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Lockin Thermography with Optical or Ultrasound Excitation

Andreas Gleiter - Christian Spießberger - Gerd Busse*
University of Stuttgart, Institute of Polymer-Technology, Germany

Thermography is a well established non-destructive testing (NDT) technique providing images of temperature distributions. If the temperature field on a sample surface is modulated by periodical injection of heat either from outside or inside the sample, the time dependence of the temperature field provides information on thermal features hidden underneath the surface. Using the Fourier-transform, this information is finally compressed into a phase and an amplitude image. Phase images are more robust than amplitude images, because surface features and reflections are effectively suppressed.

With excitation by ultrasound, the heating mechanism is local conversion of elastic energy into heat which occurs preferably due to local friction losses caused e.g. by the relative motion of boundaries in a crack. As intact material and boundaries are suppressed in such an image, it displays defects selectively. The techniques and their applications are illustrated by examples that were obtained on various industry-relevant components.

Keywords: optical lockin-thermography, ultrasound lockin-thermography, defect-selective imaging

0 INTRODUCTION

Lockin-Thermography is an NDT method with a broad field of applications. It can be used for quality assurance during production processes or for maintenance purposes. Many types of defects are detectable, e.g. bonding seems and rivets, or delaminations of layered materials, connection of inner structure elements or inclusions of impurities.

Maintenance of aerospace structures is a challenge for NDT which requires methods that respond with a high probability of detection (POD) to such high-specific-strength materials and their defects. Conventional NDT like x-ray inspection or ultrasound cannot always satisfy those needs. Some defects are caused by imperfect manufacturing processes, others occur due to in-use damage. Therefore, fast and robust methods for industrial environments and in-field measurements are needed. Lockin-Thermography with phase evaluation complies with those requirements.

0.1 Optically Activated Lockin-Thermography

Heat deposition can be done by a pulse (e.g. flash lamps) or by modulation (e.g. halogen lamps, laser). The simplest way of evaluation is to record a temperature image sequence after a pulse and to evaluate just the image of highest contrast. The disadvantage of this transient method is a poor signal-to-noise (S/N) ratio and the fact that images are highly affected by reflections and surface features. The lockin-technique solves these problems. Lockin-Thermography with optical excitation is sensitive to thermal boundaries within the sample as the thermal wave propagates into the sample and is reflected back to the surface. An infrared camera records an infrared image sequence of the surface over several excitation periods (Fig. 1).

A Fourier transformation at the frequency of amplitude modulation ("lockin frequency") analyses this thermography image sequence at each pixel and compresses the information into an amplitude and a phase image. Some early lockin-thermography approaches are given in [1] to [3]. The Fourier transformation is equivalent to a narrow band filtering with a corresponding improvement in S/N ratio. Artefacts caused by inhomogeneities of infrared emission coefficient or of power deposition are reduced. Another advantage of Lockin-Thermography is the adjustable depth range given by the thermal diffusion length.

The thermal diffusion length depends on material parameters like thermal conductivity or specific heat capacity but also on the lockin frequency. The depth range can therefore be increased by decreasing the lockin frequency.

The disadvantage of optically activated thermography is that not only defects are visible in the results but also all other thermal features

*Corr. Author's Address: Gerd Busse, Institute for Polymer Technology, NDE Group (IKT-ZfP), University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany, gerd.busse@ikt.uni-stuttgart.de

within the thermal depth range. This reduces the probability of defect detection (POD) in samples with complicated thermal structures like CFRP stringer panels.

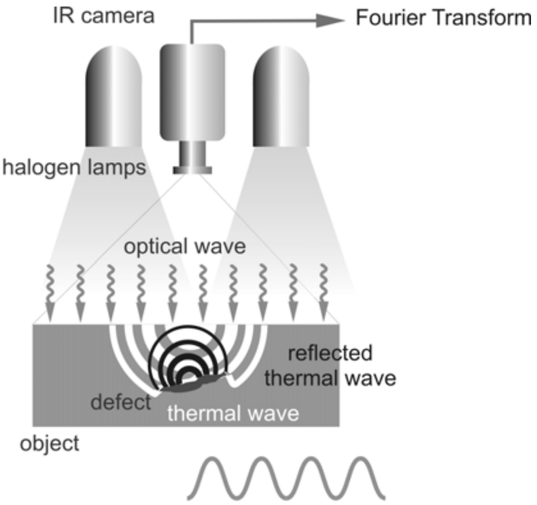


Fig. 1. *Schematical setup of optically activated Lockin-Thermography*

0.2 Ultrasound Activated Lockin-Thermography (ULT)

Heat can also be generated at damaged areas directly by ultrasound excitation. The elastic energy is converted into heat in areas of stress concentration and defects like cracks or delaminations [4] and [5]. These heat sources can be detected by an infrared camera even in the presence of complicated intact features. Ultrasound activated thermography ("ultrasound attenuation mapping") is a defect selective "dark field" NDT-technique as only defects produce a signal.

The operation principle of ultrasound activated Lockin-Thermography (ULT) is shown in Fig. 2. The elastic excitation waves are amplitude modulated at the lockin frequency which is typically in the range of 0.01 to 1.0 Hz [6] and [7]. This results in periodical heat generation so that the defects are pulsating at the modulation (lockin) frequency and thereby emitting thermal waves.

Ultrasound activated thermography with a fixed carrier frequency close to a resonance frequency of the sample can lead to a strong standing wave pattern which might appear as a superposed temperature pattern hiding defects. In addition to the amplitude modulation, ultrasound frequency modulation can solve this problem [8]. The frequencies causing the standing wave pattern are reduced and a more homogeneous phase image with an improved signal-to-noise ratio is achieved. Another version is burst phase ultrasound thermography which is basically multi-frequency ULT [9] and [10].

It should be mentioned that there are further methods of activating a specimen. For electric conductive materials, eddy current could be used [11] to [14].

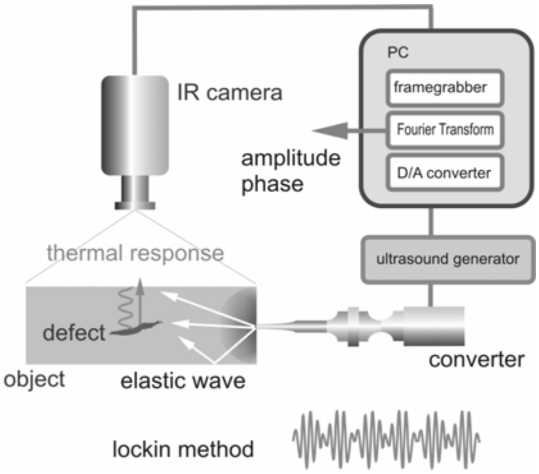


Fig. 2. *Schematical setup of ultrasound activated Lockin-Thermography*

1 APPLICATIONS

For thermography measurements it is advantageous to deal with specimen surfaces of high infrared emissivity. Therefore, especially carbon fibre reinforced plastics (CFRP) are suited for thermographic testing methods.

1.1 Maintenance of CFRP Rims

In addition to being used in aviation industry, light weight constructions are used in racing cars. The following example is a CFRP rim. Different layer thickness and metal inserts can be investigated. This measurement shows an intact rim (see Fig. 3). At very low lockin-frequencies (here 0.03 Hz) the kernel made of foam becomes visible. Higher lockin-frequencies

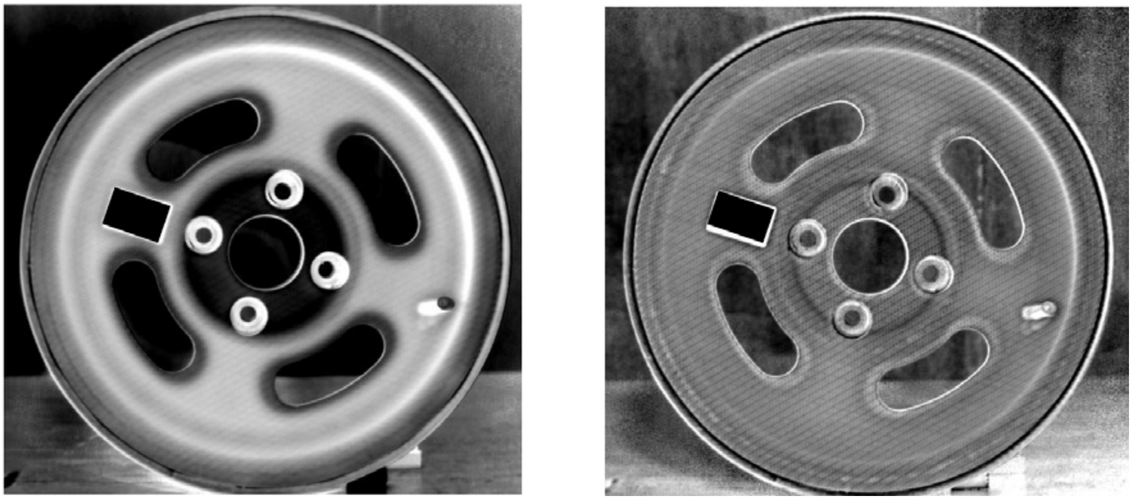


Fig. 3. *Phase images at 0.03 and 0.2 Hz; specimen from "Rennteam Uni-Stuttgart" [15]*

may reveal near-surface delaminations. Here (at 0.2 Hz) no defect was detected.

1.2 Testing of Turbine Blades

Fig. 4. *Cooling channels of a turbine blade, imaged with optically excited Lockin-Thermography (lockin frequency 1 Hz)*

Modern turbine blades have complex-shaped cooling channels, which can be imaged non-destructively with optically excited Lockin-Thermography. OLT is well-suited for this task because the method provides information about heat flow through the walls of the turbine blades which is exactly the property essential for the cooling process. Fig. 4 shows different types of cooling channels within a turbine blade measured with OLT at a lockin frequency of 1 Hz.

1.3 Detection of Stringer Delaminations with OLT

Stringers are used to improve the stiffness of large CFRP structures like fuselage panels of airplanes. This is why stringer disbonds together with excessive loading could cause a loss of structural integrity. Therefore, a fast and reliable detection of such defects in an early stage is needed.

A stringer reinforced CFRP panel was tested during a cyclic compression test (performed at DLR Braunschweig [16]). One result is shown in Fig. 5. Starting with an intact specimen the stringer delaminations grow slowly after each cycling test. The image was obtained when the panel was mechanically loaded. Therefore, a high contrast in the OLT measurement is achieved, because the delaminated stringers have lost thermal contact with the skin layer.

Another example is an ultra light aircraft (type: Fascination). The skin of the wing is made of glas fibre reinforced plasics (GRFP). OLT was used to monitor the bonding quality of the connection between wing beam and GRFP-surface. Note that the straight lines and the arrows are drawn on the surface.

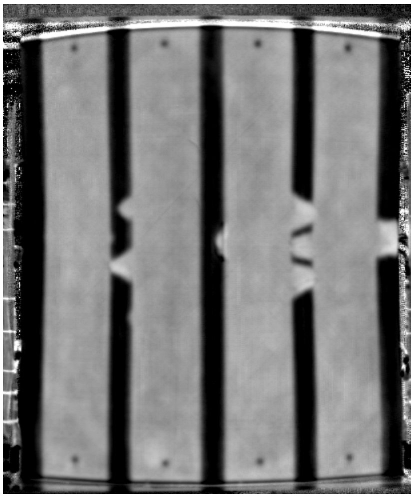


Fig. 5. *Growing stringer delaminations in cyclic compression testing; phase image of the loaded panel at 0.1 Hz*

1.4 Detection of Loose Rivets with ULT

Loose rivets, cracks, corrosion, and fatigue are critical defects in aerospace structures. For these kind of problems, ultrasound excited Lockin-Thermography can be a solution. An example is shown in Fig. 7 where a panel made for demonstration purposes is imaged using Lockin-Thermography with access only to the outer surface. With optical excitation the whole hidden structure is imaged regardless of the riveting quality. With ultrasound generation, however, loose rivets cause heating by friction, so they appear selectively as bright areas [17].

1.5 Crack Detection with ULT

Another example for applying ULT is shown in Fig. 8. The ULT amplitude image reveals cracks (bright spots) in a defect gearwheel.

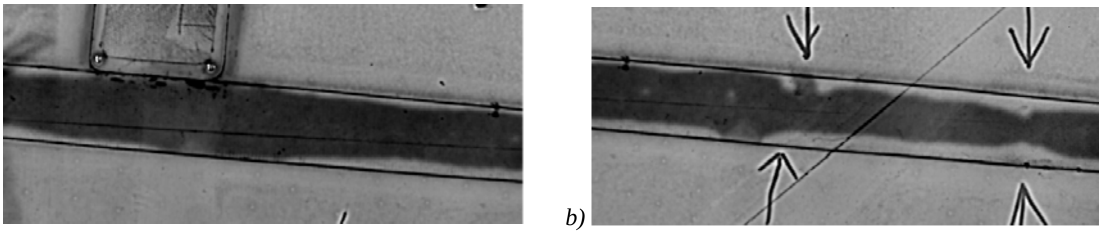
a)  *b)*

Fig. 6. *Hidden bonded area of an aircraft wing: a) tolerable bonding area, b) poor bonding (phase images at lockin-frequency 0.05 Hz)*

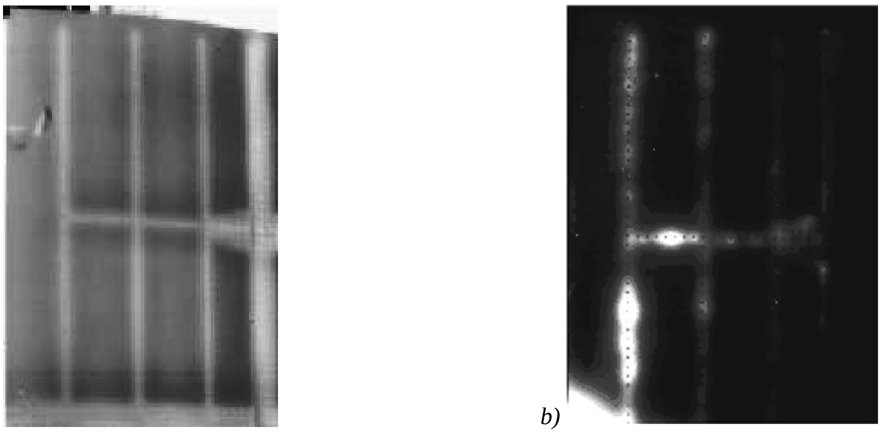
a)  *b)*

Fig. 7. *Riveted fuselage panel of A340: a) inspected with OLT, b) ULT [17]*

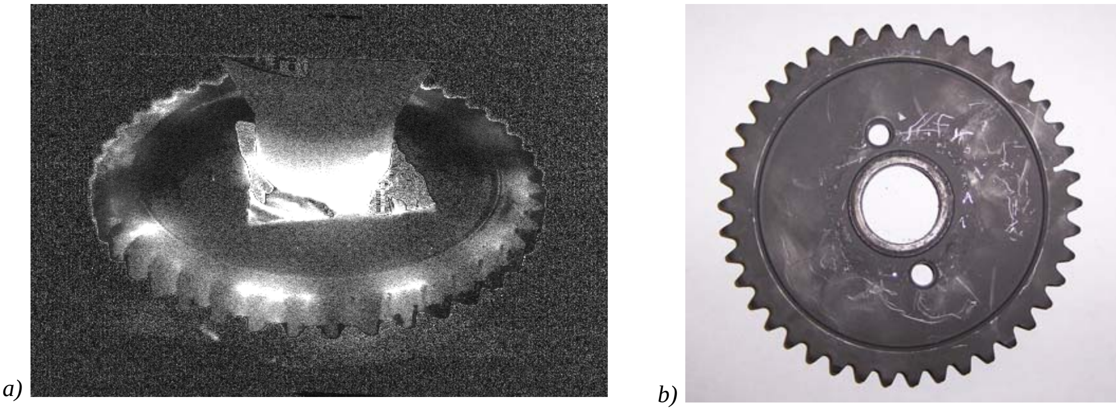


Fig. 8. *a) ULT amplitude image at 0.2 Hz reveals the cracks in a gearwheel, b) photo of the specimen*

2 CONCLUSIONS

New materials like CFRP and complex structures are a challenge for modern NDT. In many cases these requirements can be met by Lockin-Thermography methods. The excitation can be adapted to the specific application so that defects can be detected in a fast and reliable way. Using the lock-in method, the signal to noise ratio is enhanced substantially. OLT phase images as well as ULT amplitude images are homogeneous and artefacts like stationary infrared reflections are suppressed effectively. Therefore, the results obtained with these methods are suitable for automated defect evaluation. It should be emphasized that OLT and ULT complement each other since they are based on different physical mechanisms.

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