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Thermal ageing evaluation of composite plates through electromechanical impedance

Pierre Maréchal[*], **Elhadji Barra Ndiaye, Hugues Duflo**

Laboratoire Ondes et Milieux Complexes (LOMC), UMR 6294 CNRS, Le Havre Normandie University, France;
*corresponding author, E-mail: `pierre.marechal@univ-lehavre.fr`

Abstract

Electromechanical impedance monitoring is investigated to quantify changes in physical and mechanical properties during the ageing of composite plates.

In this context, an experimental measurement protocol is proposed, on the basis of a broadband 1 MHz center frequency piezoelectric transducer. After a preliminary characterization of the parameters of the transducer itself, the acoustical impedance of the front medium is deduced. More particularly, the acoustical properties such as longitudinal wave velocity and attenuation are identified in the studied composite carbon/epoxy plates. From the electrical measurement results in the MHz frequency range, the acoustical impedance of the plate is plotted in the complex plane, showing characteristic signatures corresponding to the actually monitored composite plate. The ageing is quantified, showing the effectiveness of this non-destructive evaluation method.

First, the acoustical parameters of a plate made of a carbon/epoxy composite are modeled in order to study their sensitivity. During the ageing, those acoustical properties are known to evolve significantly, i.e. a decrease of the wave velocity and an increase of the attenuation, which can both be related to the increase of the porosity level in the plate. Secondly, these acoustical properties are evaluated on a set of samples which were submitted to a range of ageing duration from 500 to 5000 h performed at a thermostated temperature of 180°C. The feasibility of the evaluation of the ageing is demonstrated, and the precision of this measurement is discussed both in terms of temperature dependency and reproducibility.

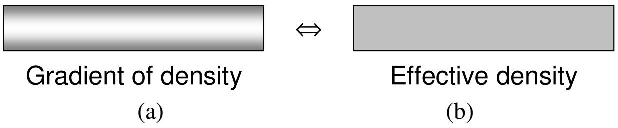
1. Introduction

In this study, composite plates are characterized using the electromechanical impedance (EMI) measurement. The objective of this work is to establish a reproducible method for the ultrasonic characterization of composite plates being aged by thermal solicitations. In order to quantify the aging effect, the thermal ageing was obtain calibrated and performed at a thermostated temperature of 180°C, for a duration raging from 500 to 5000 h. The EMI characterization method simply involves a piezoelectric transducer which is placed in contact with the inspected front medium [1-3]. The measurement results are finally expressed in terms of a set of acoustical parameters that are monitored versus the ageing duration.

2. Composite plates

The studied composite plates are made of eight plies set up in a symmetric way [0/+45/–45/+90/+90/–45/+45/0]° and resulting in a quasi-isotropic laminate. Each ply consists in a woven folds of carbon fiber, pre-impregnated in an epoxy matrix. The initial samples are fabricated following the same process, both for the curing and post-curing temperature cycles. The ageing of those initial sample plates is obtained by the way of a simplification of the temperature effect, which is known to imply ageing. Thus, the ageing consists in a continuous stay (i.e. without any temperature cycle) of the composite plates in air at a constant temperature of 180°C at ambient pressure.

As a result of the ageing, the composite plate is subject to porosity increase from the top and bottom surface in the direction to the median plane (Fig.1). Nevertheless, for the simplicity of the study, only the effective properties of these plates are considered. This is a commonly accepted assumption since no complementary information can be precisely obtained.



(a) (b)

Figure 1: (a) Geometrical repartition of the density of an aged plate observed on micrograph and (b) related effective density measured experimentally.

3. Modeling the electromechanical impedance

The EMI measurement consists in extracting the information of the surrounding media of a piezoelectric plate vibrating along its thickness. As a result of usual piezoelectric transducers, only the front medium is varied since the back medium is a damper chosen to broaden the bandwidth of the transducer.

3.1. Electrical impedance

Using the Redwood-Mason model [4], the electrical input impedance of a piezoelectric transducer [5] was shown to depend of the properties of the piezoelectric layer itself, and on those of the surrounding back and front media [6, 7]. The piezoelectric properties are usually reduced to a set of parameters such as $\{t_p, c_{Lp}, \delta_p, \rho_p, k_t, \varepsilon_{33,r}{}^S\}$, i.e. the thickness, the longitudinal wave velocity, the density, the thickness coupling coefficient, the relative dielectric constant at constant strain, respectively. The acoustical impedances surrounding the piezoelectric layer are modeled through the normalized back and front face input impedance $z_b = Z_{in,b} / Z_p$ and $z_f = Z_{in,f} / Z_p$, respectively :

$$Z_e = Z_0\left(1-k_t^2\frac{\tan(\theta_p/2)}{\theta_p/2}K_{bf}\right), \tag{1}$$

where
$$K_{bf} = \frac{(z_b+z_f)\cos^2(\theta_p/2)+j\sin\theta_p}{(z_b+z_f)\cos\theta_p + j(1+z_bz_f)\sin\theta_p}, \tag{2}$$

$$Z_0 = \frac{1}{j2\pi fC_0}, \tag{3}$$

$$\theta_p = \frac{2\pi f}{c_{Lp}}t_p, \tag{4}$$

$$Z_{in,n} = Z_n\frac{Z_{in,n+1}+Z_n th(j\theta_n)}{Z_n + Z_{in,n+1}th(j\theta_n)}, \tag{5}$$

The electrical impedance Z_e (eq. (1)) involves four main ratios that are the damping of the surrounding media K_{bf} (eq. (2)), the static capacity electrical impedance Z_0 (eq. (3)), the angular delay due to the thickness propagation θ_p (eq. (4)). The input acoustical impedance (eq. (5)) [8] seen at the back and front face, $Z_{in,b}$ and $Z_{in,f}$, respectively, is calculated recursively from N down to 1 with $1 \le n \le N - 1$, where N is the total number of considered layers.

3.2. Front medium sensitivity

If the other parameters are considered constant, the electrical impedance of the piezoelectric layer is only depending on the latter front layer. Since the air behind the composite plate is negligible compared to that of the plate $Z_{air} << Z_N$, this last input acoustical impedance (eq. (6)) can be expressed and simplified as:

$$Z_{in,c} = Z_c\frac{Z_{air}+Z_c th(j\theta_c)}{Z_c + Z_{air}th(j\theta_c)} \approx Z_c th(j\theta_c), \tag{6}$$

Therefore, the sensitivity of this input impedance of the composite plate can be illustrated for a typical set of values, i.e. a wave velocity $c_c = 3000$ m/s, a density $\rho_c = 1500$ kg/m^3, a loss parameter on the velocity $\delta_c = 3\%$ and a thickness $t_c = 3$ mm. As a result (Fig.2), the modulus of the input acoustical impedance function shows minimum values periodically, spaced by $\Delta f = 0.5$ MHz in the case of $c_c = 3000$ m/s, corresponding to a real part of the angular delay $\Re\{\theta_c\} = n.\pi$, i.e. $f = n.c_c/t_c$, where n is an integer. For these particular values, the input acoustical impedance is purely real and its analytical value can be expressed as $Z_{in,c} = Z_c.th(\pi n\delta_c) \approx Z_c.\pi n\delta_c$. Similarly, some local maxima can be observed on the modulus of the input acoustical impedance, corresponding to a real part of the angular delay $\Re\{\theta_c\} = \pi/2 + n.\pi$, i.e. $f = (2n+1).c_c/(2t_c)$. Once more, for these particular values, the input acoustical impedance is purely real and its analytical value is $Z_{in,c} = Z_c/th((2n+1).\pi/2.\delta_c) \approx Z_c.2/(\pi.(2n+1).\delta_c)$.

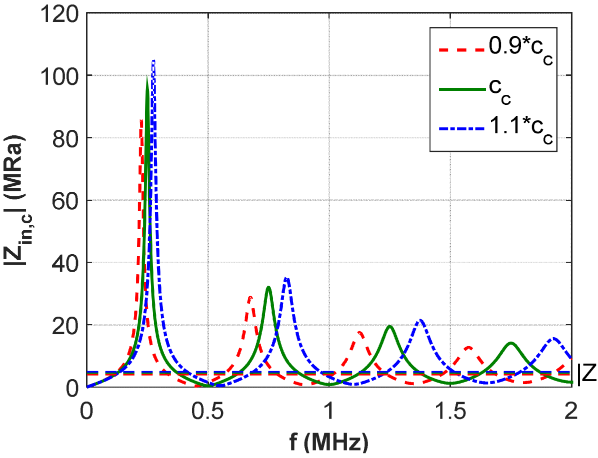


Figure 2: Sensitivity of the wave velocity c_c on the input impedance of a composite plate $|Z_{in,c}|$ (eq. (6)), with a wave velocity $c_c = 3000$ m/s, a density $\rho_c = 1500$ kg/m^3, a loss parameter $\delta_c = 3\%$ and a thickness $t_c = 3$ mm.

4. Results

4.1. Experimental setup

The experimental setup as been extensively and widely described in a previous work [9].

4.2. Fitting procedure

Following an optimization procedure, the measurement of the electrical impedance is fitted to that of the model in order to match the two curves as much as possible. The matching criterion is based on a minimization function ΔY defined as the sum on the whole spectrum of the absolute difference of the experimental and theoretical admittance $\Delta Y_n = Y_{E,n} - Y_{T,n}$ both on the real and imaginary parts:

$$\Delta Y = \frac{1}{N_f}\sum_{n=1}^{N_f}\left|\Re(\Delta Y_n)\right| + \left|\Im m(\Delta Y_n)\right|, \tag{7}$$

where N_f is the total number of acquired frequency points, and $Y_{E,n}$ and $Y_{T,n}$ are the experimental measurement and theoretical modeled electrical admittances.

4.3. Validation procedure

As a result of the first fitting procedure (eq. (7)), the reference composite plate set of four parameters $\{Z_c\ ;\ \rho_c\ ;\ c_c\ ;\ \delta_c\}$ has been identified and lead to the values $\{4.29$ MRa ; 1414 kg/m^3 ; 3030 m/s ; 1.5%$\}$, respectively. This EMI characterization result was confirmed to be in agreement with classical pulse-echo characterization methods.

4.4. EMI measurements

As an illustration [10], the EMI measurements are illustrated for several aged samples. The effect of the ageing is clearly visible, both on the modulus (Fig. 3 (a)) and phase (Fig. 3 (b)).

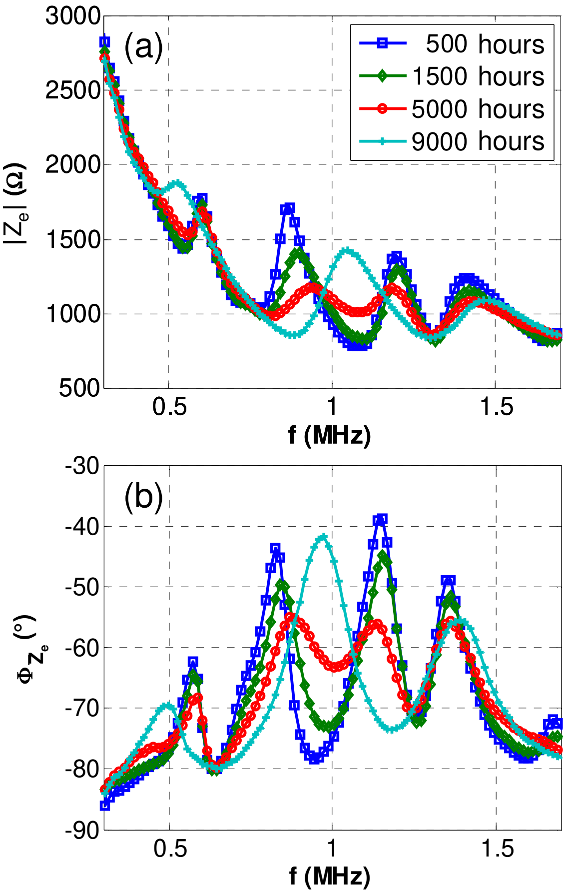


Figure 3: EMI measurements versus the frequency, in the bandwidth of the transducer, centered at $f_0 = 1$ MHz: (a) Modulus of the electrical impedance $|Z_e(f)|$, (b) Phase of the electrical impedance $\mathrm{Arg}(Z_e(f))$.

4.5. Acoustical parameters

This EMI characterization method can give a very fast and reproducible result in order to evaluate the ageing of an initially known composite plate. Nevertheless, some uncertainties can be estimated and are shown (Fig. 4) on the identification of the acoustical parameters deduced from the EMI measurements results. Based on this estimates, a confidence interval can be elaborated in view to give a more precise information concerning the ageing of a composite plate in case of inverse problem. Both the acoustical and density evaluations (Fig. 4 (a) and (b)) are showing a decrease of 35% after 2500 h of aging. The wave velocity (Fig. 4 (c)) appears to be less sensitive with a decrease of only 7% after 5000 h. The loss parameter (Fig. 4 (d)) shows a strongly linear sensitivity in log scale, so that it can be modeled: by $\delta_c = \delta_{c,ref}.(\delta_{lin,D})^D$.

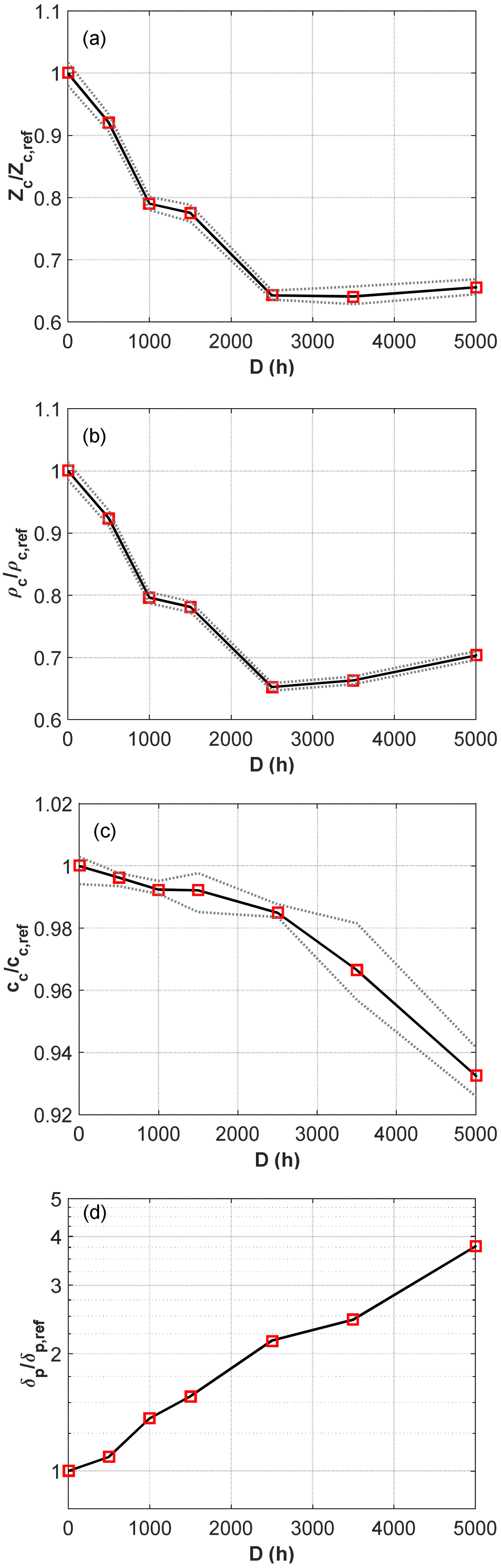


Figure 4: Normalized acoustical parameters versus the ageing duration, from 500 to 5000 h: (a) Acoustical impedance $Z_c/Z_{c,ref}$, (b) Density $\rho_c/\rho_{c,ref}$, (c) Wave velocity $c_c/c_{c,ref}$, (d) Loss parameter $\delta_c/\delta_{c,ref}$.

4.6. Discussion

Those measurement results are strongly dependent on the considered frequency range. The perturbations due to the porosity level at the surface induced by the aging should be a limiting factor at higher frequency.

Moreover, even if averaged on multiple acquisitions in order to reduce the noise level, these values were obtained for a single measurement point. An average on several measurement site would provide a map of the acoustical properties and an improved diagnostic. In addition, a significant methodological improvement would be a repeatability study by mounting and unmounting the contact transducer. An optimization of the input electrical chirp used for the electrical impedance measurement is also a way of improvement of the efficiency of the EMI method.

Nevertheless, these results show a tendency to the decrease for both the density and wave velocity. As a product of these two acoustical parameters, the acoustical impedance of the plate is a robust estimator of the aging, in the limit of validity of the assumption of homogeneous effective medium.

5. Conclusions

In this work, the monitoring of the acoustical properties of composite plates was conducted through the EMI measurement. This characterization method gives reproducible results on plane samples that can be considered as homogeneous medium, i.e. through their effective properties relatively to the wavelength, in the frequency bandwidth of the used piezoelectric transducer. The main advantages of this EMI method are its fast use and robustness, as long as the initial properties of the inspected material is preliminary measured, recorded and used as reference for a comparison standard all along the aging.

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