. The ultrasonic immersion technique was shown to retrieve the stiffness matrix components including the transverse shear and out-of-plane properties. It is important to note that the transversal shear and out-of-plane properties are difficult to determine experimentally especially for thin laminates.

A different method that did not require the specimen to be submerged into water was utilized by Kriz and Stinchcomb [12]. Kriz and Stinchcomb [12] used two ultrasonic sensors; (i) a transducer placed on the front surface of the specimen; and (ii) a receiver placed on a delay block which in turn was placed on the back surface of the specimen. The delay block was used to increase the distance between the transducer and receiver thereby increasing the difference in the time of flight between waves. The non-submerged method used did not rotate the specimen in the desired orientation to perform the different experiments needed to retrieve all the stiffness components. The specimens were cut in the desired plane to retrieve a specific stiffness component. Kriz and Stinchcomb [12] reported that a 0.1% variation in phase velocity resulted in a 35% variation in C_{12} an C_{13} values, they therefore recommend recording the data with sufficient accuracy. Important to state, not all the stiffness matrix components were retrieved directly, only the components corresponding to E_1, E_2, G_{12}, G_{23} and ν_{12} were retrieved from the experiments and the other values were obtained by imposing the transversely isotropic conditions.

Karim et al. [13] and Mal et al. [14] on the other hand used leaky Lamb waves (LLW) instead of through-transmission wave propagation to determine the material properties. Both research groups inverted the LLW dispersion curves and determined the corresponding elastic properties. Hosten et al. [4], however, stated that phase velocity dispersion curves are not sensitive enough to determine the viscoelastic properties of a material when using LLW.

Marguères and Meraghni [15] and Marguères et al. [16] performed a series of investigation in which they characterize the effects of damage on the stiffness components using the ultrasonic immersion technique. When specimens were only impacted shear properties showed a decrease in value, however, an overall stiffness reduction was recorded when a post-impact fatigue cycle was applied. The investigations [15,16] showed that the ultrasonic immersion technique was also applicable to damaged specimens.

Similar to [15,16] Hufenbach et al. [17] used the ultrasonic immersion technique to investigate the damage evolution in glass fiber and a thermoplastic polypropylene matrix specimen under tensile loading.

Pant [18] proposed a technique using Lamb waves and the pitch-catch method with a set of piezoelectric wafer active sensors (PWAS) to determine the elastic constants. Pant [18] reported excellent results for the tensile and transverse properties and acceptable results for the shear modulus. A disadvantage of the method proposed by Pant [18] is it a large plate with multiple PWAS bonded on it, while ultrasonic immersion techniques require no bonding of PWAS and use smaller specimens.

More recently, Ong et al. [19] used a laser vibrometry to determine the elastic properties of woven composite panels. The optimization and retrieval of the elastic properties used by Ong et al. [19] is similar to the ultrasonic immersion technique discussed earlier.

In this manuscript the LAMSS approach which combines the through-transmission technique, the critical angle approach and pulse-echo to retrieve the stiffness matrix of a material non-destructively is introduced.

2. Ultrasonic characterization approaches

The experimental setup and methodologies for three different approaches (Markham's-, Kriz and Stinchcomb's- and LAMSS approach) are discussed and elaborated in this section.

2.1. Marham's approach

To retrieve the stiffness matrix components non-destructively the ultrasonic immersion technique discussed in [1–5,7,8] were utilized. The ultrasonic immersion technique is based on transmitting an ultrasonic plane wave through a specimen and receiving the wave field on the other side; this method is known as the through-transmission method. A variation of the through-transmission method replaces the receiver with a reflector to reflect the wave field back through the plate. The reflected waves are recorded using the same sensor used to generate the wave. This approach is known as the double through-transmission method [20]. Both methods (schematically represented in Fig. 1) used the time-of-flight (ToF) to determine the propagation velocity, which in turn was used to retrieve the stiffness matrix components.

The transmitter–receiver (the through-transmission method) setup was preferred over the double through-transmission method due the capability to obtain a 2D scan that contain additional information (refraction angle of the transmitted wave). An existing water tank was retrofitted and fixture (shown in Fig. 2)) to hold the composite specimen in place was manufactured. The fixture allowed for in-plane rotation by the angle ϕ (Fig. 3)) and an out-of-plane rotation by angle of θ_i (Fig. 3(a)) of the composite specimen. The out-of-plane rotation was accomplished by utilizing the water tank turn table, such that an incremental change in incident angle was feasible. The in-plane rotation required manual adjustment to orientate the composite specimen in the desired plane (markings on the fixture allowed the specimen to be rotated with increments of 5°). The center of the specimen and fixture coincide such that the transducer was focused to the same point regardless of the rotation in ϕ or θ_i, this was important since material properties change with location for anisotropic specimens. Prior to each experiment the transducer was placed in position and lateral scan was made using the receiver to determine the optimal location to receive the strongest signal by the receiver. After the optimal position was determined, the experiments were conducted: for each specimen at a given ϕ the wave propagation was recorded for multiple incidents angles.

In Markham's approach the stiffness matrix components are retrieved by solving the inverse problem (the phase velocities are a given