Iterative improvement of lockin-thermography results by temporal and spatial adaption of optical excitation

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Abstract

Lockin-thermography is usually performed using modulated lamps. Unfortunately, their intensity distribution is inhomogeneous even on a flat specimen, thereby producing lateral heat flows within the inspected sample. These heat flows are unwanted effects that mask the images of the interesting defect structures, i.e. reduce lateral resolution.

The idea proposed in this paper is to use an LCD-projector as a heat source with its ability to assign each excitation pixel individually its oscillation amplitude, intensity offset, and phase lag. By an iterative self-learning process an illumination pattern is generated in such a way that lateral heat flow is eliminated and resolution enhanced.

1. Introduction

Lateral heat flows result from an inhomogeneous temperature distribution caused by inhomogeneities in e.g. excitation, geometrical conditions or thermal properties of the specimen. In addition local variations of optical absorption or emission coefficients can contribute. Especially low lockin-frequencies are affected and result in blurred phase images, while high frequencies are less affected but lack depth range [1]. In consequence, with conventional lamps there is no chance to suppress lateral heat flow.

An LCD-projector is a new light source with a broad flexibility for temporal and spatial manipulation of optical excitation down to the level of individual pixels. By application of a line pattern or its two-dimensional counterpart one may induce illumination edges and resulting local lateral heat flows that respond to thermal diffusivity variations along the surface directions [2]. Alternatively, instead of using patterns to generate lateral heat flow, one can design complicated patterns to suppress it by applying an iteratively self-learning process.

The idea is to use an LCD-projector first for a conventional optically excited lockin-measurement to obtain a phase image and a magnitude image. This result is then used to compute a new projection pattern aiming at a reduction of temporal or spatial differences in the temperature distribution at the specimen surface. This process can be performed repeatedly and automatically. As many influences have to be taken into account, it takes several iterative steps to level out the amplitude, intensity, and phase satisfactorily. Ideally this process leads to a completely homogeneous phase and amplitude image indicating that no lateral differences and hence no lateral heat flows exist anymore. The result provided by this procedure is the final excitation pattern that is required to make heat flow virtually one-dimensional. This approach resembles compensation techniques e.g. in electrical engineering. The illumination pattern required for compensating lateral heat flow is a finger print of the structure causing it; hence the pattern is an image of the inspected structure. The phase image is a figurative representation of the particular phase lag needed in each pixel. As this iterative effort has been put into counteracting lateral heat flows, the resulting image is less blurred than the original phase image.

2. Theory

2.1 Optically excited Lockin Thermography

Optically excited Lockin Thermography [3-6], OLT, is a useful tool for nondestructive evaluation. In a relatively short time defects like delaminations in carbon fibre reinforced plastic [7] can be detected remotely (Fig. 1).
Triggered by optical excitation, thermal waves propagate into the specimen. At subsurface boundaries the thermal waves are partially reflected, hence they interfere with the incident waves. The resulting temperature modulation on the surface depending on the inner structure, is recorded by an IR-camera. A Discrete Fourier Transformation, DFT, of the obtained image stack provides phase and amplitude of local temperature oscillation. Both phase and amplitude are sensitive to the depth of material inhomogeneities, but the phase’s depth range is about twice of the amplitude’s one \[^1\]. The thermal depth range is determined by the thermal diffusion length \(\mu\) \[^8\]:

\[
\mu = \frac{2\alpha}{\omega},
\]

with thermal diffusivity \(\alpha\) and angular frequency \(\omega\) of light intensity modulation.

The halogen lamps usually used as heat source in OLT-measurements can easily be transported and operated, but have the disadvantage of an irregular intensity distribution. In consequence, because of the inhomogeneous excitation specimen areas with higher excitation appear undesirably brighter in amplitude images. Phase images are less sensitive to inhomogeneous excitation due to the quotient formation of imaginary and real part. However, an intensity distribution may cause lateral heat flow which in turn influences phase angles.

2.2. LCD-Projector as optical heat source

One can avoid or at least minimize the disadvantages of halogen lamps by using an LCD-projector. Its homogeneous excitation improves amplitude images and diminishes lateral heat flow caused by irregular illumination. On the other hand a specially adapted excitation can even reduce lateral heat flow due to inner structures. Consequently lateral resolution is increased – phase images are less blurred. As a disadvantage an LCD-projector has a comparably low excitation intensity which limits the maximal sample size and the measurable materials.

To perform an OLT-measurement, an excitation video is projected by an LCD-projector on the inspected specimen. Each pixel of the video displays independently sinusoidal transitions between different gray scale values. The brighter the gray scale value the more energy is deposited to the specimen. Thus a white pixel achieves a maximal energy input whereas a black pixel supplies no intensity. Owing to the periodically changing gray scale values, thermal waves start at the sample surface comparable to those generated by other heat sources. As a novelty, each LCD-projector pixel triggers its own excitation characterized by three components: intensity offset, oscillation amplitude and phase lag (Fig. 2). The intensity offset represents the smallest gray scale value, the oscillation amplitude the range of all values. On different areas on the specimen thermal waves can additionally be launched with a predefined phase lag.
Fig. 2: Elements of excitation via LCD-projector. Left: Definition of intensity offset and oscillation amplitude. Right: Definition of a phase lag which enables a temporally adapted excitation.

This segmentation allows a time and spatial dependent excitation which is e.g. useful for reducing lateral heat flow.

Lateral heat flow on a specimen surface generally results from locally different temperatures which can be attributed to variations of the mean temperature, amplitude and phase angle of the thermal wave. If it is possible to level out all three parameters, lateral heat flow will be diminished. This can be achieved by suitable adaption of excitation. For leveling the mean temperature, an adaption of the intensity offset is necessary. Cooler areas of a specimen need a higher energy input during the measurement by a higher offset of the corresponding excitation pixels. In the same way the resulting amplitude image can be leveled out with locally adapted oscillation amplitudes, the phase image with appropriate phase lags. The process of leveling needs several iterative steps but can be automatized to a self-learning process.

The mean intensity, the amplitude and the phase image of a conventional OLT-measurement represent the starting point of iteration. First, the excitation intensity is regarded. The excitation intensity \( I_{\text{exc}} \) is composed of the exciting oscillation amplitude \( A_{\text{exc}} \) and the intensity offset \( O_{\text{exc}} \):

\[
I_{\text{exc}} = \frac{A_{\text{exc}}}{2} + O_{\text{exc}} \quad (2)
\]

Areas which are warmer during the conventional measurement need a lower excitation intensity in the subsequent iterative step. Therefore the new excitation intensity is computed for each pixel separately:

\[
I_{\text{exc}}^\text{new} = \frac{I_{\text{exc}}^\text{old}}{2} \left( 1 + \frac{T_{\text{end}} - T_{\text{c}}}{\bar{T} - T_{\text{c}}} \right) \quad (3)
\]

Here, \( I_{\text{exc}}^\text{old} \) is the excitation intensity and \( \bar{T} \) the mean temperature of the preceding measurement. \( T_{\text{end}} \) relates to the desired uniform temperature at the end, \( T_{\text{c}} \) is the ambient temperature. By adaption of the excitation intensity, the mean temperature is leveled step-by-step with each new measurement. For homogenization of the resulting amplitude the oscillation amplitude has to be fitted in a similar way:

\[
A_{\text{exc}}^\text{new} = \frac{A_{\text{exc}}^\text{old}}{2} \left( 1 + \frac{A_{\text{end}}}{A_{\text{res}}} \right) \min \left\{ 2, \frac{I_{\text{exc}}^\text{old}}{A_{\text{exc}}} \left( 1 + \frac{T_{\text{end}} - T_{\text{c}}}{\bar{T} - T_{\text{c}}} \right) \right\} \quad (4)
\]

The new exciting oscillation amplitude \( A_{\text{exc}}^\text{new} \) depends among others on the old oscillation amplitude \( A_{\text{exc}}^\text{old} \) and the resulting amplitude \( A_{\text{res}}^\text{old} \) of the previous measurement. \( A_{\text{end}} \) represents the final resulting amplitude all pixels should adopt. The first part of equation (4) adjusts the oscillation amplitude effectively; the second part is a scaling which considers that the oscillation amplitude has to be equal or smaller than the newly computed excitation intensity. Knowing \( I_{\text{exc}}^\text{new} \) and \( A_{\text{exc}}^\text{new} \), the intensity offset \( O_{\text{exc}}^\text{new} \) for the next measurement is accessible (equation (2)). The last parameter to be determined is the phase lag \( \varphi_{\text{exc}}^\text{new} \):

\[
\varphi_{\text{exc}}^\text{new} = \varphi_{\text{exc}}^\text{old} + \varphi_{\text{res}}^\text{old} \quad (5)
\]
It consists of the exciting phase lag $\phi_{\text{exc}}^{\text{old}}$ and the resulting phase angles $\phi_{\text{res}}^{\text{old}}$ of the previous measurement. For leveling out the phase image, $\phi_{\text{exc}}^{\text{new}}$ has to be subtracted during the following measurement.

Several iterative measurements and suitable adaptions of the excitation parameters level out satisfactorily mean temperature, resulting phase and amplitude images. During the last measurement the surface temperature is consequently almost uniform. A lack of local differences in temperature results in reduced lateral heat flows. In this case the excitation values, especially the phase lag, are the actual result of all previous efforts. The phase lags of all pixels can be depicted as an image, similar to conventional OLT phase images. As a difference between both pictures, the excitation phase image has a better lateral resolution and appears less blurred due to the reduced lateral heat flux. The degree to which phase images can be improved is considered in the following section.

3. Results

In the following, the capability of the present approach is demonstrated with model specimens exhibiting simple geometries. More complicated samples and components used in reality will be tested in future.

3.1 Polymer step wedge

The first sample is a step wedge made of poly(ethylene-terephthalate glycol), PETG (Fig. 3). The thickness ranges from 1.5 mm to 7 mm; the step widths are 15 mm (at 1.5 and 7 mm thickness) and 10 mm (all others). As lockin-frequency 0.01 Hz was chosen. The smooth surface was illuminated, i.e. from below in Fig. 3.

Fig. 3: PETG step wedge with given thicknesses in mm.

Fig. 4 shows the resulting images of a conventional measurement, Fig. 5 shows those of a measurement with adapted excitation.

Fig. 4: Results of a conventional OLT-measurement at 0.01 Hz. Left: mean temperature. Middle: amplitude. Right: phase.

Fig. 5: Results of an OLT-measurement with adapted excitation at 0.01 Hz. Left: mean temperature. Middle: amplitude. Right: phase.
It is obvious that the leveling process succeeded: all desired parameters are leveled out. As mentioned before, the adjusted phase lag leading to the depicted phase image (Fig. 5) is the true result. A horizontal phase profile along the black line in Fig. 4 is exemplarily examined more precisely. Fig. 6 (left) shows both the resulting leveled out phase (blue curve) and the according excitation phase lag (red curve). According to the previous consideration, the phase is less blurred which is demonstrated in Fig. 6 (right) obtained for the phase across the first step (between 1.5 mm and 2 mm thickness). The absolute slope of the phase profile rises in the area of the step as predicted. To quantify this improvement, the slope between the two plotted black lines was determined. In the conventional result the slope is about -0.30 °/pixel, whereas in the adapted excitation the slope is nearly doubled with -0.59 °/pixel.

3.2 Step with continuously increasing height in polymer

A combination of a wedge and a step with a continuously varying step height (between 0 and 5 mm) characterizes the second sample made of epoxy resin (Fig. 7).

![Fig. 7: Wedge-sample made of epoxy resin. The thickness ranges between 0 mm and 5 mm.](image)

The contrasting juxtaposition of the conventional result and the adapted excitation phase image implies that the method of reducing lateral heat flux works. Edges appear relatively clear, the step in the sample center is sharper (Fig. 8).

![Fig. 8: Phase images of the epoxy resin wedge at 0.005 Hz (Fig. 7). Left: Resulting phase image of a conventional measurement. Right: Phase lag image resulting from the adapted LCD-projector excitation.](image)

To estimate the improvement, several phase profiles marked in Fig. 8 (left) were evaluated (Fig. 9 and Fig. 10).
Similar to the preceding example the absolute slope increases, caused by the adjusted excitation. In this case, the slope steepens by a factor of 1.8. Besides the step, the area of the continuous wedge is interesting (Fig. 10).

The phase angles (Fig. 10) along two adjacent lines should coincide since the cross section of the sample is the same. This is approximately true for the adapted excitation. In contrast, for the conventional resulting phase image the maximal deviation between both curves reaches almost 7°. Summarizing, improvements are visible in all considered phase profiles.

3.3 Flat bottom holes in carbon fibre reinforced plastic (CFRP)

In contrast to the foregoing polymer samples, carbon fibre reinforced materials (for example used for high-tech aerospace applications) are characterized by anisotropic heat conductivity. Typical samples for the present basic feasibility studies are plate-shaped specimens provided with flat bottom holes drilled from the rear surface, in this case a plate made of carbon fibre reinforced plastic (CFRP) (Fig. 11).
Fig. 11: Carbon fibre reinforced plastic plate with flat bottom holes of different diameters and depth locations.

It has the built-in difficulty that the fibres have a high thermal diffusivity so that macroscopic diffusivity of the plate is higher parallel to the surface than perpendicular to it. The specimen combines precisely known geometric properties with challenging lateral heat flows.

Fig. 12 shows the conventionally obtained lockin-thermography phase image (left image) in comparison to the figurative representation of the necessary phase lag to level out any lateral heat flows (right image), both at a modulation frequency of 0.025 Hz.

Fig. 12: Comparison of conventional phase image (left) and result of iteratively adapted excitation (right). CFRP plate described in Fig. 11, modulation frequency: 0.025 Hz.

Subjectively, the adapted excitation yielded a better result in terms of defect contrast. For a more objective examination, a phase profile was extracted along the horizontal line across the bottom row of defects (all close to the surface at an equal distance) and plotted in Fig. 13 (left), and the vertical equivalent along the two left largest holes at different distances from the front surface (right).
Fig. 13: Horizontal profiles (left) and vertical profiles (right) of the lockin-thermography phase angle by means of conventional (blue) and adapted excitation (red).

The two figures indicate that the conventional (blue curves) results are inferior to those obtained by the adapted self-learning excitation (red curves). The contrast gained by the described procedure is obviously much better than with conventional lockin-measurements so that holes become visible that were lost in noise before. Hence the efficiency of the concept is experimentally validated.

4. Conclusion

In this paper the applicability of an LCD-projector used as a heat source for optically excited Lockin Thermography has been investigated. The excitation consists of a video pattern projected on the specimen surface. Thereby each excitation pixel changes periodically its gray scale value, defined by three adjustable parameters: oscillation amplitude, intensity offset, and phase lag. Via an iterative self-learning process the values are gradually adapted in such a way, that the final excitation-pattern leads to a leveled out mean temperature, amplitude and phase. Associated with this, lateral heat flow is diminished and edges of inner structures appear less blurred. The pattern that achieves this leveling of thermal wave parameters by compensation is the finally resulting image of the sample with a significantly improved lateral resolution (about factor 2).

This concept has been validated by measurements of several model specimens. Further measurements of industrially important components are planned to determine the signal to noise ratio and the potential use for fully automated defect detection and characterization.

REFERENCES