Thermal ageing evaluation with nonlinear elastic wave spectroscopy method of carbon fiber reinforced plastic composite plates

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The excellent and specific properties of composite materials in the various fields such as aeronautics, transport, energy, the nuclear power and civil engineering led to the need of knowing their behaviours in presence of defect (crack, ageing, delamination...). Therefore, the aim of this paper is to study the thermal ageing of the carbon fibre reinforced composite plates, using their nonlinear behaviours.
The method used to achieve this work is the NEWS method (Non-linear Elastic Wave Spectroscopy), where some alternatives of this one are used. SIMONRUS which involves a study of the nonlinear response of a single resonant mode of the plate according to various amplitudes of excitation. In this case, the nonlinear phenomena analysed are resonance frequency shift and damping characteristic of different level ageing of plate. Evolution of non linear effects are then correled to ageing duration.

1 Introduction

The interest of non destructive techniques testing for the diagnosis of the damage in materials, in particular the composite materials, have increased more and more for several decades. Many studies were made by using linear acoustic methods.

They consist in evaluating by physical methods (dispersion and propagation of Lamb wave, radiograph, tomography…) materials where one can find defects (fatigues, delaminations, cracks…). The knowledge of the physical properties of materials is necessary to detect and characterize the defect (its localization, dimension and density). However, non-linear effects resulting by the presence of the defects in materials led to use non-linear methods [1,2,3,4]. Among these methods, we choose nondestructive control by ultrasound NDT-NEWS (Nonlinear Elastic Wave Spectroscopy) [5]. It consist in studying the non-linear vibratory behavior of materials through the relative variation of the frequency, a mode of resonance, according to the increase in the level of excitation. It shows a shift of the frequency of resonance towards the low frequencies and a deformation of the curves of resonance thus a reduction in their quality factors.

In this article, we applied this method to characterize the thermal ageing of a composite plate laminate containing polymer-carbon. Firstly, we studied the behavior of a healthy plate. Then, we followed the evolution of its behavior after several thermal ageings for various durations. The results obtained show the effectiveness of this method for detection of ageings of composite materials.

2 Experimental setup

This method implies a study of the nonlinear response of one or more modes of resonance of the plate according to the amplitude of excitation. In the case, of a healthy plate the curves of resonance of the various levels of excitation do not present a great shift around the frequency of the studied resonance. However, for damaged materials (out-of-date, cracked …), the frequency of resonance shifts towards the low frequencies and the curves become broader testifying the increase to the attenuation [6].

We applied NDT-NEWS to characterize the thermal ageing of a composite plate laminate containing polymer-carbon. For that, we employed the experimental setup presented in fig. 1. This device comprises a loudspeaker supplied with a generator of the sinusoidal signals. It allows to make vibrate, according to vibration modes, the composite plate. The vibration is measured by an accelerometer or is recorded by a microphone. The signal is amplified then visualized on an oscilloscope. The amplitude and the frequency of the signal sent on the loudspeaker can be increased gradually. The whole of the recordings (for various frequencies and various amplitudes) will make it possible to characterize the ageing of a composite plate.

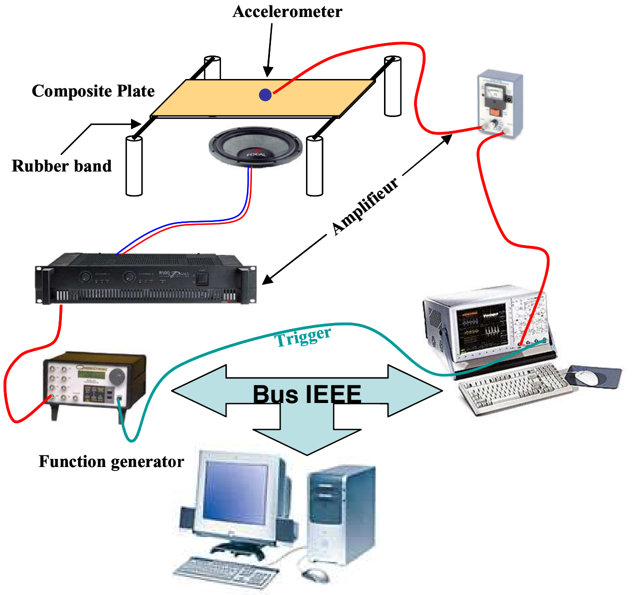

Fig. 1 Experimental setup

2.1 Plate description and vibration modes

The tests were carried out on a laminated composite plate with carbon fibre, with a width of 10 cm, a 15 cm length, a 2.3 mm thickness and a density of 1530kg.m^{-3}. The matrix of elasticity of this plate is given by Eq.(1).

$$C=\begin{pmatrix} 56,9 & 9,7 & 9,7 & 0 & 0 & 0 \\ 9,7 & 14,7 & 9,7 & 0 & 0 & 0 \\ 9,7 & 9,7 & 14,7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4,2 \end{pmatrix}\times 10^{9} \qquad (1)$$

The plate is suspended horizontally by rubber bands on the two sides as shown in Fig. 1.

The experimental modes of vibrations are located by the use of two accelerometers placed at two points different from the plate. For each resonances, the signals from the accelerometers are measured as well as the differences of phases and amplitudes between the two. This process is repeated for each pair of points of the configuration represented in Fig. 2. For each mode of vibration of the plate, we determined the precise place to fix the accelerometer in order to obtain the maximum of amplitude.

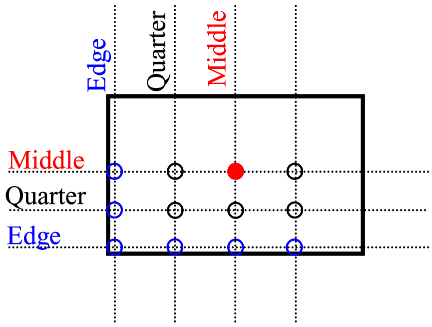

Fig. 2: Different position of accelerometers on the composite plate

2.2 Finite element simulation

We also studied the various theoretical modes of vibration of our plate, from a modeling by finite elements (software COMSOL®). This modeling made it possible to check the type of the vibrations detected by the experimental recordings. The frequencies of the experimental modes described previously are close to those obtained by finite elements for a free plate (Fig. 3). A light difference exists which can be easily explained by the small mass of the accelerometers when they are fixed on the plate, or by the values of the coefficients for the matrix C of the model which are not identified exactly.

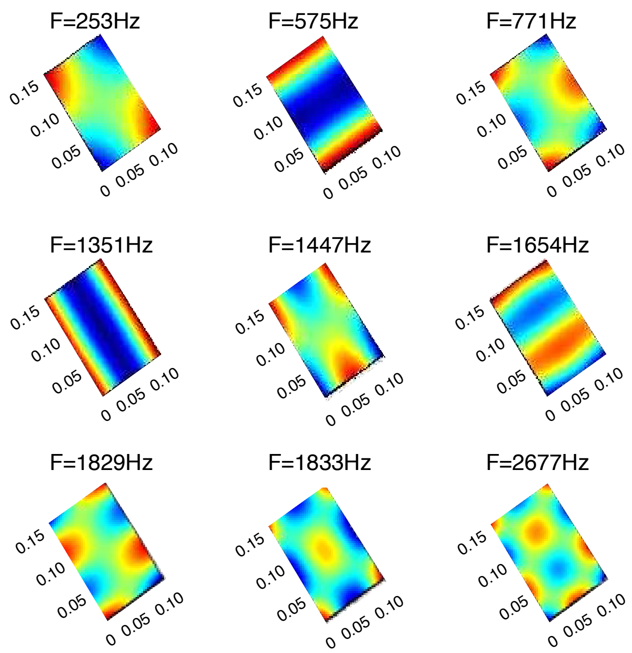

Fig. 3: Cartography of the first modes of vibration of a free plate obtained by COMSOL Multiphysics

Studies were led to various frequencies corresponding to situations common to the experimental recordings and with simulations. In the continuation of the article, only a frequency is studied for F close to 575Hz. In this case (see Fig. 4), the accelerometer is placed in the midle of the plate. This position is easily locatable.

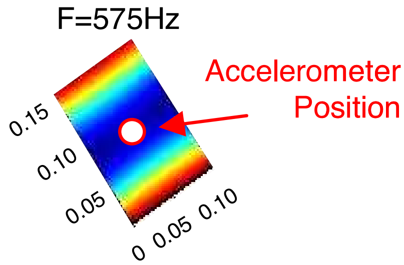

Fig 4: Selected mode of vibration, location of the accelerometer

3 Implementation of NDT-NEWS

We used NDT-NEWS to characterize the thermo-oxidative ageing of a laminated composite plate with carbon fibre. It corresponds to an ageing in the air. To the effects of the temperature the effects of oxidation by oxygen are added. The plate is placed in a drying oven whose temperature is controlled with 200°C. This temperature is raised, but remains lower than the temperature of vitreous transition (Tg close to 210°C). A preceding study to show that the effect of the temperature significantly increased the presence of micro cracking [8]. The same plate is put out of drying oven, then tested after each period of ageing. That makes it possible to avoid the change of the frequencies of resonance which can be produced by the small differences (geometry, mass…) between two different plates, and ensures us to measure only the influence of thermal ageing.

The excitation of the plate is ensured by the loudspeaker with a varying sweeping around the frequency of resonance for tensions from 0.2 to 1.4 volts.

First of all, we carried out tests on the healthy plate (without thermal ageing). The results obtained (frequencies and amplitudes) for the healthy plate were taken as reference of comparison. The same experiments were remade on the same plate after ageing of durations 4, 8, 16 and 24 hours.

3.1 Signal analysis

Measurements (frequencies, amplitudes) were completed with a frequency step adapted around the resonance, and the duration of sweeping. To accelerate sweeping and to have a better precision, we chose a frequential step of 1 Hz which the program will divide by 4 when one approaches the resonance frequency. An extrapolation by the described function Eq. 2 was then carried out to determine the frequency (of resonance) and the maximum amplitude.

$$m(f) = k \times A_{exci} \times \frac{(f - f_1)^2 + a}{(f - f_2)^2 + b} \qquad (2)$$

Where
m is the amplitude measured by the accelerometer,
f is the frequency,
k, f_1, f_2, a and b are constants,
A_{exci} is the amplitude of excitation.

Fig. 5 shows an example of extrapolation (red curves) of the experimental data points (blue dots) of these measurements and the resulting relative error calculated in the represented zone by the rectangle.

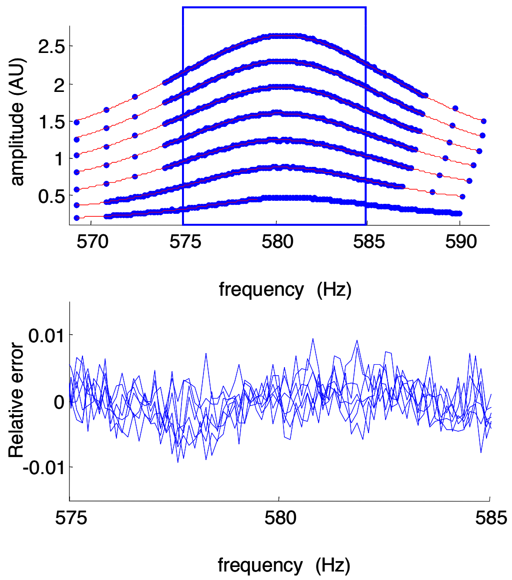

Fig. 5: Extrapolation of the experimental data

In order to take into account in our measurements the repetitivity of the results we took several measurements for each test on the plate. Then, we determined the average curves which will be useful to us thereafter (Fig. 6)

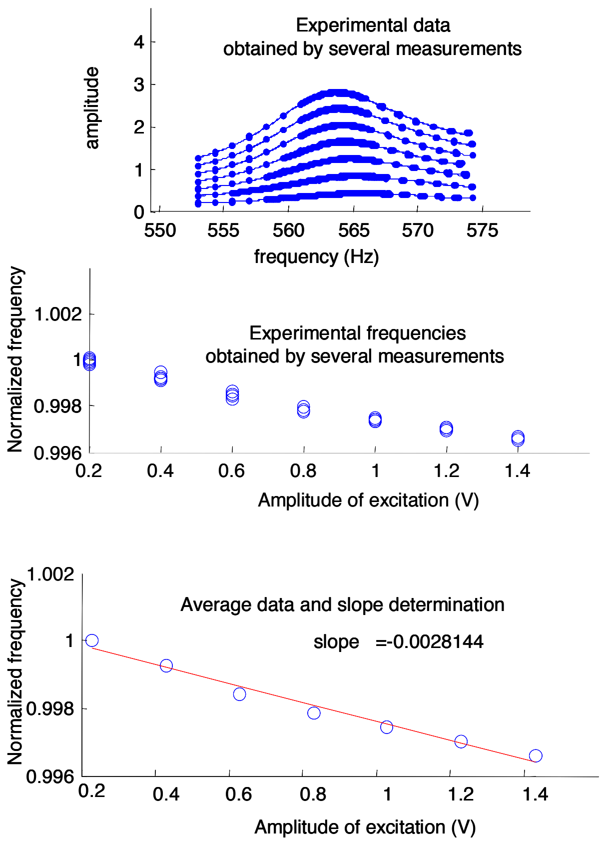

Fig 6: Experimental data obtained by several measurements and average resulting slope.

The average amplitude, measured on the surface of the plate opposed to that excited by the loudspeaker, is represented according to the frequency, for amplitudes of increasing excitations. The passage of a level of excitation to the other is made in a continuous way without leaving time to material to release itself.

3.2 Results

The Fig. 7b shows the shift of the frequencies of resonance for the plate aged during 24 hours. The shift is quasi null in the case of the plate before ageing (healthy plate) (Fig 7a).

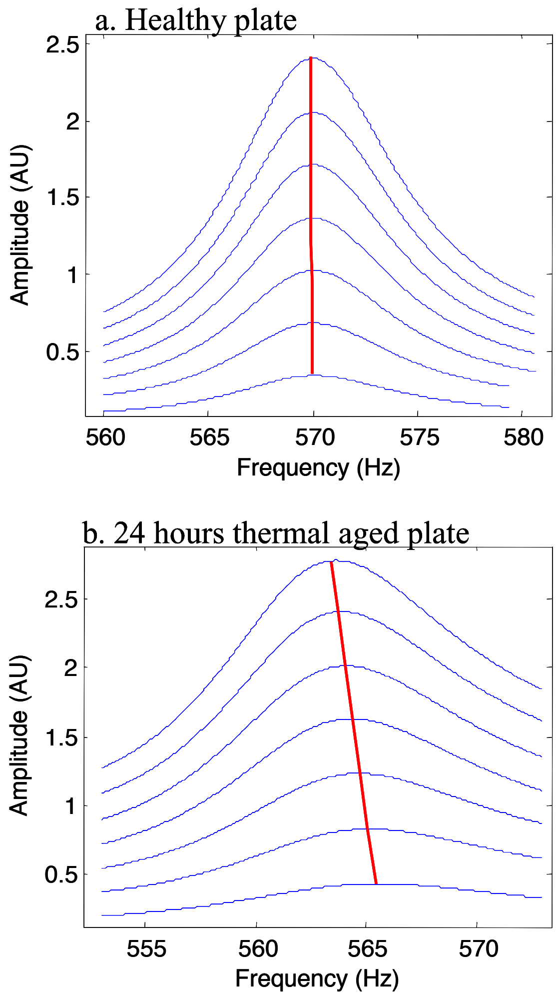

Fig. 7: Shift of the frequencies of resonance for healthy plate (a) and T=24hours aged plate (b).

It is around these shifts of frequencies of resonance that we carried a great interest to compare the various phases of ageing of the plate from 0 to 24 hours. To facilitate that, we calculated the relative shifts $\Delta f / f_0$ ($\Delta f = f_r - f_0$, with f_r is the frequency of resonance and f_0 is the frequency of resonance of the lower level of excitation) according to the amplitude of excitation for the various phases of ageing of the plate. These relative shifts are represented in their turn by linear straight regression lines (Fig. 8).

The values of the slopes of these lines are summarized in the following table and are represented in Fig 9. The healthy plate is noted T0, the 4 hours thermal aged is noted T4 and so one.

	T0	T4	T8	T16	T24
Slope $\Delta f / f_0$ ($^0/_{00}$)	-0.094	-0.359	-0.840	-1.025	-2.814

Table 1 : evolution of the slopes (frequency shift) with the thermal ageing duration

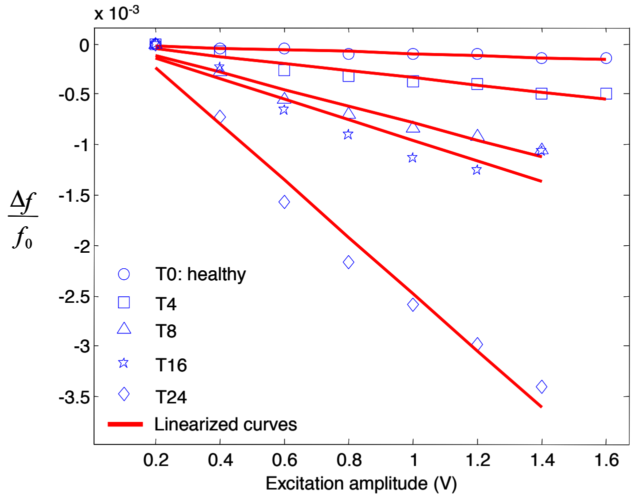

Fig. 8 : Variation of $\Delta f / f_0$ according to the amplitude of excitation for 0, 4, 8, 16 and 24 hours of ageing

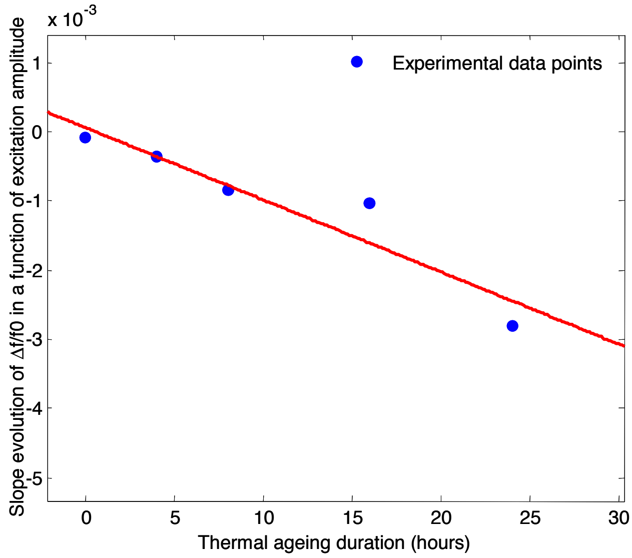

Fig. 9: Evolution of the slopes according to the thermal ageing duration

Fig. 9 consolidates the theory of the non-linear effects hysteretic, which envisages a relation proportional between the relative variations of the frequency of resonance and the deformation of the material [7].

In addition to, at the healthy state, the material exhibe a light non-linear behavior that one can to check through the evolution of the frequency of resonance which decreases slightly when the amplitude of excitation increases.

4 Conclusion

In this work, we presented the method of NDT known as NEWS to characterize thermal ageing in a composite material containing carbon fibre. The results obtained encourage us to use this method for this kind of characterization and allows us to use it for indicator of ageing. The voluntarily high temperature (near to the temperature of vitreous transition), strongly damaged the structure of the composite plate. Between T16 and T24, it appeared on the plate of the traces of delaminations, in addition to the microscopic cracks nonvisible with the eyes. After checking by Cscan, the plate is délaminated (> 30%). The delamination caused between 16 and 24 hours is certainly the origin of the strong variation of the slope observed in experiments.

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