THE USE OF LAMB WAVES TO MONITOR THE MOISTURE CONTENT IN COMPOSITE MATERIALS

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Abstract

Non-destructive material health monitoring is of great importance for aerospace industries, in particular for tanks made of composite materials, the mechanical properties of which can be altered by hydrothermal environment. The sensitivity of Lamb waves to various levels of moisture in carbon-epoxy plates has been investigated. Low-order modes are generated and detected using air-coupled transducers, and signal processing allows both wave number and attenuation to be measured. A carbon-epoxy plate has been manufactured and submitted to different cycles of hydrothermal aging and drying. For various steps of these cycles, both changes in weight and ultrasonic data are measured. The wave number of modes is shown to be not sensitive to the moisture level of the material. However the attenuation of the A_0 mode is very sensitive to the moisture content and its changes follows those of the plate weight, thus making it a promising mode for NDT tests.

Introduction

The moisture content monitoring in composite material is a well-known problem [1,2]. Hydrothermal aging can cause micro-cracks at the interface between fibbers and matrix in composite materials. This process is partially reversible if the temperature during the experiment is below the vitreous transition temperature (T_g) of the composite material [2]. The use of ultrasonic waves to monitor the moisture content in composite materials is not really widespread [1]. So, it is interesting to use a contact-less ultrasonic method to monitor the moisture content in some kind of composite materials as carbon-epoxy plates. This paper presents the use of ultrasonic guided Lamb modes to gauge the moisture content in a carbon-epoxy plate. The contact-less, ultrasonic, experimental set-up and the measurement of complex wave-numbers are briefly reminded. Then, a study on the measurements reproducibility is presented. Hydrothermal aging and drying procedures as well as ultrasonic data monitoring are described. During the several steps of hydrothermal aging and drying, the change in weight of the plate and the complex wave-numbers of the three Lamb modes A_0, S_0, and S_1 are measured. By comparing these ultrasonic measurements to numerical predictions, an inverse problem is solved for inferring the material properties, i.e. the complex viscoelastic moduli of the plate [3]. This process allows changes in the viscoelastic moduli due to the moisture level in the material to be followed.

Experimental set-up

The experimental campaigns are carried out by using the Lamb waves generation/detection set-up presented in Figure 1. Two air-coupled capacitive transducers are placed at the same side of the tested sample to permit unilateral contact-less access. These transducers are made at the laboratory from a back plate that is roughened with sand blasting and a thin polymeric metallized membrane. Their large diameter (45 mm) makes the energy entering in the plate being of high amplitude, so enhancing the signal to noise ratio. Moreover, their angular aperture is very narrow because their diameter is much larger than the wavelength in the air (1 mm), thus making them mode selective [3].

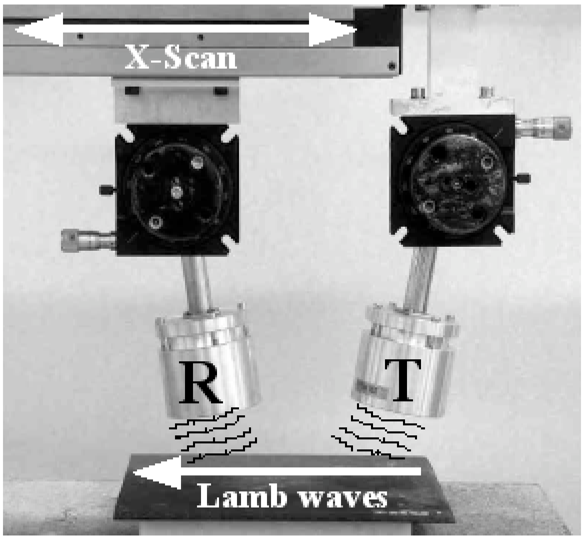

Figure 1: Contact-less ultrasonic experimental set-up.

The two transducers are oriented at opposite angles, and , defined to select one particular mode. These angles are adjusted according to the frequency F_0, which is changed depending on the mode, and obtained by previously plotting the dispersion curves for the composite plate. The transmitter (T) is excited by a 5-cycle toneburst at a central frequency F_0. The receiver (R) detects a part of the guided mode radiation in the air. It is moved along the mode-propagation path, a temporal signal being measured for each of its positions. The length of the propagation path is comprised between 50 mm and 200 mm, thus making the technique appropriated for controlling quite widespread zones of material plates. Specific signal processing then allows the experimental complex wave-number to be plotted versus the frequency, for each mode propagating along the plate [3-5]. The real part, K', is linked to the phase velocity while the imaginary part, K'', represents the attenuation.

Experiments are carried out on a $[0/90]_{6s}$ carbon-epoxy plate, which thickness is (5.3 ±0.3) mm and density is 1.5. The complex wave-numbers have been measured for three Lamb modes, A_0, S_0, and S_1, by setting up the frequency F_0 and angle θ, as described in Table 1.

Mode	F_0 (kHz)	θ (°)
A_0	100	15
	250	15
S_0	250	3.5
	300	7
S_1	300	3

Table 1: Viscoelasticity moduli (GPa) for the $[0/90]_{6s}$ carbon-epoxy plate.

A two-dimensional semi-analytical model is then used for plotting the complex wave-numbers of guided modes [6]. Requested input data are viscoelastic moduli, thickness and density of the material plate. The two latest have been previously measured, but the complex viscoelastic moduli C_{ij} are optimised so that best fitting is obtained between predicted and measured wave-numbers. Only one plane of propagation is investigated in the whole study, namely plane P_{12} formed by axis x_1 normal to the plate and axis x_2 alternatively normal and parallel to the fibbers. Table 2 presents the measured C_{ij} for this plane.

C_{11}	C_{22}	C_{66}	C_{12}
12 + i 0.6	60 + i 2.5	3.5 + i 0.15	7 + i 0.3

Table 2: Viscoelasticity moduli (GPa) for the $[0/90]_{6s}$ carbon-epoxy plate.

Measurement reproducibility

Two experimental campaigns are conducted to quantify the wave-numbers measurements reproducibility, which is given in percentage by the following formula:

$$100\left(\sum_{i=1}^{n} \frac{X_i^2 - X_i^1}{X_i^1}\right) \quad (1)$$

where X_i^1 and X_i^2 are the experimental values of K' or K'' of a given mode, for campaigns 1 and 2, respectively, and n is the number of frequency steps. The wave-number measurements reproducibility is on average about 1% for the A_0 mode, 3% for the S_0 mode and 4% for the S_1 mode. The attenuation measurements reproducibility is on average about 6% for the A_0 mode, 8% for the S_0 mode and 10% for the S_1 mode.

Hydrothermal aging

A hydrothermal aging is applied to the composite plate until it reaches a state close to the saturation. This plate is placed in an oven at 65°C and with 70% of moisture during four months. The complex wave-numbers of the three Lamb waves A_0, S_0, and S_1 are measured during the aging. Figure 2 presents the real and imaginary parts of these wave-numbers, before and after the aging, i.e., at the initial state of the plate, and when it is saturated, respectively.

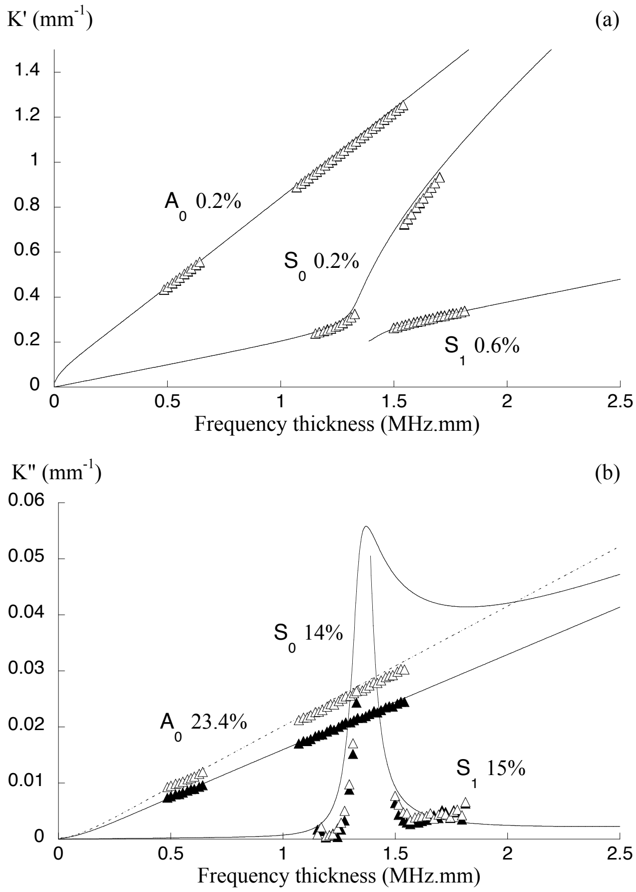

Figure 2: Measurements (triangles) and numerical predictions (lines) before (▲,) and after (△,) hydrothermal aging; (a) real and (b) imaginary parts of wave-number.

The relative variation between the measurements before and after hydrothermal aging is calculated using equation(1) where X_i^1 and X_i^2 are the measured

K' or K'' before and after aging, respectively, and for a given mode.

Figure 2.a shows that changes in the real parts of the wave-numbers of A_0, S_0 and S_1 modes are smaller than the reproducibility measurements. Therefore, K' is not sensitive enough to the kind of damage caused by the hydrothermal aging.

The variations in the imaginary parts of the wave-numbers of S_0 and S_1 modes are just slightly higher than the reproducibility measurements (Figure 2.b). These changes are then not large enough to conclude on a significant sensitivity. Only the attenuation of the A_0 mode is highly sensitive to the moisture content. Indeed, it changes by 23.4%, which is much larger than the reproducibility measurement (6%). Moreover, a previous study on the sensitivity of Lamb modes to viscoelastic moduli showed that the A_0 mode is mainly sensitive to the Coulomb modulus C_{66} [3]. Its real wave-number is sensitive to the real part of C_{66} and its attenuation (imaginary wave-number) to the imaginary part of the C_{66}. Consequently, the rise of the A_0 mode attenuation represents an increase of about 26% of the imaginary part of the Coulomb modulus C_{66}. The changes caused by the hydrothermal aging are then principally detectable by A_0 mode attenuation measurements.

Drying

Drying is made to see if the material can return to its initial state, and also to check if ultrasonic measurements can follow this change. The composite plate is placed in an oven at 65°C. This temperature is supposed to dry the material without altering it. The complex wave-numbers of the three Lamb waves A_0, S_0, and S_1 are measured during the drying. Figure 3 presents the real and imaginary parts of these wave-numbers, before and after the drying.

The relative variation between the measurements before and after drying is also calculated with the formula(1), where X_i^1 and X_i^2 are the measured K' or K'' before and after drying, respectively, and for a given mode.

The real parts of the wave-numbers for all the generated modes, and the attenuations of the S_0 and S_1 modes exhibit no sensitivity to this drying (Figure 3). Effectively, their changes before and after drying are smaller than or about the reproducibility measurements.

The A_0 mode attenuation decreases by 21.6% during the drying (Figure 3.b). This variation is linked to a decrease of about 21% of the imaginary part of the Coulomb modulus C_{66}. This clearly shows that the material almost returns to its initial state, thus showing the reversibility of the phenomenon.

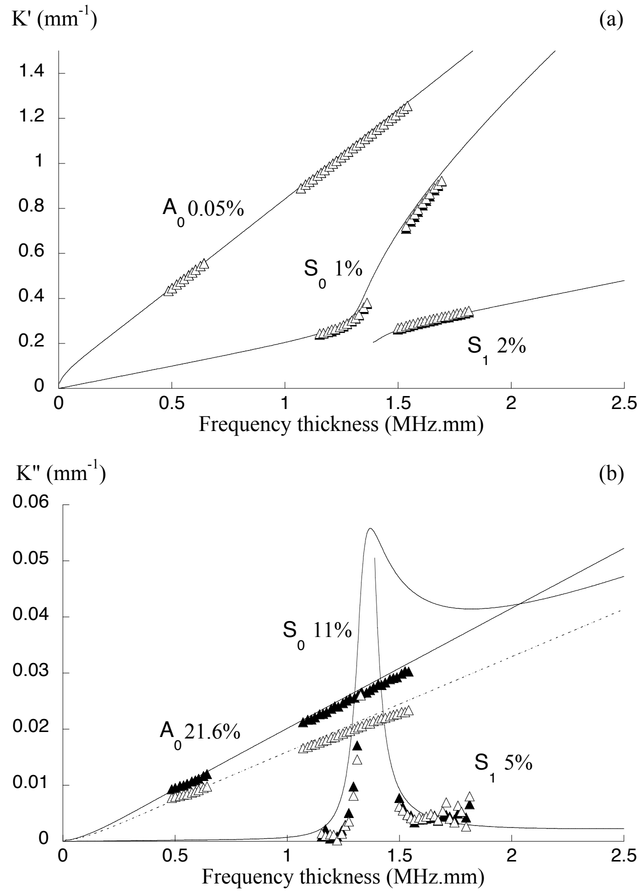

Figure 3: Measurements (triangles) and numerical predictions (lines) before (▲,□) and after (△,□□□) drying ; (a) real and (b) imaginary parts of wave-number.

Hydrothermal aging-drying monitoring

At several steps of the previous aging and drying, changes in the plate weight have been measured, to have another control of the moisture content. Previous measurements of the A_0 mode attenuation can then be compared to the changes in weight.

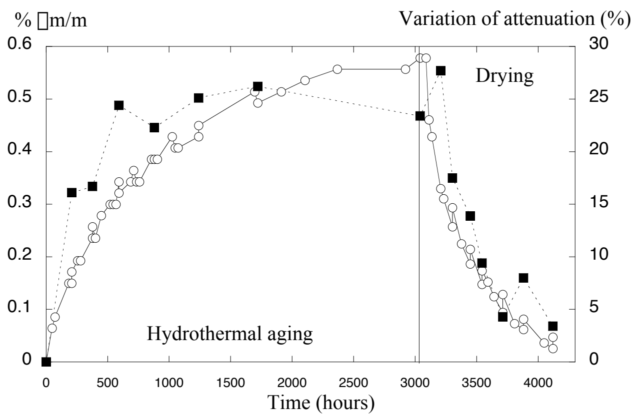

Figure 4 : Variation of the A_0 mode attenuation (▪) compared to the change in weight (○) during the aging and drying.

Figure 4 shows that the changes in the A_0 mode attenuation are in very good agreement with those of the weight, all along the hydrothermal aging and drying. Consequently, the variation of A_0 mode attenuation is a good gauge of the moisture content in carbon-epoxy composite plates.

This campaign of hydrothermal aging and drying has been made twice using the same plate to check the repeatability of the A_0 mode attenuation variations and of the plate weight changes. Very similar results confirmed that the whole aging-drying process could be reliably monitored by measuring either changes in weight or in A_0 attenuation. Air-coupled, ultrasonic measurement of the A_0 mode attenuation is therefore a very promising way to control moisture content in carbon-epoxy structures, since it can be done with single-sided and contact-less access.

Conclusion

The sensitivity of Lamb waves to the moisture content in a $[0/90]_{6s}$ carbon-epoxy composite plate has been investigated. Experimental measurements of the complex wave-numbers have been made for the three modes A_0, S_0, and S_1. The technique uses air-coupled, capacitive transducers, which allow single-sided, contact-less access to the tested specimen.

It has been shown that the A_0 mode attenuation is a good gauge of the moisture content in the material, since its changes during aging-drying processes follow very well those of the plate weight. Since the A_0 mode is known to be sensitive to the Coulomb modulus, a numerical tool has been used for quantifying the imaginary part of this parameter, which is linked to the measured A_0 mode attenuation.

Acknowledgments

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References

[1] Y. Jayet, R. Gaertner, P. Guy, R. Vasoille, D. Zellouf, "Application of ultrasonic spectroscopy for hydrolytic damage detection in GRFC : correlation with mechanical tests and microscopic observations", Journal of Composite Materials, vol. 34, pp. 1356-1368, 2000.

[2] Z.A. Mohd-Ishak, U.S. Ishiaku and all, "Hygrothermal aging and fracture behavior of short-glass-fiber-reinforced rubber-toughened poly(butylene terephthalate) composites", Composites Science and Technology, vol. 60 (6), pp. 803-815, 2000.

[3] B. Hosten, M. Castaings, H. Trétout, H. Voillaume, "Identification of composite materials elastic moduli from Lamb wave velocities measured with single-sided, contact-less, ultrasonic method", Review of Progress in Quantitative Non Destructive Evaluation, Ed Thompson D.O. and Chimenti D.E., AIP Conf. Proc., New York, vol. 20.B, pp. 1023-1030, 2001.

[4] D. Alleyne, P. Cawley, "A two-dimensional Fourier transform method for the measurement of propagating multimode signals", J. Acoust. Soc. Am., vol. 89, pp. 1159-1168, 1991.

[5] M. Castaings, B. Hosten, "Guided waves propagating in sandwich structures made of anisotropic, viscoelastic, composite materials", J. Acoust. Soc. Am., vol. 113.(5), pp. 2622-2634, 2003.

[6] B. Hosten, M. Castaings, "Surface impedance matrices to model the propagation in multilayered media", Ultrasonics, vol. 41, pp. 501-507, 2003.