Application of data fusion to thermal wave imaging with lockin thermography

G. Busse, C. Spiessberger, and A. Gleiter
Institute of Polymer Technology (IKT), – Non Destructive Testing (IKT-ZfP) –,
University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany
gerhard.busse@ikt.uni-stuttgart.de

Abstract. Lockin-thermography has become a valuable tool for non-destructive testing (NDE) of materials since it provides in a short time phase images of hidden defects. However, besides finding defects it is important to derive more information to characterise them. We present an innovative way to combine phase images obtained at different lockin-frequencies by using scatter plots. Besides defect depths this method of data fusion allows for feature extraction like thermal wave reflection coefficient, local planarity, and edge effects due to the lateral heat flow caused by them. The extracted features can be traced back to the original image.

1. Introduction
Since the start of this conference 30 years ago there is a permanent interest to apply thermal waves for imaging of hidden defects so that they can be used in NDE for quality management in production and maintenance inspection. The technique of “thermal wave radiometry” [1] has made considerable progress and matured to “lockin thermography” [2-5] where within seconds or minutes (depending on the required depth range) robust phase angle images are produced which display hidden defects in large components of all kinds of materials. This development is also due to sensitive focal plane thermography cameras and powerful computers that can handle the tremendous amount of data.

The next step to be done is to improve the information on the defects to have finally -and that is the ultimate goal- a chance to predict remaining life time of a component so that it can be replaced just in time and without any risk of catastrophic and expensive failure.

This goal is far away from what is feasible presently, but maybe a first step into this direction is data fusion where information from various techniques or images taken with different parameters is combined to extract features that are related to the kind of defects or to their origin.

2. Simple approach: Overlay of images
Image comparison is simple if the sample is imaged in all inspection from the same point of view and using the same pixel arrangement. Otherwise the shape of the inspected component needs to be measured and considered as well.

The same angle of view is maintained if e.g. different modes of lockin thermography are being used when neither the thermography camera nor the component are moved with respect to each other while only the kind of excitation is being changed. An example is optical excitation and ultrasound injection.
for heat generation. The ultrasound transducer can stay inactivated and clamped to the inspected component while optically excited Lockin thermography (OLT) is performed, and for the second image the lamps are switched off and the transducer is activated to perform ultrasound lockin thermography (ULT) [6]. The first method displays thermal boundaries, the second shows selectively areas where ultrasound is converted to heat e.g. by friction in cracks [7]. The two images in the following example (Fig. 1) were obtained on fibre ceramic material C-SiC produced by infiltration of liquid silicon into a carbon fibre matrix at about 1600 °C. If infiltration is not homogeneous, thermal contraction is locally during the cooling down process, stress induced cracks start in the boundaries. This interpretation is confirmed when the two images are merged: The cracks are initiated by the boundaries.

Figure 1. Phase images obtained on a 0.2x0.2 m² sized plate of C-SiC. OLT (left) and ULT (right) merged together (middle) to show that cracks start at the boundaries.

This approach of a simple overlay is helpful if one only wants to compare structures. It is not helpful for feature extraction or parameter analysis in images.

3. Examples
We apply the scatter plot concept to feature extraction. Basically, a scatter plot correlates data taken from two different kinds of observation data (e.g. temperature and growth rate of grass) to generate a cloud of data points and to look for a systematic dependence or response behaviour. If instead of the two kinds of processes one correlates two images so that the 2 values of corresponding pixels are plotted versus each other for all pixels across the whole image, one obtains a straight line if the images are identical (Fig. 2, left), otherwise not. It is important to note that the originally localized information in the images is not localized any more in the scatter plot: One point on the straight line corresponds to all areas having this same gray value, and by using a look-up table these areas can be traced back into the image and displayed selectively. This process is a rather trivial visualisation.

Figure 2. Scatter plot applied to imaging. One of the two originally identical airplane images was modified (letter exchanged). This resulted in cloud formation outside the line formed by 106 pixels.
However, an interesting situation results if the two images are taken on the same sample under different conditions, e.g. phase angle images with lockin thermography at two different modulation frequencies. The result is simply illustrated on a wedge where phase as a function of thickness can well be determined. If the lateral size of the wedge is much larger than thermal diffusion length, we can assume one dimensional heat flow so that phase depends only on thickness and on the thermal wave reflection coefficient $R$ at the boundary (which was determined by a fit in the measured scatter plot to be $R=0.905$). The numbers in the left scatter plot relate to various reflection coefficients.

The curved line for the wedge displays the effect of thickness variation in the 1d-model. If the scenery is enriched by adding to the setup a flat plate provided with three rear surface flat bottom holes, the lateral modulated heat flow in this sample results in a deviation of thermal wave propagation from the 1d model. However, the central part of the holes can be considered as an approximation to a flat area.

The usefulness of the scatter plot for feature extraction can well be illustrated on this example (Fig. 4) since similar thermal wave features are all gathered in the same area of the scatter plot. Therefore, selection of this area for inversion by using the look-up table will result in highlighting all image areas that have this feature in common. This backtracing process based on selecting/filtering of certain areas in the scatter plot has its counterpart in optics where filtering in the Fourier plane allows for image processing and pattern recognition. This way of thermal feature extraction is demonstrated in Fig. 5 on the scatter plot generated in Fig. 4.

![Figure 3.](image1.png) Theory (left) and experimental data for OLT on wedge standing on a table in the lab. Wedge data are on the indicated line.

![Figure 4.](image2.png) Experimental arrangement (left), OLT phase images (middle) and resulting scatter plot (right). Circles indicate features related to the holes in different depths. The small distance between circles and the line standing for the wedge shows approximately flat areas of the holes.
The dashed rectangular area contains hole 1 including its edge effects plus a small part of the 1d wedge. Back inversion displays selectively the hole and a section of the wedge together with its edge effects. The dotted area is far away from the curve which stands for 1d-effects, therefore filtering with this area displays only edge effects related to hole 1 and to the wedge.

4. Conclusion
We have shown a procedure allowing to distinguish certain thermal features of a sample which is inspected by using lockin thermography. The idea is based on the properties of the scatter plot resulting from data fusion of two phase angle images taken on the same sample at two different modulation frequencies. As the orientation of sample and camera with respect to each other is unchanged during the measurements, this method does not require corrections for the shape of the inspected sample. The information derived from the scatter plot (e.g. hidden areas with lateral heat flow and flat areas) can be used in a back tracing process to display selectively certain features of the hidden structures.

The extension of the principle to combine results obtained with other methods and their combinations is obvious, also extension to more than two dimensional scatter plots for deriving more features.

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