

# NDE of adhesive joints and riveted structures with lock-in thermography methods

Thomas Zweschper\*<sup>a</sup>, Alexander Dillenz<sup>a</sup>, Gerd Busse<sup>a</sup>

<sup>a</sup>Institute of Polymer Testing, University of Stuttgart

## ABSTRACT

Elastic waves sent into the component propagate inside the sample until they are converted into heat. A defect causes locally enhanced losses and consequently selective heating up. Therefore amplitude modulation of the injected elastic wave turns a defect into a thermal wave transmitter whose signal is detected at the surface by lock-in thermography synchronized to the frequency of amplitude modulation. This way ultrasound lock-in thermography allows for selective defect detection which enhances the probability of defect detection in the presence of complicated intact structures.

Measurements were performed on various kinds of mechanical joints. The results of our feasibility study indicate that both optical (OLT) and ultrasound excited lock-in thermography (ULT) are reliable tools for the rapid identification of damaged riveted structures. We demonstrate that one can locate a screw joint or a riveting which provide only a reduced stress. Investigations on airplane components were performed which confirmed the applicability of lock-in thermography for remote maintenance inspection within a few minutes.

**Keywords:** thermography, lock-in thermography, thermal waves, mechanical joints, adhesive joints, rivets, ultrasound

## 1. INTRODUCTION

Photothermal radiometry and its multiplex version lock-in-thermography are being used since several years for remote non-destructive testing and evaluation. They are based on propagation and reflection of thermal waves which are launched from the surface into the inspected component by absorption of modulated radiation. Phase angle images obtained by superposition of the initial thermal wave and its reflection display hidden structures down to a certain depth underneath the surface.

Reliable inspection techniques are required for the maintenance of safety relevant structures (e.g. aerospace equipment and vehicles) where one needs to detect defect areas early enough to prevent catastrophic failure. As many structures still consist of metal, the rapid and remote identification of loose rivets is a topic of major concern. Therefore a method is required that is applicable during inspection procedures to monitor the integrity of structures.

In this paper we demonstrate that both optical excited (OLT)<sup>1-5</sup> and ultrasound excited lock-in thermography (ULT) can be used for such remote inspections.

## 2. LOCK-IN THERMOGRAPHY

Thermal waves<sup>1</sup> have been used very early for remote monitoring of thermal features, e.g. cracks, delaminations<sup>2</sup>, and other kinds of boundaries. After the advantage of signal phase had been discovered<sup>3-5</sup>, phase angle imaging using photothermal techniques<sup>6</sup> became a powerful tool for imaging of hidden structures due to the enhanced depth range and its independence on optical<sup>7</sup> or infrared surface patterns.

As the thermal diffusion length is the important parameter for depth range<sup>8</sup>, it turned out very soon that imaging of features deep underneath the surface requires very low modulation frequencies and a correspondingly long time to obtain a photothermal image. Unfortunately many industrial questions are related to samples with defects at about a millimeter depth. An image obtained pixel after pixel at a modulation frequency in the 1 Hz range could easily require several hours. This is of not of real interest for many industrial applications.

One approach allowing for a reduction of inspection time is lock-in thermography where the low frequency thermal wave is generated simultaneously on the whole surface of the inspected component and monitored everywhere several times per modulation cycle in order to obtain an image of amplitude and phase of temperature modulation<sup>9-12</sup>. In this case the inspection time is given by a few modulation cycles. As one can image square meters of airplanes within a few minutes<sup>13</sup>, one has a powerful method for fast inspection of safety relevant structures with a depth range of several millimetres in polymer composites.

\*zweschper@ikp.uni-stuttgart.de; phone +49 711 685 2694; fax +49 711 685 2066; <http://www.ikp.uni-stuttgart.de/zfp>; Institute of Polymer Testing, University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany

In all these cases absorption of intensity modulated radiation generates on the whole surface a thermal wave. It propagates into the interior where it is reflected at boundaries so that it goes back to the surface where it is superposed to the initial wave (see Figure 1, left). This way a defect is revealed by the local change of phase angle.

Therefore both defects and intact structures are imaged at the same time. Defects can be revealed only by comparing the observed features with expected patterns provided by theory, by reference samples or by design drawings. Even for an experienced inspector it is difficult to distinguish defect areas from these thermal features.

Further investigations aimed at a method where a defect responds selectively so that the image would display only the defect and not the confusing background of the intact structure. Defect detection would be much easier if such a mechanism were involved because the “human factor” is reduced. Defects differ from their surroundings by their mechanical weakness. They may cause stress concentrations, and under periodical load there may be hysteresis effects or friction in cracks and delaminations. As defects may be areas where mechanical damping is enhanced, the ultrasound is converted into heat mainly in defects<sup>14, 15</sup>.

Modulation of the elastic wave amplitude results in periodical heat generation so that the defect is turned into a local thermal wave transmitter (see Figure 1, right). Its emission is detected via the temperature modulation at the surface which is analysed by lock-in thermography tuned to the frequency of amplitude modulation<sup>16</sup>. The amplitude image displays the efficiency of local mechanical losses, so it shows the imaginary part of elastic properties. The ultrasonic transducer is attached at a fixed spot from where the acoustic waves are launched into the whole volume where they are reflected several times until they disappear preferably in a defect and generate heat. These high frequencies are very efficient in heating since many hysteresis cycles are performed per second.

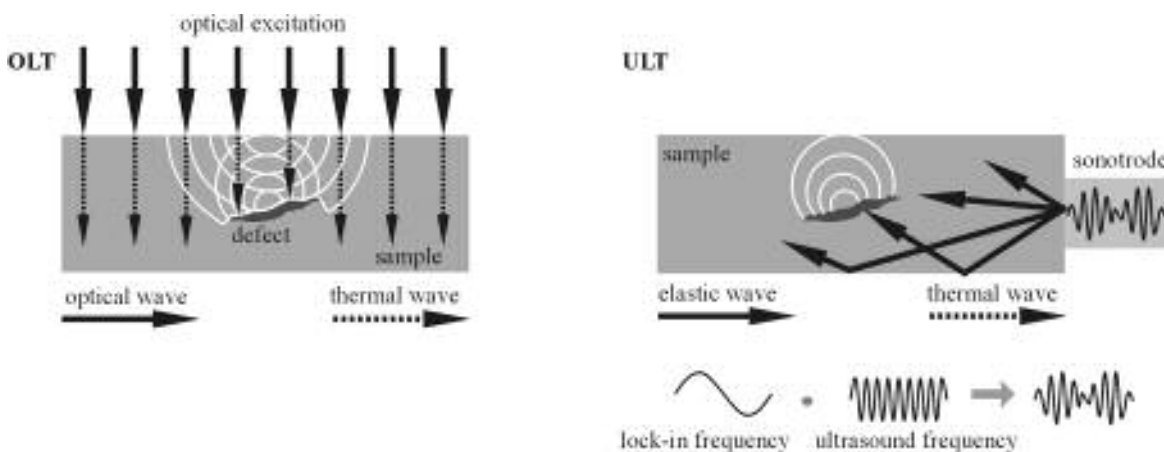


Figure 1: Principle of optical (left) and ultrasound excited lock-in thermography (right).

Lock-in thermography methods are currently being used for the rapid and remote identification of subsurface structures and defects such as impact damages, delaminations, and hidden corrosion<sup>17, 18</sup>.

The rapid identification of loose rivets is also a major concern for airlines and manufacturers in order to monitor the structural integrity of safety relevant structures in aircraft. Therefore our investigations aimed at the early detection of loose rivets. In this paper we want to demonstrate that these two lock-in thermography methods, both OLT and ULT, are also reliable tools to inspect the tightness of mechanical joints in e.g. aerospace equipment and vehicles. The basic idea is that heat transport in the inspected component is a sensitive probe for the metal/metal contact in the compressive area around screws or rivets.

In previous papers<sup>19, 20</sup> we analyzed the OLT phase image signature obtained on two metal plates pressed together by screws fastened at various torque levels. A clear relationship was established between the remotely measured phase angle and the torque level at which the screws had been fastened. Based on these results our investigations were extended to riveted samples. We compared OLT images with the corresponding ultrasound excited lock-in measurements to emphasize the advantages of the defect selective ULT method.

### 3. EXPERIMENTAL ARRANGEMENT

For these experiments we used a CEDIP infrared focal plane array camera (Jade II). The 320 x 240 detector array captures radiation in the 3-5  $\mu\text{m}$  spectral band at a frame rate up to 200 Hz. The OLT experimental configuration is illustrated on the left side in figure 2. This set-up is similar to the one used before for other investigations with OLT. A lock-in module (CEDIP Altaïr LI) and a signal generator provided the modulated thermal source which is synchronised to the recording process of thermal images. In most cases we use two halogen lamps each with the power of 1 kW. There are up to 12 lamps possible which allow for an inspection area of several  $\text{m}^2$ . The phase angle between the sinusoidal illumination of the sample surface and the local thermal wave response (affected by reflection from defects) is colour coded and visualized on the screen as a phase angle image of the inspected surface area.

Figure 2 (right) displays the corresponding experimental ULT arrangement. The acoustic or ultrasonic transducer is attached to the component which is monitored by a lock-in thermography system tuned to the low frequency of amplitude modulation. The elastic wave frequency was typically around 20 kHz while the amplitude modulation frequency was usually below 1 Hz. The acoustic energy provided by the source was in most experiments several hundred Watts. Duration of a measurement was typically 3 minutes.

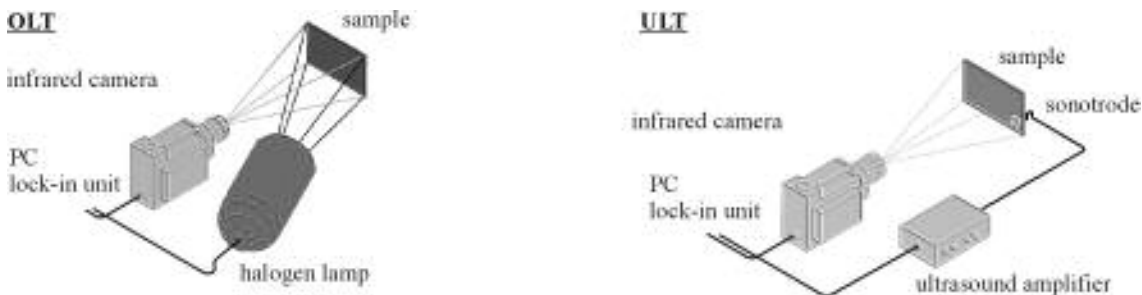


Figure 2: Experimental arrangement of OLT (left) and ULT (right).

In the following we describe results that were obtained on various mechanical joints and riveted structures.

### 4. SAMPLES

Experiments were first performed on model samples where the quality of mechanical joints was simulated in a reproducible and adjustable way by screws fastened at different levels of torque or compressive stress, respectively. As the obtained results – some samples are shown in figures 3 and 4 – confirmed the applicability of the method, we extended our measurements to realistic riveted structures and components.

Figure 3 displays a series of the different phase signatures of a screw joint tightened at an increasing torque level from left to right. In the OLT measurement one can recognize the correlation between phase angle and applied torque. The tighter the joint the higher the averaged phase angle around the screw head. It is obvious that thermal wave propagation is affected by the compression of the metal plates thereby making the signal phase a good indicator for the achieved compressive stress.

Surprisingly one cannot recognize a relationship between the applied torque and the phase signature in the corresponding ULT measurement (bottom row). Only the loose screw on the left is remarkable for not delivering any signal. The other phase angles are quite similar, a correlation between torque and compressive stress could not be established.

The images in figure 3 confirm that the signal phase of OLT is well suited as an indicator for the achieved compressive stress around the screws. If such a dependence is intended to be used as a calibration curve, one must keep in mind that it is highly specific for the geometrical dimension and the material both of the screws and the plates. In our investigation we found that a few other factors affect the phase signature of a mechanical joint. The influence of eccentricity, corrosion, surface roughness of the plates pressed together, and a possible applied sealant could be established.

In some cases we detect an asymmetric phase pattern around the screw head. In order to understand this effect we investigated how optical excited lock-in thermography responds to the eccentricity of surface pressure. In the samples shown in figure 4, we vary the diameter of the borehole. The smaller borehole diameter – very close to the outer thread diameter of the screw – allows no eccentric joint, whereas the larger borehole causes an eccentricity of surface pressure. The higher phase values (appearing bright in the image) are shifted to the left side where the compression was stronger.

Figure 5 demonstrates the effect of high load – visualized by ULT – on a three row countersunk riveting. These rivet joints were overloaded in a shear test. In such a test the external force is spread symmetrically, where the two outer rows are higher loaded than the inner row. In the ULT phase signature at 0.2 Hz the damaged rivets (partly disbonded) in the two outer rows appear bright, whereas the intact rivets in the middle are inconspicuous.

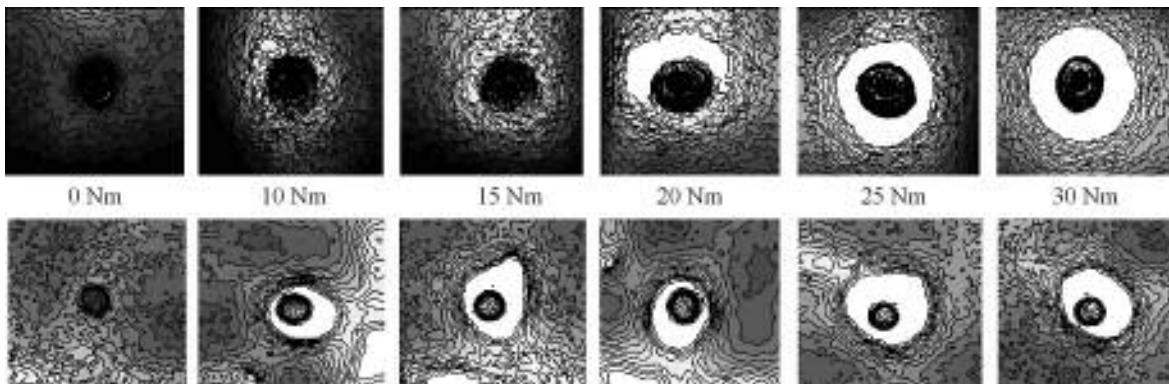


Figure 3: Phase images of a M8 screw joint fastened at different torque levels. Optical excited lock-in thermography at a frequency of 0.06 Hz (OLT, upper row) and ultrasound excited lock-in thermography at a frequency of 0.06 Hz and a power of 700 W (ULT, bottom).

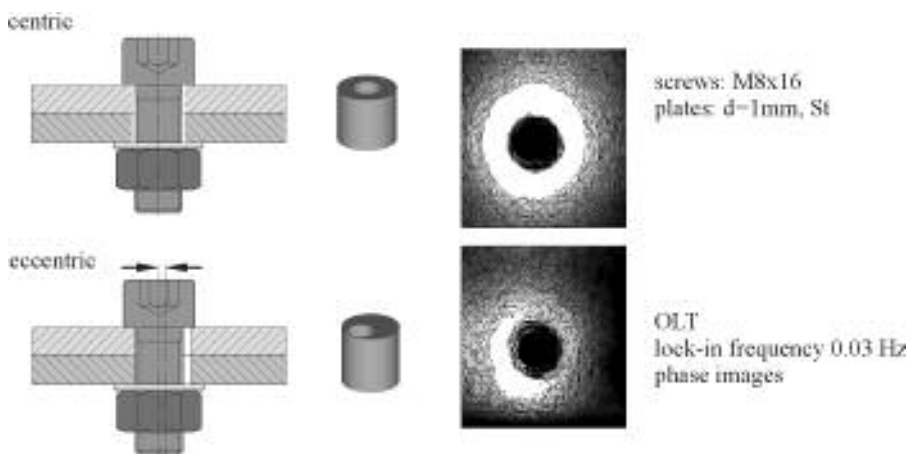


Figure 4: Eccentricity of surface pressure of a M8 screw joint fastened with 20 Nm.

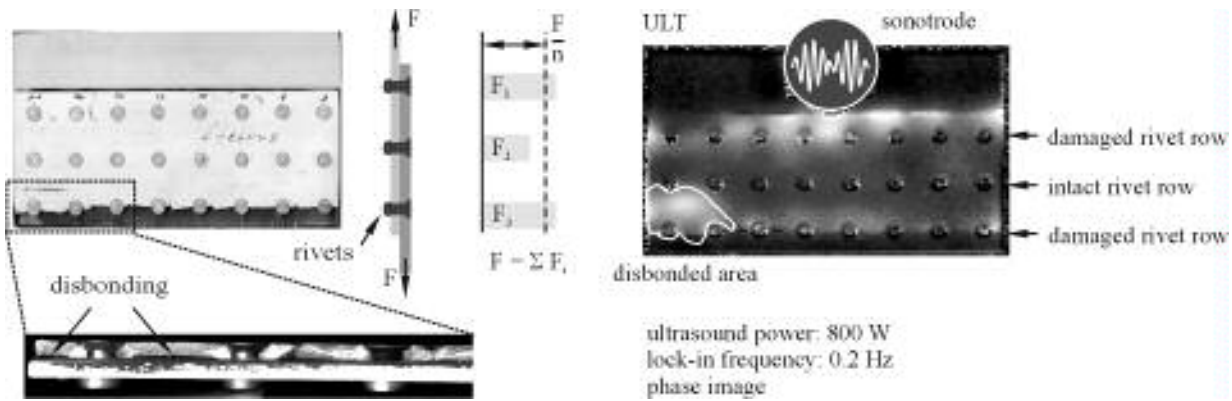


Figure 5: Countersunk riveting after a shear test.

In figure 6 two aluminum plates were pressed together by an array of nine rivets. We used two different blind rivet systems, one consists of a copper sleeve and a brass arbor, the other combines an aluminum sleeve with an arbor made of steel. The rivet joints – hidden under black paint – had the same geometrical dimensions, so it was impossible to distinguish one from the other. But each of the two blind rivet systems provides a different compressive stress because of the varying material combinations. This effect can be visualized with ULT. The phase image taken at 0.5 Hz and a power of 600 W demonstrates that it is possible to distinguish the copper-brass rivet from the aluminum-steel system.

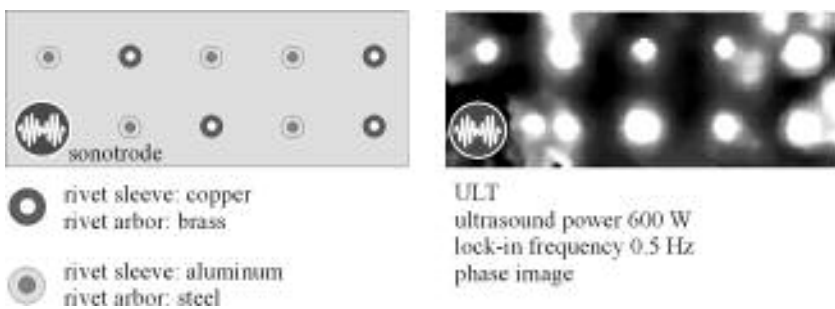


Figure 6: Different ULT phase signatures of different blind rivet systems.

The detection of a crack along a row of rivets as an example for the maintenance and inspection of safety relevant structures is shown in Figure 7. The crack length had been known from eddy current inspection (figure 7a).

At first we investigate the riveted aluminium structure using OLT. In figure 7b it is obvious that the amplitude image taken at 0.11 Hz is sensitive to the non-uniform intensity distribution. As the phase image (figure 7c) is insensitive to all kinds of perturbations, it shows essentially the thermal features from the surface down to a depth of about two times the thermal diffusions length  $\mu$ . One can recognize clearly the reinforcement of the aluminium plate on the right and the apparent intact riveting. No damage and no crack could be detected.

But using ultrasonic excitation a bright area was found with a significantly larger extension (figure 7d). These rivets provide a reduced compressive stress so that the integrity of the riveting is no longer sure. The ULT measurement revealed that the damaged area is larger than expected from the eddy current results. To detect the crack only and to reaffirm the eddy current results all rivets were removed and an amplitude (figure 7e) and a phase image (figure 7f) were taken again with ULT. As there was no more any rubbing contact to the rivets or the rib, only the tip of the crack caused hysteresis losses whose locations are identical with the result of the eddy current measurement. The hot spot on the left is no defect, it was caused by the rubbing contact between rib and plate. This example shows how efficiently ULT can be applied for the selective imaging of fatigue cracks.

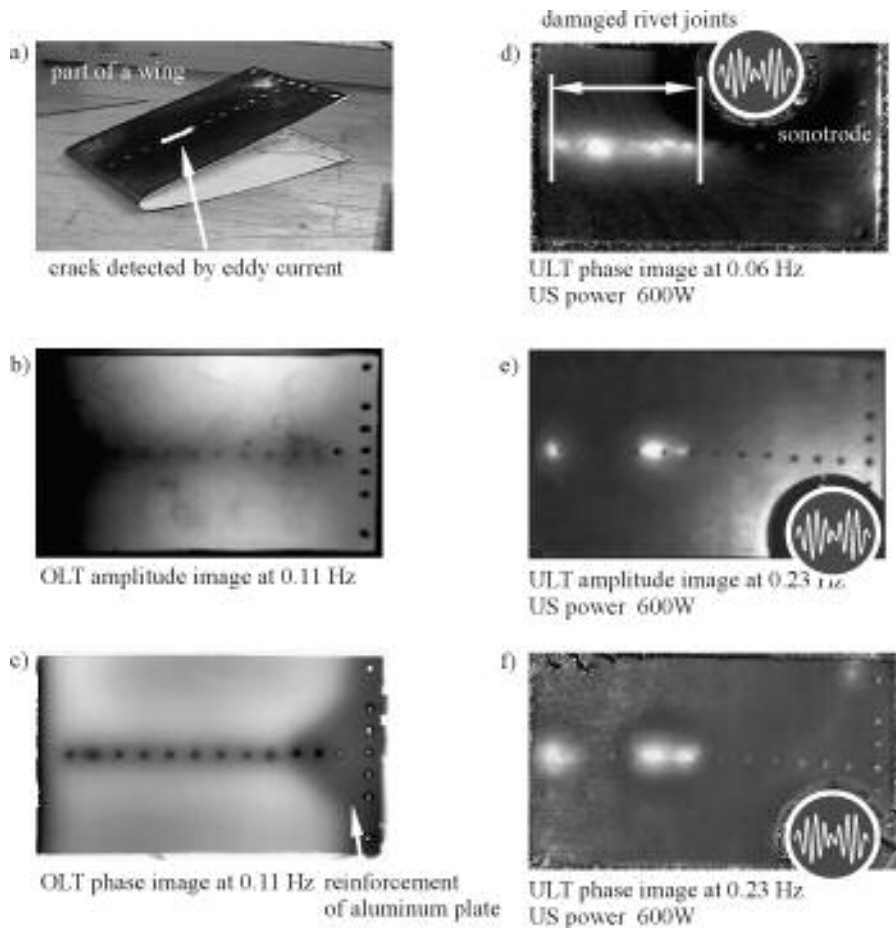


Figure 7: Detection of a crack in an aluminium plate and the resultant damaged rivet joints.

## CONCLUSION

From our feasibility study performed with OLT we conclude that one can locate screws and rivets which provide only a reduced stress. Also the effect of excessive load on rivet compression could be established. This result should be of interest for inspection and maintenance of safety relevant structures. This is of particular importance if the rivets are hidden under paint, because the homogeneous layer of paint will only cause a signal shift (depending on thickness and kind of paint<sup>14</sup>) while the relative phase changes are still visible.

Loss of compression should be detectable independently of material effect. Other effects such as corrosion etc. might be superposed also. Though they are dangerous as well it is important to separate them from loss of compressive stress. The reliable detection of corrosion in the presence of different materials and reinforced structures is of major concern.

However, further investigations need to be performed e.g. in order to reduce the ultrasound power and to extend the inspected area.

No technique offers a solution to all problems. Within the field of non-destructive testing and evaluation a combination of different techniques may be required. Nevertheless the lock-in thermography methods with their capability of producing rapid scans of large areas and in case of ULT the defect selective imaging may provide a solution to the problem of quantitative in-service and manufacturing process inspection not only of commercial aircraft components.

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