Active Thermography for Quantitative NDT of CFRP Components

Christian SPIESSBERGER, Alexander DILLENZ, Thomas ZWESCHPER
edevis GmbH, Handwerkstr. 55, 70565 Stuttgart, Germany
Email: info@edevis.de

Abstract. Optically excited thermography is applied whenever short measurement times are required. The method is robust and sensitive enough to be used even in harsh industrial environments. It is particularly applicable to non-destructive testing of aerospace components made of fiber reinforced materials. The surface of the sample to be tested is warmed up either by flash lights or halogen lamps. The resulting heat flow into the material is blocked by thermal boundaries like impacts, delaminations or the rear of the sample. The resulting “hot spots” at the surface are detected by an infrared camera. The sensitivity of optically excited thermography can be increased substantially using lock-in analysis techniques. A Fourier transformation at the modulation frequency compresses the acquired infrared sequence into a phase and amplitude image. Using phase angle imaging, artefacts resulting from variations of emission coefficients or inhomogeneous excitation are reduced significantly. However, quantitative evaluation based on lock-in thermography is difficult because phase values are not directly linked to important parameters like thicknesses or interface properties. A common approach to solve this problem is the creation of calibration tables. This means a high effort because a lot of samples with slightly different properties have to be built and measured.

This contribution presents a calibration-free approach to determine thicknesses and interface parameters out of at least two lock-in measurements at different modulation frequencies. The separation between properties of the layer and the interface beneath is particularly important for the characterization of adhesive joints. The presented approach could open new applications for active thermography especially for in-production measurements.

1. Introduction

Aerospace structures are a compromise between low weight and high safety. Therefore new materials are attractive in terms of weight reduction and fuel economy. Maintenance of these light-weight structures is a challenge for non-destructive testing (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 are due to in-use damage. Therefore, fast and robust methods for industrial environments and in-field measurements are needed. Active thermography very often complies with those requirements.

In many cases, the signal ratio is enhanced by Fourier transforming the acquired infrared sequence. The result is a phase image which is independent of inhomogeneous illumination or varying emissivities along the surface of the sample. However, the phase is not in direct correlation with physical values, like thicknesses, defect depths or other
material properties. However, these parameters are of vital importance to monitor production processes or to estimate retained strengths of components nondestructively. The paper describes a possible approach to solve this problem by correlating two lockin measurements at different excitation frequencies.

2. Active Thermography

1.1 Optical excitation

Optically excited thermography is a well-known method to identify and characterize interfaces that are oriented parallel to the surface [1-4]. The surface of the specimen to be tested is heated by a short flash (pulse thermography) or periodically (lockin thermography) and the generated heat flux is examined. Defects like delaminations in laminates or voids in metals disturb the heat flux. The resulting temperature difference at the surface is detected by an infrared camera. Fourier transforming the acquired temperature sequence and calculating a phase and an amplitude image can enhance the signal-to-noise-ratio of the resulting images significantly. The phase image maps the local delay between excitation and thermal response, thereby revealing hidden boundaries and thermal features of the inspected specimen. An advantage of the phase image over amplitude or single images is its insensitivity to some surface properties like varying emission coefficient, or to inhomogeneous heating due to non-uniform illumination or surface topography. The measurement setup for pulse and lockin-thermography are shown in figure 1.

![Figure 1: Measurement setups for pulse phase thermography (left) and optically excited lockin thermography (right).](image)

The lockin phase value in two-layer systems depends on the normalized thickness \(d/\alpha^{0.5}\), where \(d\) is the thickness and \(\alpha\) the thermal diffusivity, and the so-called thermal reflection
coefficient $R$ at the interface between the two layers, which is a function of the effusivities of both layers

$$ R = \frac{e_1 - e_2}{e_1 + e_2}. \quad (1) $$

The complex amplitude of a thermal wave at the surface is [5]

$$ \Phi = \arg \left( \frac{1 + \Re e^{-2d\sigma}}{1 - \Re e^{-2d\sigma}} \right), \quad (2) $$

where $\sigma$ is the thermal wave number

$$ \sigma = (1 + i) \sqrt{\frac{\pi f}{\alpha}}, \quad (3) $$

including the lockin-frequency $f$ and the thermal diffusivity $\alpha$. The phase value can be extracted from equation (1) by

$$ \phi = \arg \left( \theta(L, f) \right). \quad (4) $$

### 1.2 Ultrasound excitation

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 [6,7]. 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 figure 2. The elastic excitation waves are amplitude modulated at the lockin frequency which is typically in the range of 0.01 Hz to 1.0 Hz [8, 9]. 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. Ultrasound frequency modulation in addition to the amplitude modulation can solve this problem [10]. 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 [11].
3. Quantitative evaluation

Calibration measurements can be used to link the local phase values to physical parameters. For thickness measurements, for instance, a test specimen with different thicknesses is produced and measured with pulse phase or lockin thermography. The measured phase angles for particular thicknesses are stored in a look-up-table (LUT) and can be retrieved to evaluate measurements at real components. One major drawback of this method, however, is the need for recalibration whenever properties of inspected coating or substrate changes.

For measurements at two layer systems (e.g. thickness measurements of CFRP), this issue can be resolved by combining lockin measurements at two (or more) different lockin-frequencies. This method was developed in collaboration with the Institute of Polymer Technology (IKT), University of Stuttgart [12,13]. Phase values are calculated for a wide range of thicknesses and reflection coefficients at the required lockin frequencies and stored within a look-up-table. By inversely using this look-up-table, $R$ and $d/\alpha^{0.5}$ can then be determined out of two phase values at different lockin frequencies. Alternatively, a direct numerical calculation for every pixel is also possible but time-consuming.

4. Results

Figure 4 shows the described procedure exemplarily at a polymer wedge. The graph at the top shows the measured phase profiles along the wedge.

Parallel or before the measurement, a look-up-table is calculated based on equations (2) and (4) for a large range of thicknesses and reflection coefficients. Thereby, a certain thickness and a certain reflection coefficient are linked to a pair of phase values acquired at two different lockin-frequencies. Using this look-up-table in an inverse way, the corrected phase profile of the wedge is transformed into thicknesses and reflection coefficients (figure 4, bottom). Since the thickness range of the wedge sample is huge, the transformation was done for four different frequency pairs and the results were combined to cover the whole length of the wedge. Therefore, the thickness and reflection coefficient diagrams shown are a combination of all five phase curves.
Figure 3: Phase profiles along a polymer wedge.

The thickness profile represents very well the geometry of the wedge. As mentioned before, the calculated thickness is normalized on the thermal diffusivity $\alpha$. Consequently, if $\alpha$ is known the thickness in mm can be measured or, vice versa, the thermal diffusivity can be determined by measuring thickness with an alternative method. The reflection coefficient is everywhere very close to unity. The very low effusivity of air behind the wedge compared to the effusivity of the polymer is the reason for this (see equation (1)).

Figure 4: Calculated thickness and reflection coefficient profiles along the polymer wedge

As a matter of course, the transformation can also be done pixelwise for whole images. This is demonstrated in figure 5 which shows the thickness and reflection coefficient images for a CFRP landing flap. The two phase images at 0.025 Hz and 0.01 Hz are hard to evaluate quantitatively, even for the expert. In contrast to this, the thickness image marks thin areas of the flap dark gray and thicker ones bright which is very easy to interpret. The levels of gray indicate linearly the CFRP-thickness. The image of the reflection coefficient is almost everywhere close to one. Again, the reason for this is the low effusivity of air behind the flap.
Figure 5: From top two bottom: lockin-thermography phase images at 0.025 Hz and 0.01 Hz and the corresponding thickness and reflection coefficient images.

5. Conclusion

Quantitative evaluation of pulse and lockin thermography phase images can be done with calibration tables. This is a very straightforward and easy-to-handle approach. However, many calibration measurements have to be performed at test specimens beforehand which can be expensive and time-consuming. The presented multi-frequency lockin approach does not need any calibration and can therefore be applied to a wider variety of specimens and testing problems.
6. Acknowledgements

The authors thank Prof. Busse of the Institute of Polymer Technology (IKT), University of Stuttgart, for the close cooperation on this research topic. Without the work at the IKT this paper would not have been possible.

References