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Phase velocity method for guided wave measurements in composite plates.

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Abstract

Carbon Fiber Reinforced Polymer is a well-recognized material for aeronautic applications. Its plane structure has been widely used where anisotropic characteristics should be evaluated with flaw detection. A phase velocity method of ultrasonic guided waves based on a pitch-catch configuration is presented for this purpose. Both shear vertical (SV) and shear horizontal (SH) have been studied. For SV (Lamb waves) the measurements were done at different frequencies in order to evaluate the geometrical dispersion and elastic constants. The results for SV are discussed with an orthotropic elastic model. Finally experiments with lamination flaws are presented.

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1. Introduction.

The Carbon Fiber Reinforced Polymer (CFRP) is one of the most important materials fundamentally used in aerospace applications. It is a composite material with anisotropic properties. It is made with several layers of carbon fabrics in resin (matrix) which are oriented according to a specific design. Plane geometries are ones of the more important applications. In these materials, it is necessary to develop nondestructive techniques for material characterization as well as flaw detection. The use of ultrasonic guided waves could be a solution for these purposes. Their long wavelengths imply that the material can be assumed as homogenous anisotropic material with effective elastic constants.

For the general case of material characterization, the elastic properties are basic to understanding and predicting the behavior of any kind of material. Several methods have been proposed for obtaining elastic constants as well as viscoelastic constants based on the measurement of phase and group velocities. In the case of anisotropic material the measurements depend on the axis of anisotropic as expressed by Chang et al. in 2006. In this paper, pulse transmission methods have been used in bulk elements. Park and Kim in 2001 evaluated a methods based on the wavelet transforms. Latif et al., in 1999 used a method based of Wigner-Ville representation for determinations of phase and group velocities in tubes. Kritsakorn in 2007 evaluated a method based on the STFT in plate elements using Lamb waves. Finally Castaings and Hosten in 1998 applied the phase of Fourier transform for measurements

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of dispersion curves in Lamb and SH waves in composites plates. In a second paper Castaing et al., in 2000 analyzed transmission methods for characterization of composites.

For the measurements of materials constants it is convenient obtaining the phase velocity measurements with high accuracy. The method of phase velocity method in pulses (PVM) propagation was developed for this purpose in elastic plates (Moreno and Acevedo, 1998) as alternative method. It is a straightforward method based on the time-distance measurement relative to a point pulse at constant phase. In another paper the PVM was used in viscoelastic plates for Lamb waves (Moreno et al., 2000).

In this paper the use of the PVM method in CFRP is evaluated. It is described for SV and SH guided waves. For the SH it is assumed a quasi-isotropic model. For SV an orthotropic elastic model is analyzed. Experiments in two samples, with and without flaws, are presented using longitudinal and torsional transducers for SV and SH respectively.

2. Theoretical Model.

In general guided waves in plate could be presented according to the plane of polarization: the “in plane” or shear horizontal (SH) and the shear vertical (SV). This second case named as Lamb waves (Auld, 1990). The dispersion phenomena are presented for both cases and several modes characterize this kind of wave propagation. In order to use guided waves methods, it is necessary to know the dispersion curves for phase and group velocities. For the case of SV modes these dispersion curves depend on the relation between the thickness/wavelength and the material properties. For the SH fundamental mode only depend on material properties. In both cases the evaluation of phase velocity with the frequency is an important task for dispersion measurements.

Fig 1 shows the reference schema for the propagation of SV and SH guided waves. SH waves produce a non-null displacement in any direction over the (x_1,x_3) plane. In this case the material could be considered as quasi-isotropic according the samples that were used in this work. The plane (x_1,x_2) will be considered as orthotropic for the SV (Lamb waves) propagation.

Using the Voigt nomenclature, the elastic constants C_{ij} that describe the propagation of SH and SV guided waves, are given by:

SH: $\boldsymbol{C_{55}}$
SV: $\boldsymbol{C_{11}, C_{22}, C_{12}, C_{66}}$

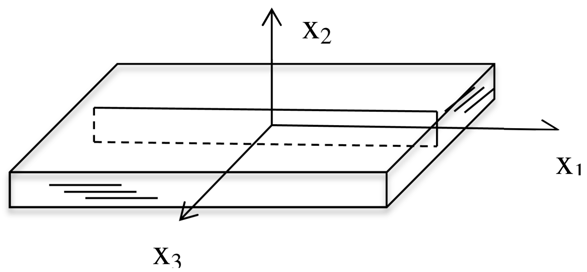

Fig.1. Plate reference system.

For the plane strain formalism, the equations of dynamic equilibrium (wave equations) for the SV case are given by:

$$\rho\frac{\partial^2 u_1}{\partial t^2} = C_{11}\frac{\partial^2 u_1}{\partial x_1^2} + C_{12}\frac{\partial^2 u_2}{\partial x_1 \partial x_2} + C_{66}\frac{\partial^2 u_1}{\partial x_2^2} + C_{66}\frac{\partial^2 u_2}{\partial x_1 \partial x_2}$$
$$\rho\frac{\partial^2 u_2}{\partial t^2} = C_{12}\frac{\partial^2 u_1}{\partial x_1 \partial x_2} + C_{22}\frac{\partial^2 u_2}{\partial x_2^2} + C_{66}\frac{\partial^2 u_1}{\partial x_1 \partial x_2} + C_{66}\frac{\partial^2 u_2}{\partial x_1^2} \quad (1)$$

In equations (1) $\boldsymbol{\rho}$ is the density and the elastic constants $\boldsymbol{C_{ij}}$ are components of the real stiffness matrix in Voigt notation.

From the equations (1) it is possible to obtain the following dispersion relations (Martineck, 1975)

$$\left(\frac{th\left(\frac{sh}{2}\right)}{th\left(\frac{qh}{2}\right)}\right)^{+/-1} = \frac{B_0 C_0}{A_0 D_0} \tag{2}$$

Where +1 is for the symmetrical Lamb waves mode and -1 for the antisymmetrical case. The arguments of ***th(x)*** functions are given by:

$$\frac{qh}{2} = \pi\frac{h}{\lambda}\sqrt{-\frac{a}{2}+\sqrt{\left(\frac{a}{2}\right)^2 - b}} \qquad \frac{sh}{2} = \pi\frac{h}{\lambda}\sqrt{-\frac{a}{2}-\sqrt{\left(\frac{a}{2}\right)^2 - b}} \tag{3}$$

Where **a** and **b** are expressed as:

$$a = \frac{C_{12}^2}{C_{22}C_{66}} + \frac{2C_{12}}{C_{22}} - \frac{C_{11}}{C_{66}} + \rho c^2\left(\frac{1}{C_{66}} + \frac{1}{C_{22}}\right)$$

$$b = \frac{C_{11}}{C_{22}} - \rho c^2\frac{(C_{11}+C_{66})}{C_{22}C_{66}} + \rho^2 c^4\left(\frac{1}{C_{66}C_{22}}\right) \tag{4}$$

In (4) ***c*** is the phase velocity. The right side in equation (2) is given by:

$$A_0 = \frac{q}{k}\left[-\rho c^2 + C_{11} - \frac{C_{12}(C_{12}+C_{66})}{C_{22}}\right] - C_{66}\left(\frac{q}{k}\right)^3$$

$$B_0 = \frac{s}{k}\left[-\rho c^2 + C_{11} - \frac{C_{12}(C_{12}+C_{66})}{C_{22}}\right] - C_{66}\left(\frac{s}{k}\right)^3$$

$$C_0 = -\rho c^2 + C_{11} + C_{12}\left(\frac{q}{k}\right)^2 \tag{5}$$

$$D_0 = -\rho c^2 + C_{11} + C_{12}\left(\frac{s}{k}\right)^2$$

Where *k* is wavevector modulus expressed as $k = {}^{2\pi}/_{\lambda}$ and $\boldsymbol{\lambda}$ is the wavelength.

For the plane (x_1,x_3) the composite plate will be considered as quasi-isotropic. Then the SH will be assumed as non- dispersive for the fundamental mode so that the phase velocity ***c*** will be related with the following elastic constants:

$$C_{55} = c^2\rho \tag{6}$$

3. Materials and Methods.

3.1. CFRP samples

In this paper two composite plates of CFRP were made according to the following laminate code which defines the ply orientations:

$$-45/+45/90/0/0/90/+45/-45/ \qquad (7)$$

Then the samples could be considered as quasi-isotropic, which means that has isotropic properties in-plane. The Fig. 2 shows the process of manufacturing this material with the carbon fiber layers, oriented as expressed in (7). These layers were immersed in an epoxy matrix. The same figure shows an example (right) where two pieces of cardboard were inserted in the middle of the layers in order to simulate laminations. The density obtained was 1.25 g/cm^3.

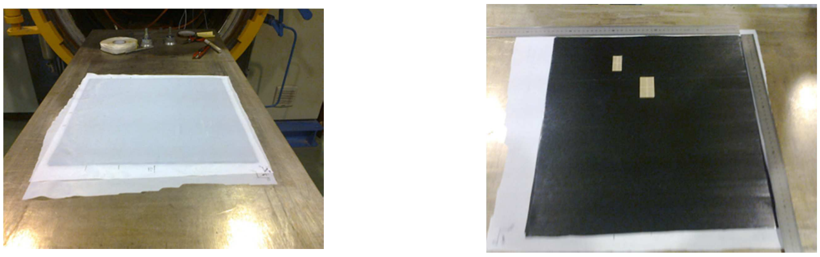

Fig.2. Two Samples of CFRP are presented. The dimensions were approximately 660x460x2.9 mm. The samples are considered in-plane isotropic (quasi-isotropic). For a perpendicular plane, the material will have different elastic constants so it could be considered as orthotropic. In the right (sample No. 2) it is shown two pieces of cardboard inserted for laminate simulation. For the left case the material is flawless.

3.2. Ultrasonic phase velocity (PVM)

The ultrasonic phase velocity method (PVM) is based on the measurement of time-distance on a constant phase point of a pulse. In the left of Fig 3, it is shown a description of this method. As we can see, the transducer is moved at different distances (i.e. Rx_1 to Rx_2) , which steps from 0.5 mm to 1 mm. The time measurement is obtained using the same phase point (i.e. t_1 and t_2).

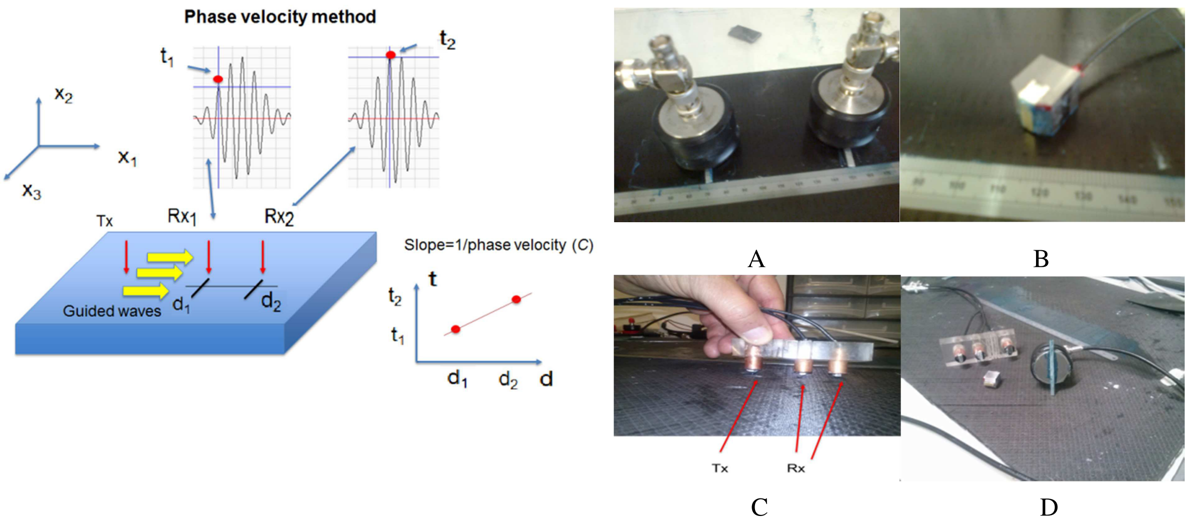

Fig.3. Left: the phase velocity method. Right: transducer descriptions. The transducer was excited with ultrasonic multichannel system SITAU from Dasel S.L.

With the distance-time measurement the phase velocity is obtained from the slope (or its inverse) using the minimum square method.

At the right of the Fig. 3A it is observed the transducer configuration for SV mode. Panametrics transducers V191 (0.5 MHz) and V194 (1 MHz), were used with an aluminiun strip. At the receiver the strip had a width of approximately 5 mm. For the transmitter it was adjusted using the criteria given by the following reference (Giurgiutiu, 2003). Fig. 3B shows a shear transducer that was developed with perpendicular polarization in soft PZT. Fig. 3C shows a configuration of three longitudinal transducers (three point transducer, TPT) that was developed as one transmitter and two receivers. This was used for the detection of flaws simulated in sample No. 2 with the proposed method.

4. Results.

4.1. Elastic constant evaluation with PVM

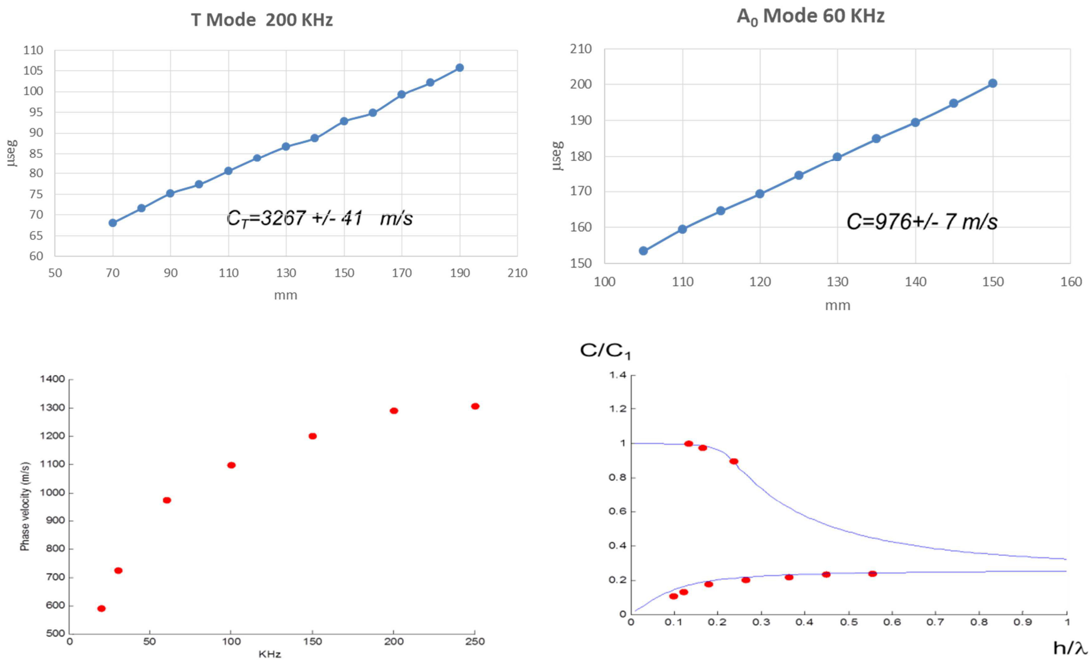

Fig.4. Upper: Time-distance graphics. Low: Dispersion curves.

Fig. 4 shows two examples of space-time diagram for the case of SH mode and antisymmetric mode, A_0 for two frequency values. Similar results were obtained for the symmetrical mode S_0 with a value of $C_l=C_S=5455$ *+/- 61 m/s* at 250 KHz. This value was used as a limit for frequency=0, for the normalized dispersion curves (lower-right part of Fig 4). At the lower-left, it is shown only the antisymmetric mode. Table I resumes the elastic constants obtained from theoretical model adjusted to experimental values.

Table I. elastic contants obtained using the PVM.

C_{11} (GPa)	C_{22} (GPa)	C_{12} (GPa)	C_{55} (GPa)	C_{66} (GPa)
38,4	7,7	3,0	13,3	2,6

4.2. Flaw detection with PVM

It is shown in Fig. 5 the signal obtained with the three point transducer at two locations for comparing the influence of laminate. According to the dispersion curves, the velocity in **A** should be 1100 m/s. In **B,** the phase velocity method shows a change evaluated at 800 m/s. Using the dispersion curve (lower-right part of Fig 4), this velocity is equivalent to a 1 mm thickness which is a good enough for the flaw positions in sample 2.

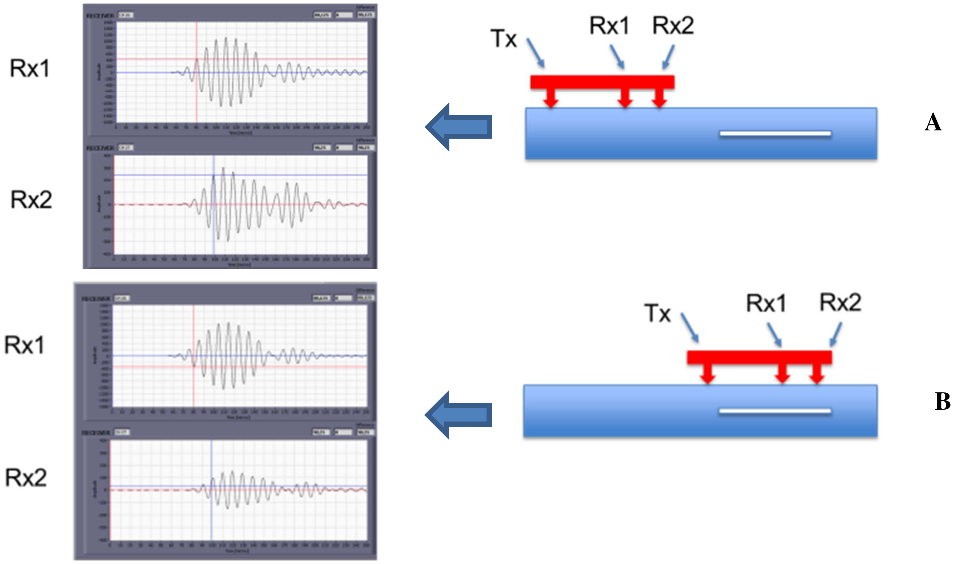

Fig.5. Evaluation of lamination using TPT with antisymmetrical A_o Lamb mode signals (SV). Frequency was 100 KHz. The red and blue cursors show the constant phase points in the pulses. Tx: transmitter, Rx: Receiver.

5. Conclusions.

The phase velocity method was presented in composite plates as a method for the evaluation of CFRP elastic properties. The method shows a good performance for the phase velocity measurements with a high precision around 1%. It was applied in the evaluation for SV and SH modes in composite plates. A three point transducer was developed based on PVM for laminate detection. The elastic theoretical model is only a first step to describe composite plates. A second step should be a linkage between viscoelastic and geometric dispersions.

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