A new technique to reconstruct the defect shape from Lock-in thermography phase images

by C. Zöcke*, A. Langmeier*, R. Stößel *, and W. Arnold**

*EADS Innovation Works, Munich, Germany
** Fraunhofer-Institute for Non-Destructive Testing, Saarbrücken Germany present address: Department of Materials, Saarland University, Saarbrücken, Germany

Abstract

We present a new method for reconstructing the shape of defects in three dimensions from optical lock-in thermography phase images with image processing algorithms. The point-spread function which describes the blurring effect of thermal images derived from optical lock-in thermography is computed. It is shown, that the depth and the shape of a planar defect can be retrieved.

Keywords: optical lock-in thermography, thermal tomography, quantitative evaluation, PSF, inverse problems, composite aircraft material.

1. Introduction

Today, the requirements about the quality on parts in the aerospace industry are rising. Defects such as delaminations, impacts damages or cracks have to be found in quality controls after manufacture or during in-service inspections. Researchers are looking for new, faster and safer methods that allow one to better detect and characterise the defects. Non-destructive testing (ndt) includes a variety testing methods that present the advantage that the part under test retains its integrity.

Thermography systems are much used in ndt. They have the advantage to be mobile so that airplanes can be inspected directly in the inspection hall. But until now, only images can be registered and no quantitative information is available on the detected defects. In this work, we will focus on the optical lock-in thermography method which provides the advantage to compute images with a high signal-to-noise ratio (SNR). In the following image processing methods are combined in order to perform quantitative evaluation of artificial defects in a carbon reinforced polymer material.

In thermography the disturbance of the diffusion of heat is the origin of the contrast to observe defects. This thermal diffusion process influences the apparent shape of the defects. The defects appear greater as they are. This process can be modelled as an inverse problem. We use the theory of Mandelis [1] of periodic thermal wave fields to compute the point-spread function (PSF) directly in the Fourier domain. The part to be inspected is assumed to be an infinite plate. To get an approximation for the PSF the Born approximation is used. With this PSF the phase images are deconvolved in order to get true defect shape and size [2]. After a theoretical description of the applied methods, measurements on the specimen with artificial defects are described and the results of the image processing and deconvolution are discussed.

2. Optical lock-in thermography

In optical lock-in thermography, the absorption of a light beam is used to deposit heat into the material to be examined. The beam is sinusoidally modulated and amplitude and phase images are computed from image sequences utilizing a Fast Fourier transform. By varying the excitation frequency, it is possible to detect defects in different depths because the thermal penetration depth

\[ \mu = \sqrt{\frac{\alpha}{\pi \cdot f}} \] (1)

depends on the frequency \( f \) of the thermal excitation wave [3].
One main advantage of optical lock-in thermography lies in the fact that the energy of the signal is concentrated into a single frequency. Consequently, the amplitude and phase images have a high SNR. In order to become a depth resolved method, several frequencies have to be used (figure 1). There is a relation between the so-called blind frequency i.e. the frequency at which the defect appears for the first time and a phase reversion occurs, and the penetration depth (Eq. (1)). Thus, the frequency has to be chosen small enough in order to be able to detect deeper defects. The measurement time is long especially when working with low frequencies and can easily be minutes. By knowing the blind frequency the depth of a defect can be retrieved.

3. Theoretical description of the PSF

We utilize the theory of periodic thermal wave fields as derived by Mandelis [1] to solve the heat equation with periodic heating [4]. The solution is sought in Fourier space, and the solution is interpreted as the steady-periodic response at a single frequency $\omega$. The heat equation in the Fourier space without volume source is

$$\nabla^2 \theta(r, r', \omega) - \sigma^2(\omega) \cdot \theta(r, r', \omega) = 0$$  \hspace{1cm} (2)

Here $\sigma = (1 + i) \sqrt{\frac{\omega}{2\alpha}}$ where $\alpha = \mu^2 \cdot s^{-1}$ is the thermal diffusivity.

By considering the Green function $G$ which satisfies Eq. (2), the solution of the thermal wave-field with no volume sources is [1]

$$\theta(r, \omega) = \alpha \int_G \left[ G(r, r', \omega) \cdot \theta(r', \omega) - \theta(r, r', \omega) \cdot G(r, r' \omega) \right] \cdot dS.$$  \hspace{1cm} (3)

Here, we assume that the side of the plate is long enough (infinite plate), that no volume source exists and that the surface is homogeneously illuminated, in order to have Neumann condition at the surface $\nabla \omega \cdot G(r, r' \omega) S_{z=0} = 0$, and that the time harmonic flux prescribed over the surface at $z = 0$ is

$$F(r', \omega) = \frac{1}{2} F_0 (1 + e^{i\omega t}) \Rightarrow \bar{F}(r', \omega) = \frac{1}{2} F_0 (\delta(\omega - \omega_s)).$$  \hspace{1cm} (4)

The resulting thermal wave-field can be interpreted as the sum of the thermal wavefield without defect and the thermal wave-field of the defect. From Eq. (3), we get

$$\theta(r, \omega) = \theta_0 (r, \omega_0) - \alpha \int_{S_1} \left[ G(r, r', \omega_0) \cdot \theta(r', \omega_0) - \theta(r, r', \omega_0) \cdot G(r, r' \omega_0) \right] \cdot dS_1$$

$$= \theta_0 (r, \omega_0) - \alpha \int_{S_1} \left[ \frac{\partial}{\partial z} (G(r, r', \omega_0) \cdot \theta(r', \omega_0)) \right] \cdot dS_1$$  \hspace{1cm} (5)

The temperature and the Green function at depth $z$ can be written as

$$\theta(r, \omega_0) = R \cdot (\theta_0 (r, \omega_0) + \Delta \theta(r, \omega_0))$$

$$G(r, \omega_0) = R \cdot (G_0 (r, \omega_0) + \Delta G(r, \omega_0))$$

where $R$ is the reflection coefficient of the defect. Following the first Born approximation, we neglect the second term in the integral term and get

$$\theta(r, \omega_0) - \theta_0 (r, \omega_0) = -\alpha \cdot R^2 \left[ \frac{\partial}{\partial z} (G_0 (r, r', \omega_0) \theta(r', \omega_0)) \right] \cdot dS_1$$  \hspace{1cm} (7)

The temperature distribution can be expressed as the convolution of the PSF with the defect shape.
\[ \theta(r, \omega_i) - \theta_0(r, \omega_i) = -\alpha \cdot R^2 \int_{-\infty}^{\infty} \frac{\partial}{\partial z} \left[ \frac{G_0(r, r', \omega_b) \theta_0(r, r', \omega_b)}{r} \right] \cdot h(x - x_0, y - y_0) \cdot dS, \quad (8) \]

The function
\[ h(x, y) = \begin{cases} 1 & (x, y) \in S \\ 0 & (x, y) \notin S \end{cases} \quad (9) \]
describes the shape of the defect and is equal one on the defect surface and zero outside the defect.

With \( G_0(r, r', \omega_b) = \frac{1}{4\pi\alpha} \left( \frac{e^{-\alpha r} + e^{-\alpha r'}}{r} \right) \) and \( \theta_0(r, \omega_b) = \frac{F_o}{2k} \delta(\omega - \omega_b) \sigma \cdot e^{-\sigma z} \), the function \( h \) can be computed and reduced to
\[ h(x, y, \omega, y) = \frac{F_o}{4\pi k} \cdot R^2 \cdot \frac{\sigma^2 \cdot e^{-\sigma \sqrt{x^2 + y^2 + l^2}}}{\sqrt{x^2 + y^2 + l^2}} \left( \frac{1}{\sqrt{x^2 + y^2 + l^2}} \right) \left( 1 + \frac{1}{\sqrt{x^2 + y^2 + l^2}} \right) + 1 \quad (10) \]

Phase PSF

As shown in [5], the point-spread function of the phase image can be approximated by the imaginary part of the complex point-spread function:
\[ \text{Phasepsf}(r, \omega, d) = \text{Im} \left\{ \frac{F_o}{4\pi k} \cdot R^2 \cdot \frac{\sigma^2 \cdot e^{-\sigma \sqrt{r^2 + d^2}}}{\sqrt{r^2 + d^2}} \left( \frac{1}{\sqrt{r^2 + d^2}} \right) \left( 1 + \frac{1}{\sqrt{r^2 + d^2}} \right) + 1 \right\} \quad (11) \]

where \( r^2 = x^2 + y^2 \). In figure 2, the evolution of the PSF in respect of the frequency is shown for different defect depth. A phase reverse occurs at a limit frequency called blind frequency.

**Phase contrast**

![Fig. 2. Theoretical evolution of the PSF for different defect depths](image-url)
Comparison between measurements and simulations

To determine the value of the thermal conductivity, the theoretical PSF has been fitted to the evolution of the phase with the frequency (figure 3). Since the depth of the defect is known, the value for $\alpha$ can be retrieved. A value of $\alpha = 0.2 \text{mm}^2 \cdot \text{s}^{-1}$ was found and taken for the simulation.

![Phase contrast](image)

**Fig. 3.** Fit of the theoretical PSF to the measured data in order to retrieve the thermal conductivity

Then, a texture pattern of composite material is used and the profile of the defect is overlaid on the pattern. Figure 4 shows a comparison between an extracted defect and the simulation of the defect formation process in the case of the direct problem for different lock-in frequencies. In figure 5 the image formation process of a defect in different depth is compared to measurements. The simulations agree with the measurements.

![Comparison](image)

**Fig. 4.** Comparison between measurement (a) and simulation (b) of a defect in 2 mm depth for different frequencies between 0.01 to 0.12 Hz
Fig. 5. Evolution of the phase image with the depth in mm for a lock-in frequency of 0.01 Hz; measurement (a); simulation (b)

4. Experiments

For the experiments, we used a specimen of composite material with drilled holes of various sizes and depth representing artificial defects (figure 6).

Fig. 6. Schematic drawing of the plate of composite material

Pre-processing of the thermal images

A set of image processing algorithms are first applied in order to better detect labels and defects and to calibrate the images. In order to diminish the texture effect of composite material, a background subtraction algorithm is applied. We used the method described in [6] where the mean value of a neighbouring area \( T_{\text{sur}(i,j,t)} \) is subtracted from each pixel value \( T_{\text{pix}(i,j,t)} \) following

\[
T(i, j, t) = T_{\text{pix}(i, j, t)} - T_{\text{sur}(i, j, t)}(t)
\]

Then a scale is introduced in the images using photogrammetric methods [7]. For this task, special retrospective labels are used. They are applied to the part and are easily detected in the images. An ellipse detection algorithm [8] is used to detect automatically the labels and determine the centre of the label. The eight parameters \( a_j \in \{1...8\} \) of the homography transformation can be computed with the positions of four reference points

\[
X = \frac{a_1x + b_1y + c_1}{a_2x + b_2y + 1} \quad Y = \frac{a_2x + b_2y + c_2}{a_2x + b_2y + 1}
\]

where \( X, Y \) are the coordinates of the reference points in the corrected image \( S \) (in m), \( x, y \) are the coordinates of the reference points in the original image \( S_p \) (in pixels). Furthermore, this approach allows one to align precisely the different phase images even when the camera positions are slightly shifted during the experiment.
Determination of the defect depth

For each image point, we determine through the evolution of the phase with the frequency the blind frequency. Since the thermal conductivity is known, the relation between the depth and the blind frequency of Eq. (1) allows us to determine the depth of a defect. Thereby, through the analysis of the histograms, an upper limit is determined and used for the detection of defects. A Gaussian curve is fitted to the histogram of each phase image and the detection limit (6 dB) is computed through the mean and width of the Gaussian curve. It must be noticed that the phase images are scaled and contain the information in a scaled way. For each pixel, a detection vector \( d_i \) is built and used to determine the blind frequency in a discrete way. When the pixel value in the i-th phase image is over the detection limit, the value of \( d_i \) is set to 1: \( d_i = 1 \). So, the detection vector contains indirect information about the depth of the artificial defects. The index of the blind frequency corresponds to the latest value 1 in the vector. The two-dimensional map of the blind frequency for an area of the phase images is shown in figure 7. In this way a map of the defect depths was calculated. There are remaining artefacts in the map, namely the lateral effects of the diffusion of the heat. We applied a clustering algorithm, the so-called kmeans [9], in order to form defect cluster and the depth of the centre of each cluster is assigned to the cluster.

Determination of the defect size

The blurred phase images can be expressed as the convolution between the real shape of the defect and the phase PSF. The theoretical form of the PSF of Eq. (11) is used in order to retrieve the shape of the defects. The pixel size is known from the calibration step. The extracted defects are deconvolved using the LucyRichardson inversion filter [10]. Figure 8 shows the result of the deconvolution of a defect. The defect appears sharper.

5. Discussion

The process of heat diffusion can be modelled and the simulation of optical lock-in phase images showed good agreement with the measurements. The effect is inversed in order to retrieve the real shape and size of planar defects.

A work of automation of the process has to be done, for example to improve the clustering. The inverse problem of deconvolution reduces the apparent size of the defect and should in future allow computing the size of the defects.
Fig. 7. Detection vector, which contains the information on the depth (a) with lateral effects (b) without lateral effect

Fig. 8. Deconvolution of the extracted defect and plot of the profile

REFERENCES


