Size retrieval of defects in composite material with lockin thermography

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Abstract. The article deals with the retrieval of the depths and sizes of defects situated in carbon fibers reinforced polymer material from optical lockin thermography phase images. A model that describes the images formation process in anisotropic, homogeneous material is presented. It is used to retrieve the depth and shape of the defects.

Quality control and non-destructive testing for aerospace applications have become more and more important and have seen several methods developed in the past years. In the aerospace field, methods have to be adapted for new generations of materials, such as carbon fibers reinforced polymer materials (CFRP).

In thermal imaging, the latest research was devoted to the development of new algorithms to get additional quantitative information of the defects from the acquired images. The goal of our work is to facilitate interpretation of images produced through optical lockin thermography.

1. Lockin thermography

In lockin thermography, the test specimen is illuminated with light which is sinusoidally modulated. Thermal waves penetrate into the material and are reflected at thermal boundaries. The temperature distribution at the surface is captured by an infrared camera. The amplitude and phase images computed by means of the Fourier transform make defects visible.

The equations are the equations of heat conduction. Through heat conduction, the defects appear blurred in the thermal images. The equation of heat in an isotropic and homogeneous solid in the Fourier space is [6]

\[ \nabla^2 \theta(r, \omega) - \sigma^2 \theta(r, \omega) = -1/k \, Q(r, \omega) \]

where \( Q(r, \omega) \) is the heat flow from the volume sources, \( \sigma = (1 + i) \sqrt{\omega/2 \alpha} \), \( \omega \), and \( \alpha \) are the frequency and the thermal diffusivity, respectively.

For lockin thermography, the maximum depth reached

\[ d = a \sqrt{\alpha / \pi f_h}, \]

\( a \) being the size of the defects.
of thermal waves is linked to the thermal penetration depth \( [2, 5] \) and thus linked to the blind frequency \( f_b \), the frequency at which the defect disappears. The parameter \( a \) equals 2.3. By choosing different excitation (lockin) frequencies, a phasegram composed of several phase images is achieved and the sample is scanned at different depths (Fig. 1).

\[ \Delta \theta = h(x, y; \omega, z) \otimes s(h(x-x_0, y-y_0)), \]

Figure 1: Examples of lockin thermography images of a CFRP panel with flat bottom holes at different depth obtained through lockin thermography at different frequencies

In thermal imaging, the thermal contrast, \( \Delta \theta \), is taken for analysis rather than absolute values. It expresses the difference in temperature between a defective and a non-defective area. It has been shown \([4, 7, 8, 9]\) that the thermal contrast in the Fourier space,

\[ \Delta \theta = h(x, y; \omega, z) \otimes s(h(x-x_0, y-y_0)), \]

can be expressed through a convolution between the point-spread function (PSF) \( h \) and the defect shape function, \( s(h(x-x_0, y-y_0)) \), that is unity on the defect shape and zero outside. The point-spread function \( h \) is found to be

\[ h(x, y; \omega, d) = \frac{F_0}{4\pi k} R^2 \frac{\sigma^2 e^{-\sigma(x^2+y^2+d^2)}}{r} \left( \frac{d}{r} \left( 1 + \frac{1}{\sigma r} \right) + 1 \right) \]

where \( r = \sqrt{x^2 + y^2 + d^2} \), \( F_0 \) is the constant heat flux prescribed at the surface of the sample and \( R \) is the reflection coefficient at thermal boundaries. By performing a change of variables, it is possible to pass from an isotropic to an anisotropic material \([1, 3]\). The point-spread function in the Fourier space for anisotropic solids of heat conductivity \( [k_1, k_2, k_3] \) is

\[ h(\xi, \eta; \omega, d) = \frac{F_0}{4\pi} R^2 \frac{(1+i)^2 e^{-(1+i)(r+d)}}{\mu_1 \mu_2 \mu_3} \left( \frac{d}{\mu_3 \rho} \left( 1 + \frac{1}{(1+i)\rho} \right) + 1 \right), \]

where \( \rho = \sqrt{\frac{\xi^2}{\mu_1^2} + \frac{\eta^2}{\mu_2^2} + \frac{d^2}{\mu_3^2}} \) and \( \mu_i = \frac{2k_i}{\omega_0 c} \) is the thermal penetration depth. For phase images, the thermal phase contrast equals in good approximation the imaginary part of the convolution product \([4]\), so that

\[ h_{\phi} = \text{Im}(h). \]

Through an inverse filtering method, the shape of the defect can be recovered. The theoretical phase contrast function agrees with the measurements (Fig. 2). The behavior of the phase contrast in respect
to the lockin frequency is well-illustrated: the phase contrast equals zero at the blind frequency where the defect disappears and is at maximum at the optimal frequency. Defect sizes and deconvolution should be evaluated at frequencies situated between these both characteristic frequencies.

Figure 2: Fit of the theoretical model to phase contrast measurements of a 2 mm deep defect ($\alpha = [0.5 \ 0.5 \ 0.22]$)

2. Experiments and results

Figure 3: Investigated parts and reconstructed depth maps.
The described methods were combined with image processing algorithms. The defect depth is retrieved by determining the blind frequency of each pixel. Each phase image of the phasegram is segmented into a defective and a non-defective area. We obtain a discrete vector for each pixel. The frequency corresponding to the first value 0 is the blind frequency. Afterwards, the defects are clustered and deconvolved using the PSF of Eq. 6. The accuracy of the depth of a defect is improved by fitting the theoretical phase contrast function to the center of each cluster.

The algorithm has been applied to CFRP parts with flat-bottom holes of different sizes and situated at different depths. The component's schemes and the resulting depth maps are represented in Fig. 3. The retrieved defect depths are represented in Fig. 4. The mean values of the retrieved depths are plotted with the maximum error domains. The maximal deviation is 1.5 mm and occurs for small defects (4 mm deep, 8 mm wide).

Fig. 5 shows the plot of the retrieved defect sizes in respect to the true sizes. Size estimation has an error of around 2 mm in most cases. The defect diameters are easily determined for defects of depth values between 1 and 2 mm. For the defects of sizes between 2.5 and 4 mm, the sizes are correct for defects larger than 10 mm. Finally, defects having a depth of 5 mm appear smaller as they are: The size is estimated with an error of 6 mm. Defects smaller than 10 mm are not detected at this depth.

![Figure 4](image4.png)

**Figure 4:** Schematic representation of the retrieved defect depths.

![Figure 5](image5.png)

**Figure 5:** Schematic representation of the retrieved defect sizes for several defects depths.
3. Conclusion
This work contributes to the quantitative evaluation of defects in anisotropic CFRP material of thermal images (lockin thermography). Phasegrams are evaluated in order to get additional information on the sizes and depths of defects. The theoretical model agreed with the measurements and allows to understand the phase response of a defect that depends on its depth and on the lockin frequency. There is an optimal frequency where the signal-to-noise ration is maximum and the defect becomes clearly visible. The shape of cross-like defects is well retrieved. The depth of defects can be recovered with a great accuracy down to a depth of 3 mm. Especially for small deep defects, greater errors are possible.

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5. References
[1] J.V. Beck, K.D Cole, A. Haji-Sheikh, and B. Litkouhi; Heat Conduction Using Green's functions. Series in Computational and Physical Processes in Mechanics and Thermal Sciences, 1992.
[2] G. Busse; Optoacoustic phase angle measurement for probing a metal. Appl. Phys. Lett., 35:759-760, 1979.
[3] H.S. Carslaw and J.C. Jaeger; Conduction of heat in solids. OXFORD, 1946.
[4] K. Friedrich, K. Haupt, U. Seidel, and H.G. Walther; Definition, resolution and contrast in photothermal imaging. J. Appl. Phys., 72:3759-3764, 1992.
[5] A. Lehto, J. Jaarinen, T. Tiusanen, M. Jokinen, and M. Luukkala; Amplitude and phase in thermal wave imaging. Electr. Lett., 17:364-365, 1981.
[6] A. Mandelis; Diffusion-Wave Fields-Mathematical Methods and Green Functions. Springer (ed.), 2001.
[7] U. Seidel, H.G. Walther, and J.A. Burt; A proposal for the reconstruction of buried defects from photothermal images. 8th International Topical Meeting on Photothermal and Photoacoustic Phenomena, Pointe-a-Pitre (France) 1994, Journal de Physique IV, page 551, 1994.
[8] U. Seidel, K. Haupt, H.G. Walther, J.A. Burt, and M. Munidasa; An attempt towards quantitative photothermal microscopy. J. Appl. Phys., 78, 2050-2056, 1995.
[9] R. L. Thomas, J. J. Pouch, Y. H. Wong, L. D. Favro, Kuo P. K., and A. Rosencwaig; Subsurface flaw detection in metals by photoacoustic microscopy. J. Appl. Phys., 51:1152-1156, 1980.