DEFECT DETECTION BASED ON THERMAL PERIODIC EXCITATION

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Abstract

A new method dedicated to defect detection in composite materials is presented in this paper. The proposed approach is based on the measurement of the material temperature resulting from a local periodic low energy heating. Effect of thermal waves propagation is investigated using a mathematical model based on complex temperature concept. Sensitivity analysis is implemented in order to highlight the interest of the whole approach in specific cases and attest to the local method's attractiveness.

1 Introduction

An accurate control of structural material properties combined with relevant structure health monitoring (assembly, bound, resin & fiber) is nowadays required to guarantee the quality of any structure. Defect inside a composite structure can be localized and analyzed using acoustic techniques. Unfortunately for such techniques (C-SCAN for example [1]) a fluid vector is usually required and can deteriorate or pollute the investigated material. In order to avoid the sample contamination, several non destructive processes based on the observation of the thermal effect of a heating step have already been investigated. Observations of the sample surface using an infra-red camera can enable defects detection. In such a context, several studies can be mentioned: [2] for crack detection at micrometric scale, [3] and [4] for recent applications. More specifically, the active thermography method proposed by authors in [3] is the step heating and consists in sample heating for a given time length (ranged between 60 s and up to 1 hour). Then thermal observations are considered during the whole relaxation process. However, non-negligible thermal energy required for this technique can induce permanent material deterioration. Then an attractive idea is to develop a method based on the analysis of the propagation of low energetic thermal waves inside the investigated sample using a periodic excitation [5-7]. Indeed, relevant information could be collected from a modulated heating of reduced energy (compared to a classical flash method for example). In the literature, various implementations of this approach can be found for parametric identification for millimetric scale [8-10] as well as for micrometric investigation [11-13]. Application in a biological context for human skin thermal properties identification is proposed in [14]. However for defect detection using a quite local periodic heating, such approach has not been investigated. In this paper, the principle of periodic method is briefly exposed and the mathematical model satisfied by temperature expressed in its complex formalism is presented. Numerical results are shown in order to illustrate the defect effect on both modulus and phase lag spatial distributions. Then several configurations are considered and assess the method attractiveness

2 Mathematical model for heat transfer

2.1 State equations

Let us consider that the periodic heating flux can be expressed without lack of generalities as follows:

$$\Phi(x,y,z;t)=\phi_0(x,y,z)\cos(\omega t) \tag{1}$$

where $(x,y,z)\in\Omega\subset\mathbb{R}^3$ is the space variable, t is the time variable, $\phi_0(x,y,z)$ is constant on a disk (radius R on the heated sample surface $\Gamma_0\subset\partial\Omega$), ω is the pulsation. For a realistic periodic signal, $\Phi(x,y,z;t)$ is the first harmonic. Temperature evolution for each sample point tends towards a periodic state after a transient one. Such oscillations are completely defined by their amplitude $\left|T(x,y,z)\right|$ and their phase lag $\varphi(x,y,z)$ when compared with a reference signal (heating input for example). Let us introduce the complex notation $\tilde{T}(x,y,z)=\left|T(.)\right|\exp(j\varphi(.))$ where $j^2=-1$ solution of the following partial differential equations system:

$$\forall(x,y,z)\in\Omega \qquad \tilde{T}(x,y,z)+\frac{j}{\omega}\operatorname{div}\left(\overset{\Rightarrow}{\alpha}\,\overrightarrow{\operatorname{grad}\tilde{T}(x,y,z)}\right)=0 \tag{2}$$

$$\forall(x,y,z)\in\Gamma_0 \qquad -\overset{\Rightarrow}{\lambda}\frac{\partial\tilde{T}(x,y,z)}{\partial\vec{n}}=h\tilde{T}(x,y,z)-\Phi_0 \tag{3}$$

$$\forall(x,y,z)\in(\partial\Omega/\Gamma_0) \qquad -\overset{\Rightarrow}{\lambda}\frac{\partial\tilde{T}(x,y,z)}{\partial\vec{n}}=h\tilde{T}(x,y,z) \tag{4}$$

where $\overset{\Rightarrow}{\alpha}=\frac{\overset{\Rightarrow}{\lambda}}{C}$ is the thermal diffusivity sensor in $\left[\mathrm{m^2.s^{-1}}\right]$, $\overset{\Rightarrow}{\lambda}$ is the thermal conductivity tensor in $\left[\mathrm{W.m^{-1}.K^{-1}}\right]$, C is the volumetric heat in $\left[\mathrm{J.m^{-3}.K^{-1}}\right]$, $\vec{n}$ is the unit vector external outward-pointing normal to $\partial\Omega$, h is the convective heat transfer coefficient in $\left[\mathrm{W.m^{-2}.K^{-1}}\right]$.

For an isotropic material, diffusion length defined as $\mu=\sqrt{\frac{\alpha}{\pi f}}$ in $[\mathrm{m}]$ is a key parameter for periodic methods. In fact, in thermal sciences, it is usually considered that effect of thermal wave vanishes at distance greater than 3μ from the heating excitation.

2.2 Direct problem resolution

In this section, direct problem $(2-4)$ is solved using finite element method (Comsol software). A semi infinite thin plate (thickness $e = 5\text{mm}$) is considered. Thermo physical parameters are presented in Table 1.

Diffusivity $\left[\text{m}^2.\text{s}^{-1}\right]$	**Conductivity** $\left[\text{W.m}^{-1}.\text{K}^{-1}\right]$	**Convective coefficient** $\left[\text{W.m}^{-2}.\text{K}^{-1}\right]$	**Heating flux** $\left[\text{W.m}^{-2}\right]$
$\alpha = 1.035 \quad 10^{-7}$	$\lambda = 0.24$	$h = 20$	$\Phi_0 = 5 \quad 10^3$

Table 1. Thermophysical parameter (PTFE sample)

Let us consider that only the heated face can be observed by infrared camera; such configuration (called reflexion) is quite general. Both modulus and phase lag are investigated on the heated face.

On the following figures, effect of excitation frequency $f = \dfrac{\omega}{2\pi}$ and disk radius R is shown.

Without any defect, an axis-symmetric configuration can be considered. If the modulus is too attenuated, phase lag analysis is meaning less. Then, for each point of the heating surface, if $\left|T(x,y,z)\right| \le 0.01 \max\limits_{\Gamma_0} |T|$ then $\varphi(x,y,z) = -150°$.

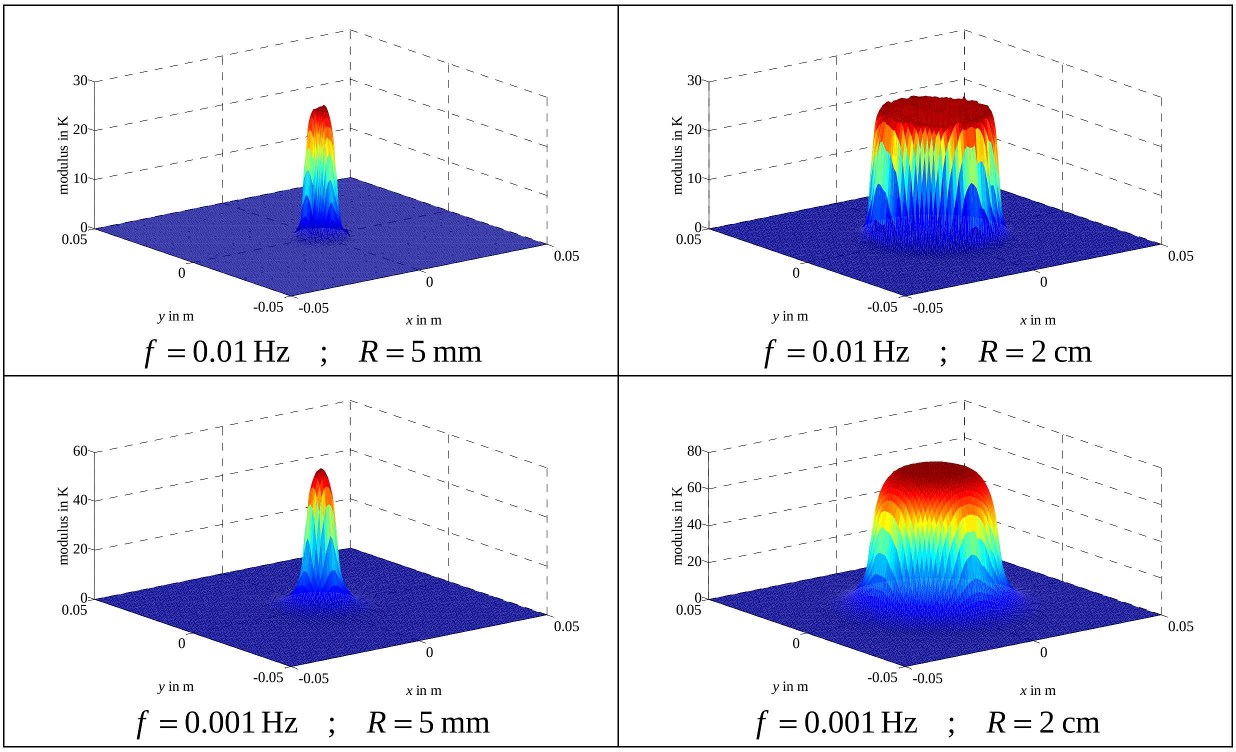

Figure 1. Modulus for several disk radius and excitation frequency

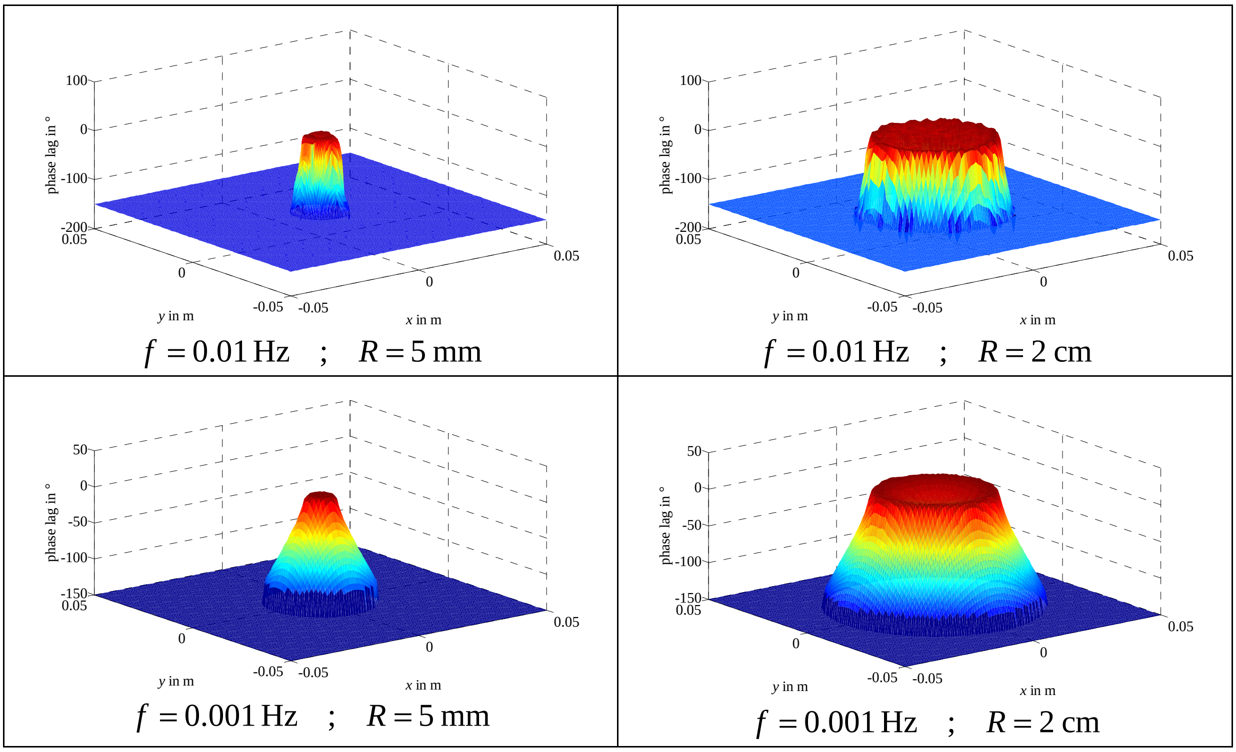

Figure 2. Phase lag for several disk radius and excitation frequency

On the previous figures, it is shown that at lower frequency, phase lag is more affected than modulus. Thermal waves propagation is investigated in the following section for defect detection.

3 Defect localization

In this section, a small aluminum disk (1 cm radius, 1 mm thickness) is located inside the previous PTFE sample. Defect thermal diffusivity is $\alpha_{def} = 6.5 \quad 10^{-5} \left[\text{m}^2.\text{s}^{-1} \right]$ while defect thermal conductivity is $\lambda_{def} = 160 \left[\text{W.m}^{-1}.\text{K}^{-1} \right]$. This defect is located at a distance of 2 cm from the PTFE plate center. Two approaches are compared. For the first one, heating disk radius is greater than the plate size in order to heat the whole PTFE surface. This first approach is called in the following “global approach”. For the second approach, a smaller heating disk radius is taken into account $R = 1\text{ cm}$ in order to provide a local heating.

3.1 Global approach

Modulus and phase lag are shown in figures 3 and 4 for a global periodic heating $R = +\infty$ at frequency $f = 0.001\text{ Hz}$. Defect effect is directly observed. Numerical effect of a coarse mesh is also put in evidence in order to show that a refined mesh is not required for such inaccurate localization.

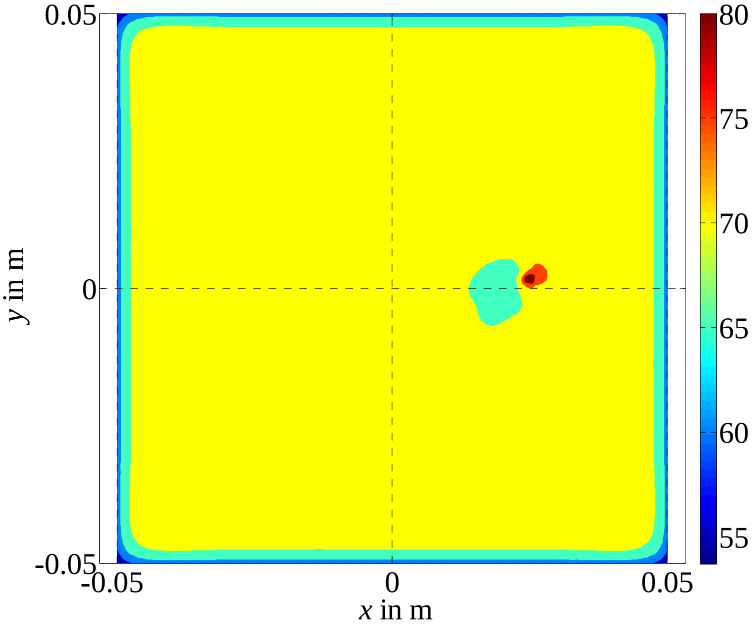

Figure 3. Modulus observation for defect localization (global approach)

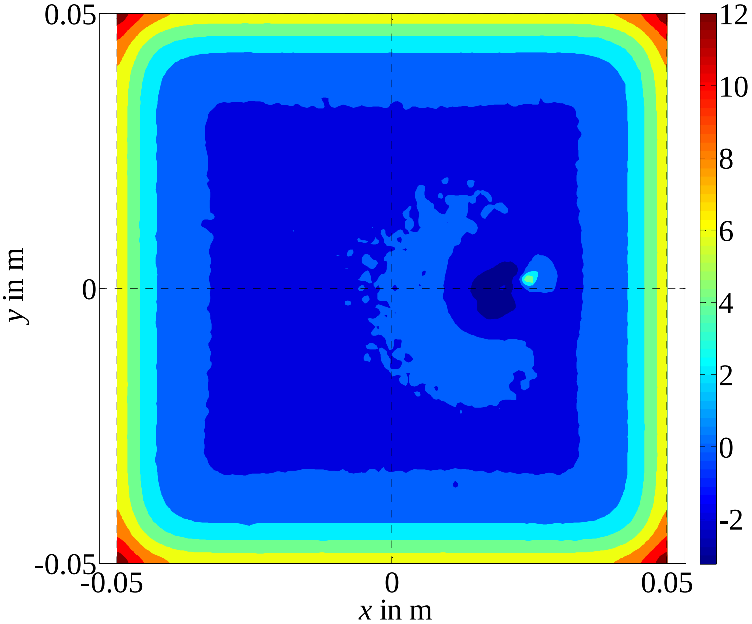

Figure 4. Phase lag observation for defect localization (global approach)

3.2 Local approach

For the local approach the heating disk radius is equal to 1 cm. In figures 5 and 6 modulus and phase lag are drawn (excitation frequency $f = 0.001\,\text{Hz}$). Phase lag observation seems more pertinent for defect localization purposes. In figure 9, modulus difference (sample with defect compared with sample without defect) is shown.

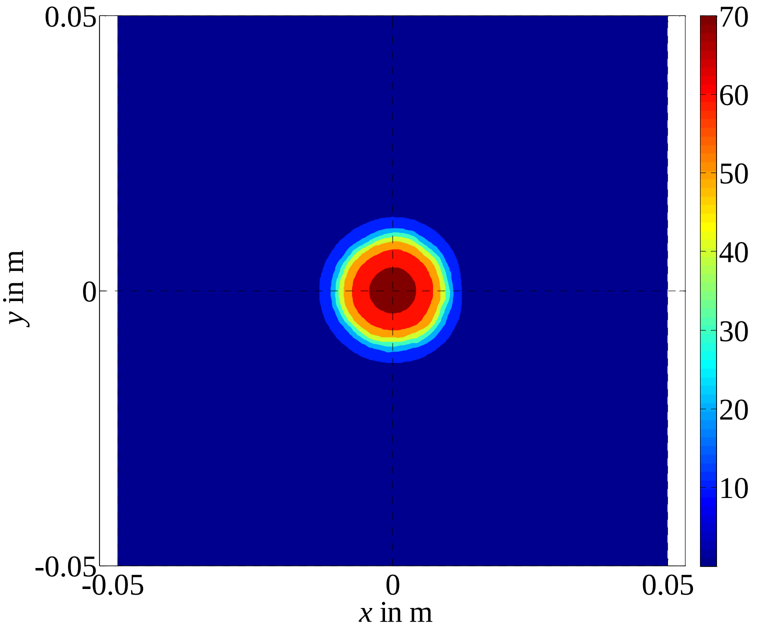

Figure 5. Modulus observation for defect localization (local approach)

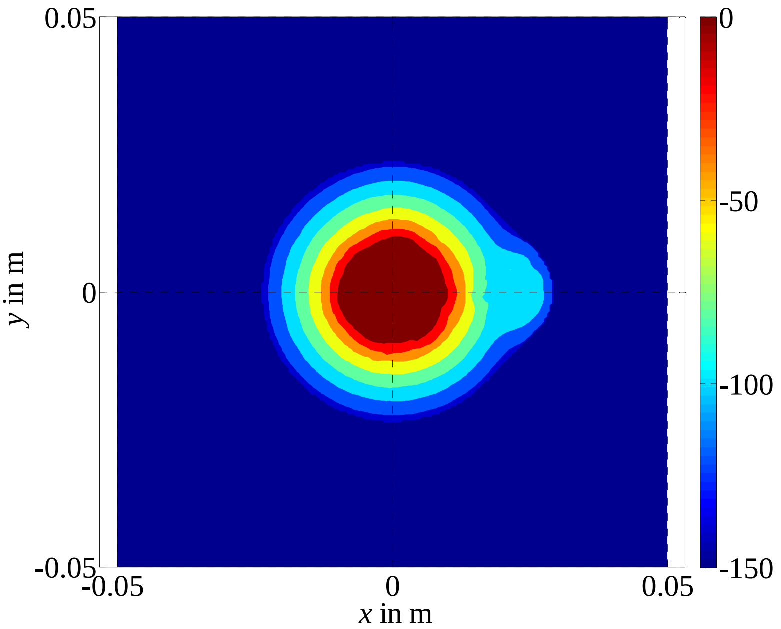

Figure 6. Phase lag observation for defect localization (local approach)

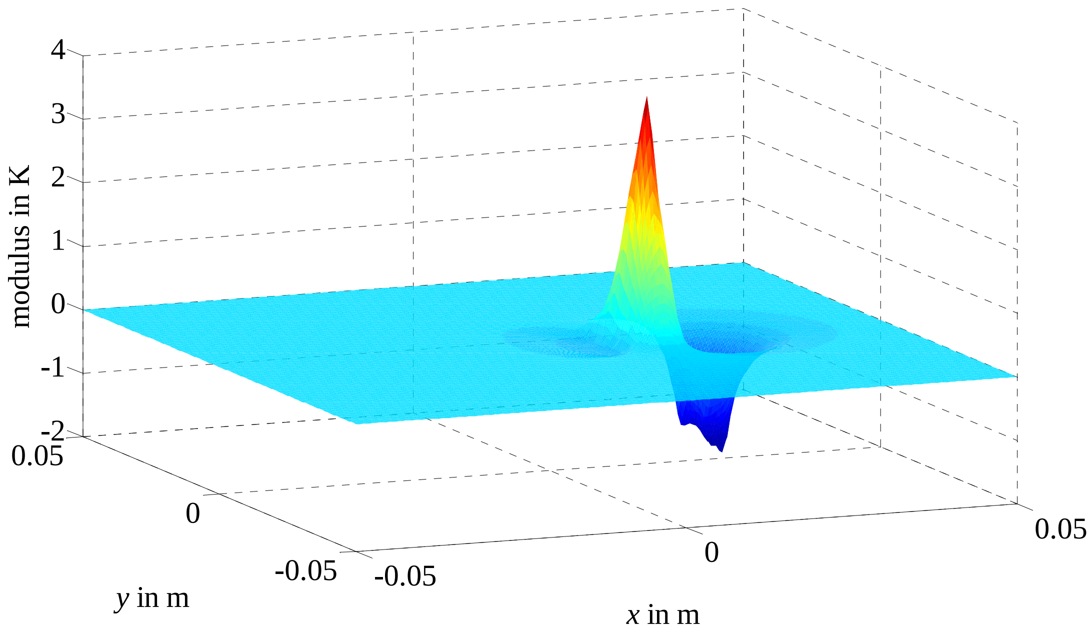

Figure 7. Modulus difference (local approach)

Considering previous figures 6 and 7, defect localization can be performed using a local periodic approach. Moreover, phase lag spatial distribution can be investigated for defect shape identification.

Conclusions

In this paper, a non-destructive approach for defect detection in composite materials based on the analysis of system state behaviour when submitted to a modulated input has been proposed. One of the main advantage of this technique is to be used even if the signal versus noise on observable output ratio is low and thus to preserve the material integrity. The local approach specificities offer an attractive alternative to more usual global approach.
Beyond the detection of a possible defect and the estimation of its position, actual work is focused on the determination of the nature and the geometry of defect (depth, shape). A scanning method is actually developed to provide an easy-to-use defect detection method (as simple as C-SCAN method).

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