Lock-in thermography as a tool for fatigue damage monitoring of composite structures

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Abstract

Fatigue dimensioning of composite structures has become a great challenge in the aeronautic industry. The estimation of the fatigue limit requires time-consuming experimental campaigns: millions of mechanical cycles are applied to one studied sample until failure, for several load levels. The alternative discussed in the present paper is to monitor the self-heating of carbon/epoxy composites under a significantly reduced number of load cycles, in order to define fatigue damage indicators. The chosen approach is to use lock-in thermography, which makes it possible to analyse the first harmonics of the heating signal, not matter how noisy it might be.

1. Introduction

The dimensioning of composite structures requires both the understanding of the damage mechanisms that occur under fatigue loading and the knowledge of their fatigue limit. In the aeronautic industry, expansive experimental campaigns of fatigue tests of millions of cycles are carried out for a great number of samples (at least one by load level). From those tests, Wöhler curves, which display the evolution of the number of cycles to failure with the maximal stress value, are plotted so that the load threshold under which the sample can supposedly be infinitely submitted to mechanical cycles without breaking can be deduced.

In order to simplify this heavy procedure, an alternative has been proposed, which consists in monitoring the global self-heating of one given composite sample under a few thousands of cycles, for increasing values of stress levels. The point of such tests is to assess the heating rate and the stabilized heating for each load level and then to detect the stress threshold from which these thermal indicators start increasing. It has been shown for metallic materials that this load value could be associated with the fatigue limit [1], while several studies are currently being validated for thermoset composites [2, 3], and more recently thermoplastic composites [4]. However, a significant issue remains: the temperature rises that are being looked for are so low (rarely exceeding a few hundreds of mK for the first load levels) that the noise, mainly due to convective effects and the measurement systems themselves (drift of the infrared camera, for instance), makes it often impossible to assess such heating indicators.

Lock-in thermography might be a promising tool to face these challenges: instead of only monitoring the global self-heating of the studied sample, the first harmonics of the thermal signal are analysed over a very limited number of mechanical cycles (no more than a dozen ones). Such procedure can be applied even to a noisy thermal signal and enables to avoid major convective effects. New fatigue indicators can then be defined, such as the difference to linearity of the first harmonic, which reflects a loss of elastic properties, and the emergence of the second one, that might reveal the first stages of fatigue damage. If it has already been successfully applied to metallic materials [5], lock-in thermography should provide decisive results for composite materials as well.

The aim of the present article is to illustrate how lock-in thermography can make it possible not only to assess the fatigue limit of composites from only a hundred cycles or so, but also to detect heat sources that might announce early failure.

2. Theoretical approach: thermoelasticity, effects of viscosity and progressive damage

When submitted to a mechanical cyclic loading of a frequency f_0 (associated with a pulsation ω_0), the time-variation of the global self-heating $\theta(t)$ of a composite material can be modelled by an exponential function [3] (first term of equation (1)). This major contribution to the heating, also referred to as the "thermal drift", is due to the viscosity of the resin and to the friction of initial manufacturing defects such as micro-cracks. Then, as damage fatigue is progressively induced, this thermal drift becomes more and more significant. Two thermal indicators are defined: the stabilized heating θ_F, usually reached after a few thousands of cycles, and the initial heating rate (ratio between θ_F and a characteristic time τ).

$$\theta(t) = \theta_F \cdot \left(1 - exp(-\frac{t}{\tau})\right) + A_1 \cdot sin(\omega_0 t + \phi_1) + A_2 \cdot sin(2 \cdot \omega_0 t + \phi_2) + ... \qquad (1)$$

However, as illustrated by Figure 1, due to thermoelastic effects, the temperature field also pulses in phase opposition with the applied cyclic load, hence the idea to look into the harmonics of the thermal signal. The first harmonic describes the thermoelastic behaviour: as long as the composite is undamaged, its modulus A_1 should keep rising proportionally to the amplitude of the load which linearly increases from one level to another. As for the second harmonic, it was shown by Krapez *et al.* that, in metallic materials, its modulus A_2 becomes non-negligible as soon as fatigue damage occurs [5].
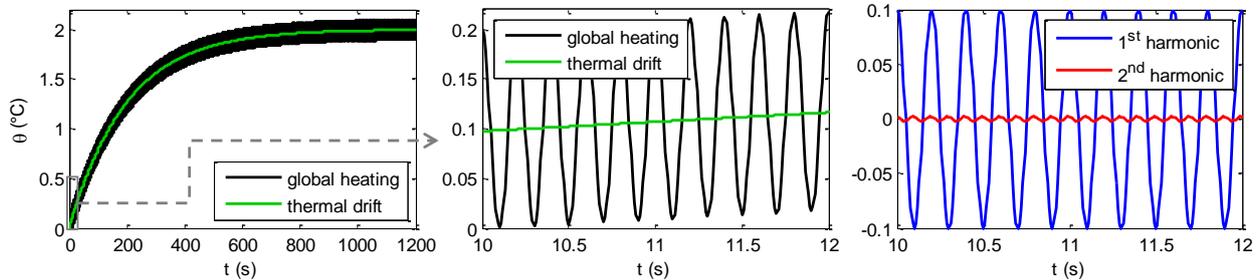

***Fig. 1**: Time-evolution of a simulated heating signal of a sample under cyclic loading of fixed amplitude and frequency. Global heating and thermal drift (left and middle, for a 2s time-window); first two harmonics (right).*

The very principle of conventional self-heating tests is to catch any trend changes in the variations of the stabilized heating and initial heat rate with the increasing load. The lock-in thermography approach proposes to try and detect a possible non-linearity of the modulus A_1 and the emergence of the modulus A_2 in the Fourier spectrum. The phases ϕ_1 and ϕ_2 can be monitored as well. Whereas the stabilized regime must be reached to properly analyse the thermal drift, only a few cycles are required for the lock-in approach, which drastically reduces the duration of the test.

3. Experimental investigation of fatigue damage in composites: contribution of lock-in thermography

All self-heating tests are carried out on 500 kN hydraulic dynamic machine. The frequency of the mechanical cycles and their aspect ratio (defined as the ratio of the minimal stress value over the maximal one) are respectively set to 5 Hz and 0.5 for every load level. The step between two following load levels is 10 kN. The front-face of the tested samples is monitored by an X6540sc FLIR mid-wave infrared camera, with a frame rate of 100 images per second.

The relevance of monitoring the thermal drift was previously studied in ONERA [3] for a carbon/epoxy 2D woven composite. It was shown that for the lowest loads, the stabilized heating and initial heating rate are almost constant; then a stress threshold is reached from which those indicators begin to increase. However, when the heating signal-to-noise ratio is too low for the exponential fitting of the thermal drift to be adequate, only the extraction of the harmonics remains possible and enables to detect the non-linearity of the first harmonic, as well as the emergence of the second one, as shown in Figure 2.
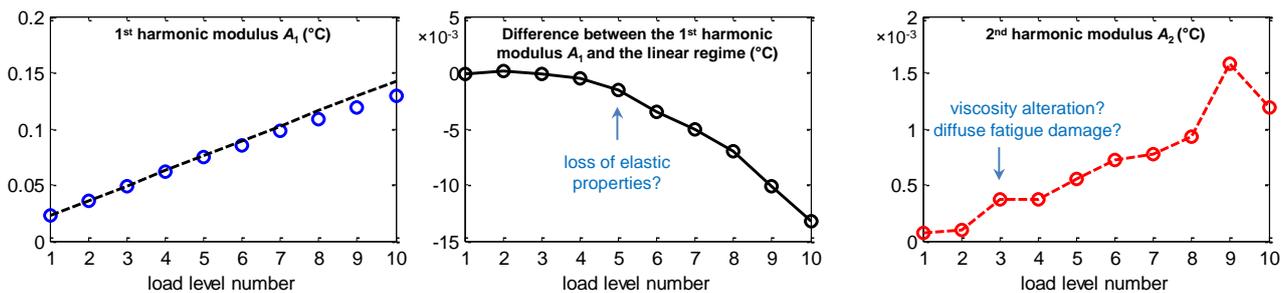

***Fig. 2**: Variations of the first and second harmonic moduli during a self-heating test from one load level to another (left & right). Highlight of the nonlinearity of the first harmonic (middle).*

The lock-in analysis can also be applied to the full-field thermal images acquired during the test. In particular, the first harmonic map can be used to deduce stress fields, accordingly to the TSA (*Thermal Stress Analysis*) approach [6]. It definitely can be used to detect the first stages of fatigue damage, as illustrated by Fig. 3 for a perforated carbon/epoxy UD composite. Hot spots, unseen by standard passive thermography monitoring, can be identified around the perforation for the lowest load levels.
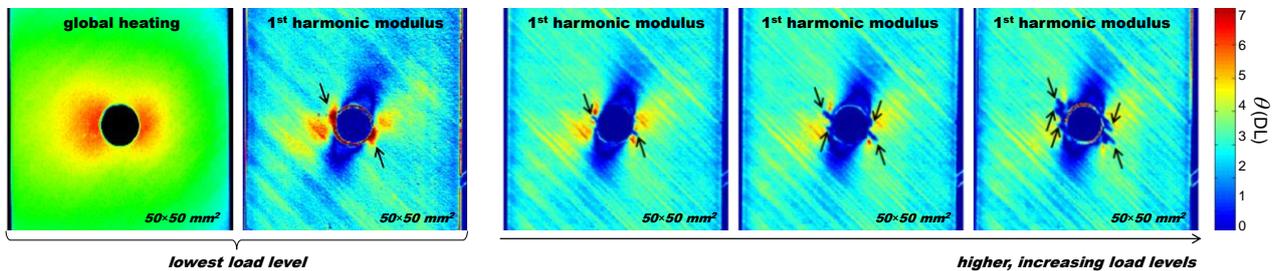

Fig. 3: *Self-heating test on a carbon/epoxy UD composite with a 10 mm diameter perforation. Global heating and first harmonic modulus maps for a low load level (left); evolution of the first harmonic modulus for higher load levels (right).*

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