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Characterization of delaminations by lock-in vibrothermography

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Abstract. Vibrothermography has proven to be a useful technique for the detection of buried defects, which reveal themselves as heat sources when mechanically excited with ultrasounds. In this work we present a method to evaluate the depth of delaminations in opaque samples, from lock-in vibrothermography measurements. It is theoretically demonstrated that the phase and the natural logarithm of the surface temperature above the delamination behaves linearly as a function of the square root frequency. The slope of this linear relation is directly proportional to the delamination depth. Measurements performed on composite plates with calibrated delaminations confirm the validity of the method, provided the width of the delamination is higher than the thermal diffusion length.

1. Introduction

Vibrothermography or thermo-sonics was introduced in the late 70s as a new type of excitation in the field of thermographic nondestructive evaluation (NDE) for the detection of defects such as cracks or delaminations [1-3]. In contrast to the more classical thermography set-up, in which the energy is delivered at the sample surface by optical means, in vibrothermographic arrangements the sample is mechanically excited by sonic or ultrasonic oscillations. The excitation is carried-out by coupling an ultrasonic transducer to the sample surface. In general, the propagation of the damped acoustic waves along the material converts mechanical energy into thermal energy, but in the vicinity of the defects the energy dissipation is bigger due to friction between the faces of the defect and/or stress concentration at the surrounding area. This mechanical excitation acts as a selective inner heat source, located just at the defect, which diffuses inside the material and can be detected as a temperature variation at its surface by means of an infrared (IR) video camera.

In the case of lock-in vibrothermography [4] a high frequency oscillation is amplitude-modulated at a low frequency and the detection lock-in system (synchronized with the amplitude varying input signal) records the amplitude and phase of the surface temperature. In a recent work we have developed a theoretical model to calculate the surface temperature rise induced by a vertical heat source simulating a vertical crack [5]. This model allowed us to characterize the size and depth of calibrated buried vertical cracks in metallic slabs.

In this work, using the same theoretical approach, we present an extension of that previous work to characterize the depth of horizontal cracks or delaminations. Measurements performed on composite plates with simulated delaminations confirm the validity of the method.

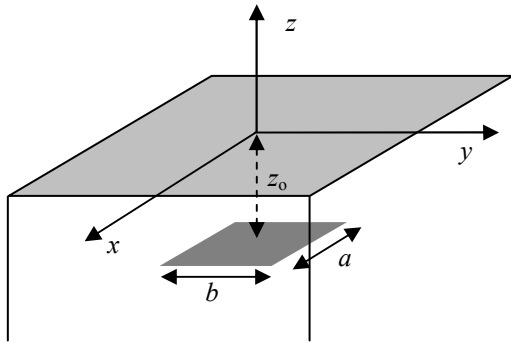


Figure 1. Geometry of the problem. The sample surface is represented in light grey, while the subsurface delamination in dark grey.

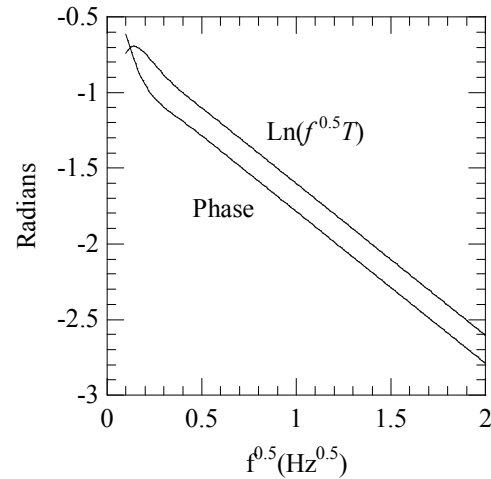


Figure 2. Simulation of evolution of the phase and natural logarithm of the surface temperature as a function of $f^{0.5}$ for a square delamination with $a = b = 10$ mm, buried at $z_0 = -0.4$ mm in a semi-infinite sample with $D = 0.5$ mm²/s, $K = 2$ Wm⁻¹K⁻¹.

2. Theory

We have modelled the heat source generated at a horizontal delamination as a flat and rectangular source of length a and width b , located at a depth z_0 beneath the surface of the sample. For the sake of simplicity, the heat source is considered homogeneous. The geometry we have worked with is shown in figure 1, where the heat source is drawn in dark grey. In lock-in vibrothermography the crack acts as a heat source modulated at the same frequency f ($\omega = 2\pi f$) as the amplitude of the ultrasonic source is modulated. In order to calculate the oscillation of the sample temperature produced by the rectangular modulated heat source, we decompose it as the superposition of infinitesimal modulated heat sources. If we consider a point-like heat source modulated at frequency f and located at coordinates (x_0, y_0, z_0) in a homogeneous and semi-infinite medium, the amplitude of the temperature oscillation at the sample surface ($z = 0$) is given by [6]:

$$T(x, y, 0) = T_o \frac{e^{-q\sqrt{(x-x_0)^2 + (y-y_0)^2 + z_0^2}}}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + z_0^2}}, \quad (1)$$

where T_o is a factor which depends on the strength of the heat source and on the thermal properties of the medium, and $q = \sqrt{i\omega/D}$ is the thermal wave vector, being D the thermal diffusivity. Equation (1) represents a highly damped spherical thermal wave generated at (x_0, y_0, z_0) . The amplitude of the temperature oscillation corresponding to the entire rectangular heat source is obtained by integrating equation (1) over its whole size:

$$T(x, y, 0) = 2T_o \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} \frac{e^{-q\sqrt{(x-x_o)^2+(y-y_o)^2+z_o^2}}}{\sqrt{(x-x_o)^2+(y-y_o)^2+z_o^2}} dx_o dy_o, \quad (2)$$

where the factor 2 accounts for the reflected thermal wave at the sample surface according to the “image method”, provided no heat transfer from the sample surface to the surroundings takes place, i.e. adiabatic boundary condition [7]. It is worth noting that equation (2) can be easily improved for different geometries of the heat source, including non-flat shapes and heterogeneous heat sources, by just appropriately selecting the power distribution and integration limits.

In figure 2 we show the behaviour of the phase and of the natural logarithm of the amplitude of the surface temperature just above the delamination centre as a function of the square root frequency. Simulations have been performed for a square delamination with $a = b = 10$ mm, buried at $z_o = -0.4$ mm in a semi-infinite sample with $D = 0.5$ mm²/s, $K = 2$ Wm⁻¹K⁻¹, the typical thermal properties of carbon fibre reinforced composites (CFRC). As can be seen, there is a linear relation whose slope is given by: $m = -z_o(\pi/D)^{0.5}$. Accordingly, the delamination depth can be obtained if the thermal diffusivity of the sample is known. This linear relation holds provided the two following conditions are fulfilled: (a) the thermal diffusion length, $\mu = (D/\pi f)^{0.5}$, is higher than the delamination depth and (b) the thermal diffusion length is smaller than the delamination size (a and b).

3. Experimental results and discussion

To verify the validity of the method proposed in the previous section we have prepared calibrated delaminations by inserting four squared films of Teflon between two plies of a CFRC plate 1 cm thick. The size of the films simulating the delamination is 15 mm x 15 mm, with increasing depths: 0.5 mm, 1 mm, 1.5 mm and 2.0 mm.

The measurements were performed with a commercial lock-in vibrothermography equipment (UTvis from EDEVIS). The surface temperature data were collected with an infrared camera (Silver 480M from CEDIP), synchronized with the amplitude varying input signal. For the measurements the sample was placed between a teflon block and the horn tip, that applies a preload pressure of 3 bar. We used an aluminium sheet to improve the mechanical contact between the tip and the sample. The equipment we have used to carry out the experiments is able to generate ultrasound frequencies ranging from 15 to 25 kHz. It has recently been demonstrated [8] that for specimens whose size is of the order of the ultrasound wavelength, normal modes of the specimen can be excited in lock-in vibrothermography experiments. If part of the delamination is located at the position of a node of the standing wave the result is an absence of vibration of the two sides of the delamination and in consequence, remains undetectable. This is the reason why performing frequency sweeps is useful in order to determine the most suitable ultrasound frequency to detect the crack in a particular specimen. We have performed such sweeps in our samples and have found an optimum ultrasound frequency of 19.75 kHz, at which data have been taken.

Figure 3 shows the phase thermogram of the CFRC plate at two modulation frequencies: 0.1 and 1 Hz. The simulated delaminations are clearly detected although the deepest one is close to the detection limit. As a further step, we are interested in measuring their depths. To do this we performed several measurements varying the modulation frequency in the range from 0.01 Hz to 5 Hz. The phase of the surface temperature at the centre of the delamination is depicted as a function of the square root frequency. The results for the delaminations labelled as (a), (b) and (c) in figure 3 are shown in figure 4. From the slope of each straight line the delamination depth was obtained taking the thermal diffusivity of the CFRC as $D = 0.45$ mm²/s. The obtained depths are 0.45 ± 0.05 mm, 1.11 ± 0.15 mm, and 1.3 ± 0.3 mm respectively. The agreement with the actual depths is very good, but the uncertainty increases with the depth of the delamination. The data for the deepest one, labelled as (d), are not good enough to retrieve its depth. Similar results have been obtained from the amplitude values, but the uncertainty is greater.

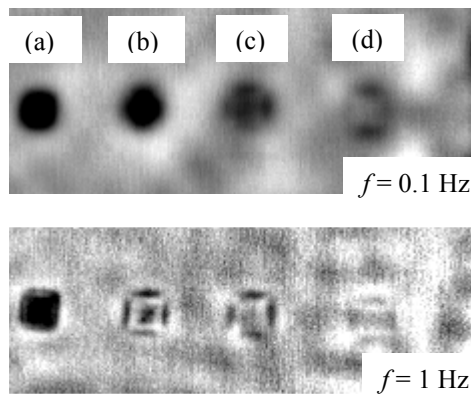


Figure 3. Phase thermograms of the CFRC plate with four buried delaminations. Their depths are: (a) $z_0 = -0.5$ mm, (b) $z_0 = -1.0$ mm, (c) $z_0 = -1.5$ mm and (d) $z_0 = -2.0$ mm,

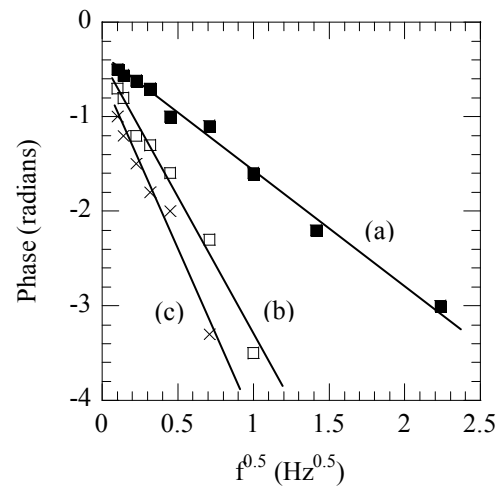


Figure 4. Experimental evolution of the phase of the surface temperature as a function of $f^{0.5}$ for the delaminations (a), (b) and (c) in figure 3. The continuous lines are the linear fits of the data.

Now we are working in developing an inverse procedure to reconstruct the whole shape of the delamination (length, width and depth) by analyzing, not only the values at the centre of the delamination, but the complete phase and amplitude thermograms.

Acknowledgments

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