ULTRASOUND LOCKIN-THERMOGRAPHY
– A DEFECT-SELECTIVE NDT METHOD
FOR THE INSPECTION OF AEROSPACE STRUCTURES

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Abstract

Photothermal radiometry and its multiplex version Lockin-thermography are being used since several years for remote non-destructive testing. 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.

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 lockin thermography synchronized to the frequency of amplitude modulation. This way ultrasound lockin thermography (ULT) 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 typical defects in aerospace structures (both metal and non-metal). The obtained phase angle images reveal areas of hidden corrosion, cracks in rows of rivets, disbonds, impacts, and delaminations. In all these cases the intact structure was suppressed since it heats up much less in the elastic wave field. We present examples which are relevant e.g. for maintenance and inspection of aircraft.

INTRODUCTION

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

As the thermal diffusion length is the important parameter for depth range /8/, 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 of not of real interest for many industrial applications.

One approach allowing for a reduction of inspection time is lockin 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 /9-12/. 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 /13/, one has a powerful method for fast inspection of safety relevant structures with a depth range of several millimetres in polymer composites.

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 fig. 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 features provided by theory or by a reference sample. Defect detection would be much easier if a mechanism were involved where a defect responds selectively so that the image would contain only the defect and not the confusing background of intact features.

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 /14, 15/.

Modulation of the elastic wave amplitude results in periodical heat generation so that the defect is turned into a local thermal wave transmitter (see fig. 1, right). Its emission is detected via the temperature modulation at the surface which is analysed by lockin thermography tuned to the frequency of amplitude modulation /16/. The amplitude image displays the efficiency of local mechanical losses, so it shows the imaginary part of elastic properties. Though the technique is related to ultrasonic inspection, 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.

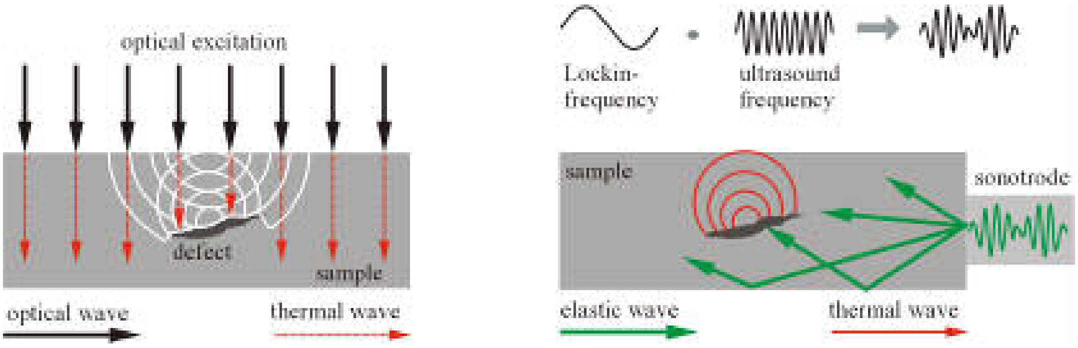


Figure 1: Principle of optical (left) and ultrasound lockin thermography (right).

EXPERIMENTAL SETUP

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 µm spectral band at a frame rate up to 200 Hz. The OLT experimental configuration is illustrated on the left side in fig. 2. This set-up is similar to the one used before for other investigations with OLT. A lockin 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 m². 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.

Fig. 2 (right) displays the corresponding experimental ULT arrangement. The acoustic or ultrasonic transducer is attached to the component which is monitored by a lockin 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.

In the following we describe results that were obtained on various materials used for aerospace applications – metal and polymers reinforced by glass (GFRP) or carbon fibres (CFRP), and ceramic material resulting from pyrolysis of CFRP and subsequent infiltration with silicon (C/C-SiC).

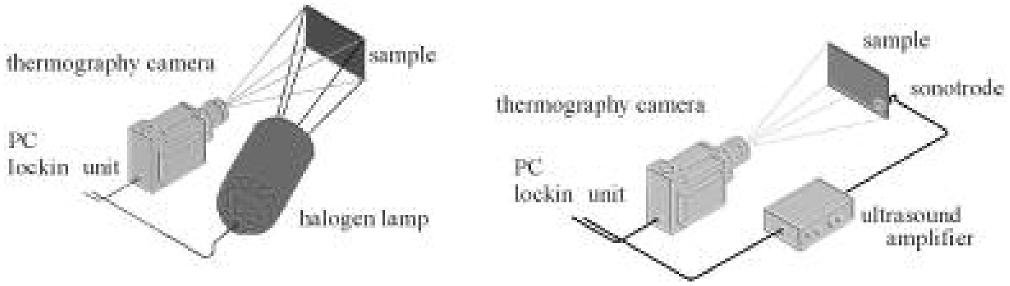


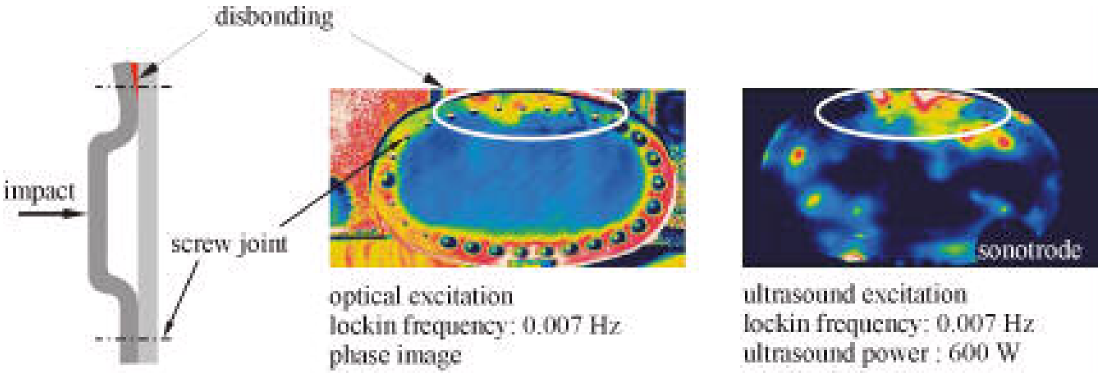
Figure 2: Experimental arrangement of lockin thermography with ultrasonic excitation.

EXPERIMENTAL RESULTS

Carbon fibre reinforced polymers (CFRP)

In a previous paper /13/ we presented examples for detection of damage in aerospace structures (GFRP and CFRP) using lockin thermography with optical excitation. Further investigations were performed with acoustic excitation (ULT) the advantage of which becomes obvious by comparison with optical excitation (OLT).

An example is the cover of an access hole for aircraft maintenance. Due to an impact (see fig. 3) there was a damage at the outer edge next to the screws. The phase image of OLT is dominated by the holes for the screws and the thermal contact of the two joint pieces of which the cover consists, while the ULT image shows mostly the defect area where boundaries are rubbing against each other.

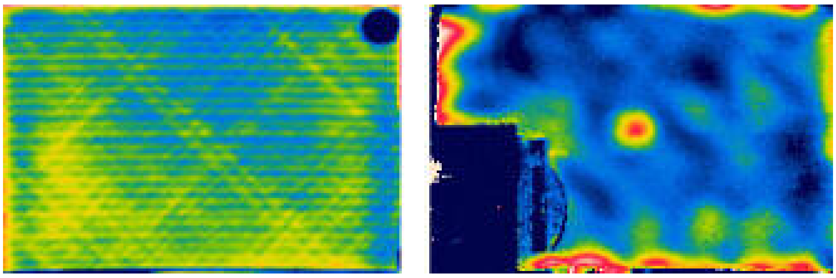


optical excitation
lockin frequency: 0.007 Hz
phase image

ultrasound excitation
lockin frequency: 0.007 Hz
ultrasound power : 600 W
amplitude image

Figure 3: Access hole for aircraft maintenance.

Similarly striking is the difference between OLT and ULT in impact detection: while the OLT image (fig. 4, left) displays mainly the fibre directions +/-45 deg. with no indication of the impact (the circle in the upper right corner is a sticker), the ULT image shows only the impact (bright central spot in fig. 4, right) in such an obvious way that it would certainly attract attention in the maintenance inspection.



Optical lockin thermography:
phase image at 0.03 Hz

Ultrasound lockin thermography:
phase image at 0.03 Hz, ultrasound power: 300 W

Figure 4: Impact damage in CFRP plate.

Stinger structures

Stringers are used if stiffness needs to be enhanced along a certain direction. Stringer disbond caused e.g. by excessive loading therefore results in a loss of structural stiffness. Therefore one is highly interested to detect such defects early enough to prevent failure.

An example is the flap shown in fig.5 where the results of OLT and ULT are compared. While OLT displays the whole structure where the small effect of the defect easily escapes attention, a small white spot in the ULT image indicates a crack and a delamination in the stringer underneath the intact CFRP-skin.

Another example is the component investigated previously (fig. 6). The photograph of the rear surface displays the structure that needs to be inspected with access only from the flat front surface. It is composed of a CFRP skin and T-shaped stringers bonded to it while the lighter rectangular areas are glass fiber reinforced polymer (GFRP) wedges attached to the structure to perform tests under load. With OLT performed on the front surface the intact structure (including the GFRP area) is revealed where the disbond appears as an interruption of the straight lines which indicate the bonded stringers. The ULT phase image shows only the area where the disbond starts since only there the components can rub against each other in the ultrasound field. Surprisingly, there is an additional small spot which is not due to disbond but rather to a crack in the perfectly bonded stringer so that the heat modulation generated by friction can propagate as a thermal wave across the bond into the front of the skin over a cm-distance.

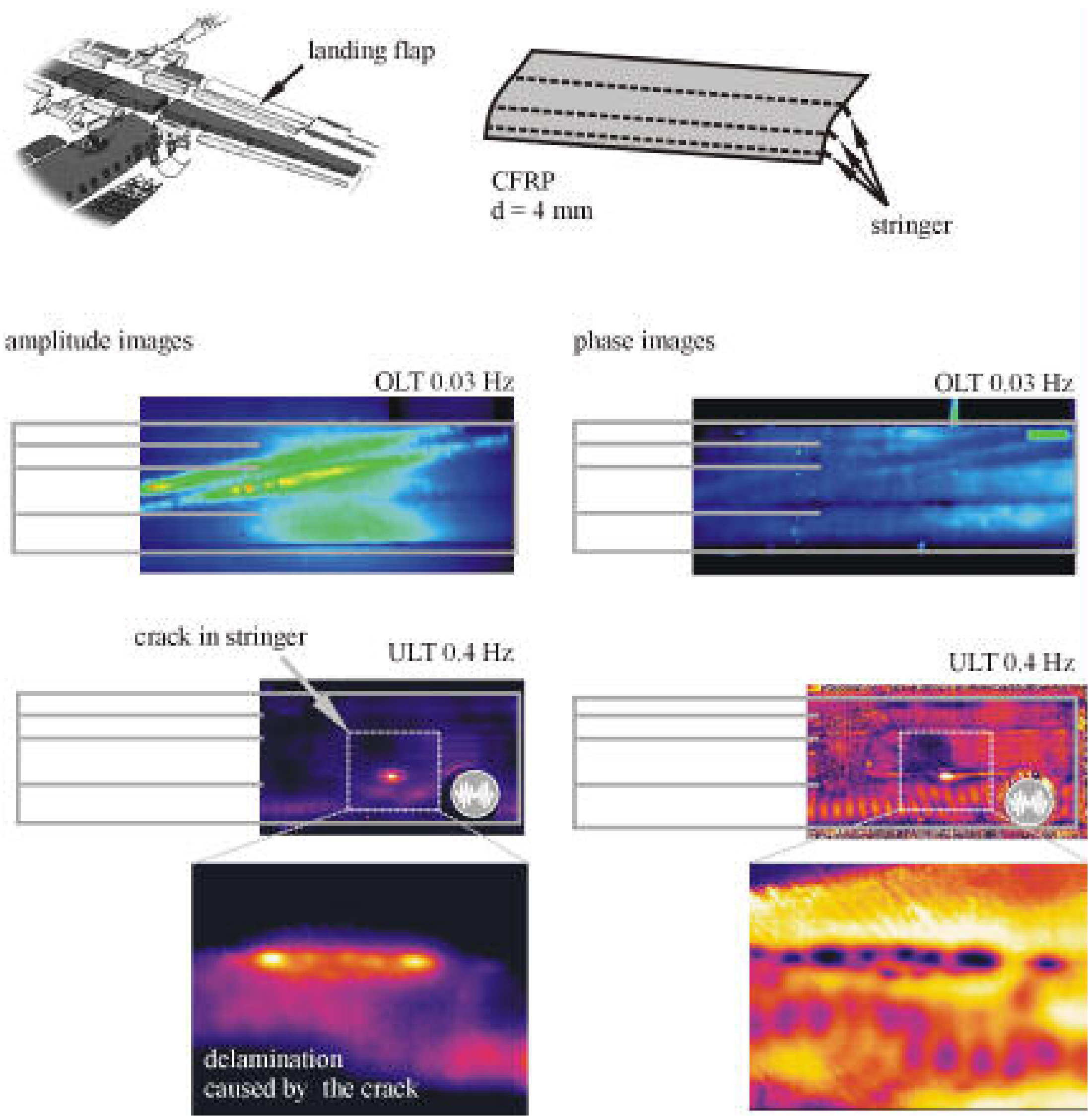


Figure 5: Crack and Delamination in stringer of a landing flap (CFRP). A comparison between OLT and ULT.

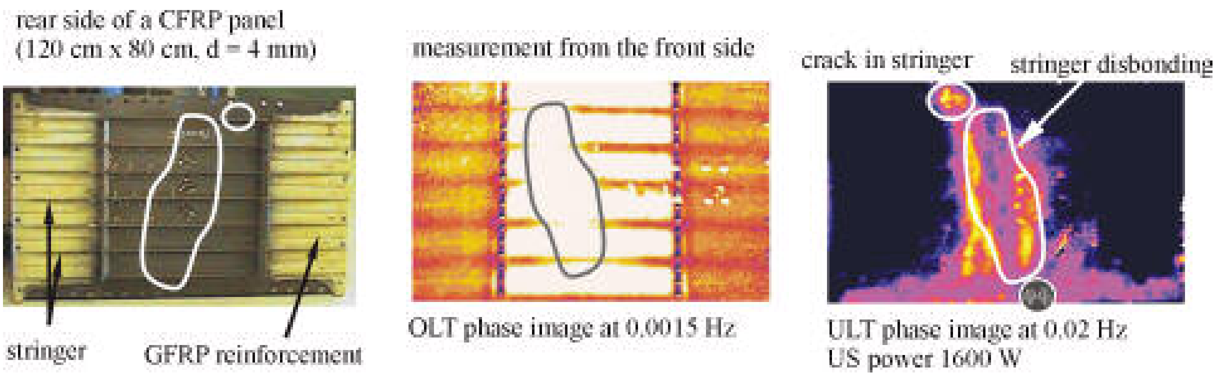


Figure 6: Stringer disbonding and cracks in a Do 328 panel.

Sandwich structures

Honeycomb structures are being used in aerospace applications due to their low weight and high stiffness. The critical area of such a component is where the skin is bonded to the structure underneath. Condensation of water can effect the quality of bonding which might result in a loss of adhesion and finally in a local loss of stiffness. That is why the reliable detection of water under a perfect outer skin is important for maintenance inspection. Such an example is presented in Fig. 7 where parts of the honeycomb structure had been filled with water with an injection needle from the rear surface while inspection was performed from the front surface.

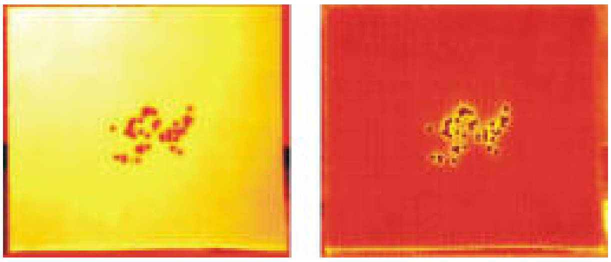


Figure 7: Water in a honeycomb structure. OLT amplitude (left) and phase signature (right) at a lockin frequency of 0.1 Hz.

C/C-SiC

Re-entry vehicles undergo rapid temperature changes where the material needs to withstand high temperatures. The same requirement holds for break disks of high speed trains: In both cases the mechanical properties may not be affected by sudden heating. Therefore it is essential to detect material inhomogeneities possibly caused by the production process of carbon fiber reinforced silicon carbide (C/C-SiC). This process includes immersion of the heated carbon fiber network into liquid silicon which diffuses into the material where it reacts to generate SiC which is an extremely hard material. If the diffusion speed is not well tuned, the material may be inhomogeneous due to concentration gradients of Si. This may result in boundaries and potentially also in cracks which are a source of trouble when the material is used. Such material had been inspected both with ULT and OLT (fig. 8). With optical excitation (OLT) where the generated thermal waves start at the surface and are reflected back to it at internal material gradients or boundaries, one finds a broad area where the thermal properties are different. With ULT one sees only lines starting at the edge of this area. They might be correlated with cracks that are generated by high gradients when the material cooled down. Here one needs to know what the structures really mean which are found by application of advanced NDE methods. It is not enough to see that “there is something”. However, one must keep in mind that such questions still exist even in X-ray techniques though they are around since many decades. To interpret these features one needs to learn interpretation art least empirically by correlating NDE results with those of destructive testing (e.g. optical inspection of material slices cut along such NDE-patterns).

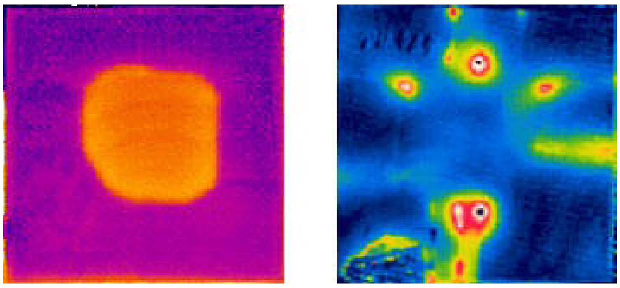


Figure 8: Phase images of a C/C-SiC sample at 0.03 Hz. Optical lockin thermography (left) and ultrasound lockin thermography (right).

While this was only a sample with a size of about 100 square inches, there is an obvious need to inspect real components made of this material. The geometry of these components may differ significantly from a flat plate, and they may be much larger. We found that structural integrity can be monitored (fig. 9) under such conditions in a very fast and reliable way.

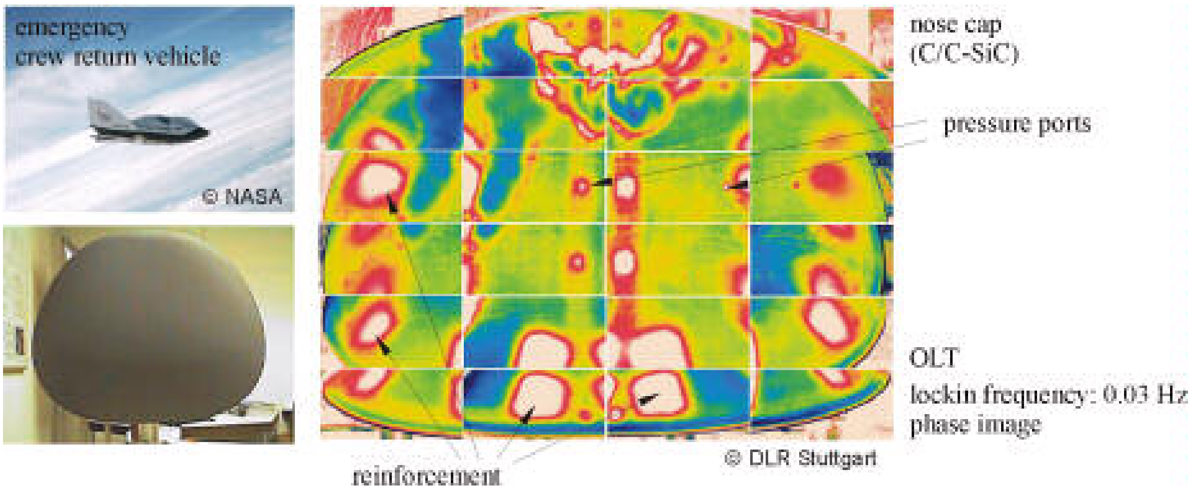
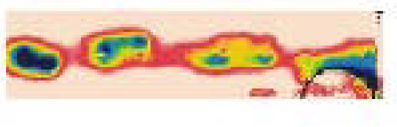


Figure 9: Phase image of a C/C-SiC nose cap of an emergency crew return vehicle

Rivets

Not all aerospace vehicles consist of modern materials with high specific strength. Light weight metal is still being used for many aircraft, and many ageing aircraft need to be inspected whose structural strength is provided by metal. Defects to be detected and monitored are e.g. cracks, corrosion, and loose rivets. In a previous paper /17/ we described how lockin thermography can be applied to monitor the compressive stress provided by screws or rivets. This way one can identify loose joints rapidly in a remote way. Detection of hidden corrosion between riveted metal plates is a major concern for maintenance inspection. Fig. 10 shows results obtained with phase angle images of OLT and ULT. OLT displays mainly how the rivets modify the transport of modulated heat. The ULT image looks different since its contrast mechanism is the local relative motion of the two aluminium plates under load.



Ultrasound lockin thermography:
phase image at 0.03 Hz

Optical lockin thermography:
phase image at 0.03 Hz

Figure 10: Riveted aluminium stringer.

Fig. 11 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.

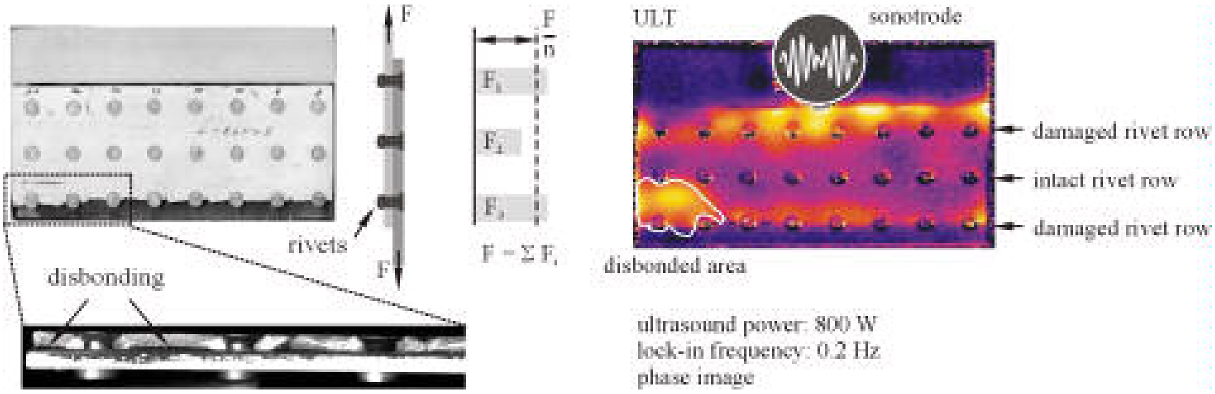


Figure 11: Countersunk riveting after a shear test.

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 fig. 12. The crack length had been known from eddy current inspection (fig. 12a).

The amplitude image taken at 0.11 Hz using OLT (fig. 12b) displays the influence of the non-uniform intensity distribution. As the phase image (fig. 12c) is insensitive to all kinds of perturbations, it shows essentially the thermal features between the surface and a depth of about twice the thermal diffusion length μ. 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.

Using ultrasonic excitation, however, a bright area was found with a significantly larger extension (figure 12d). 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 (fig. 12e) and a phase image (fig. 12f) 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 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.

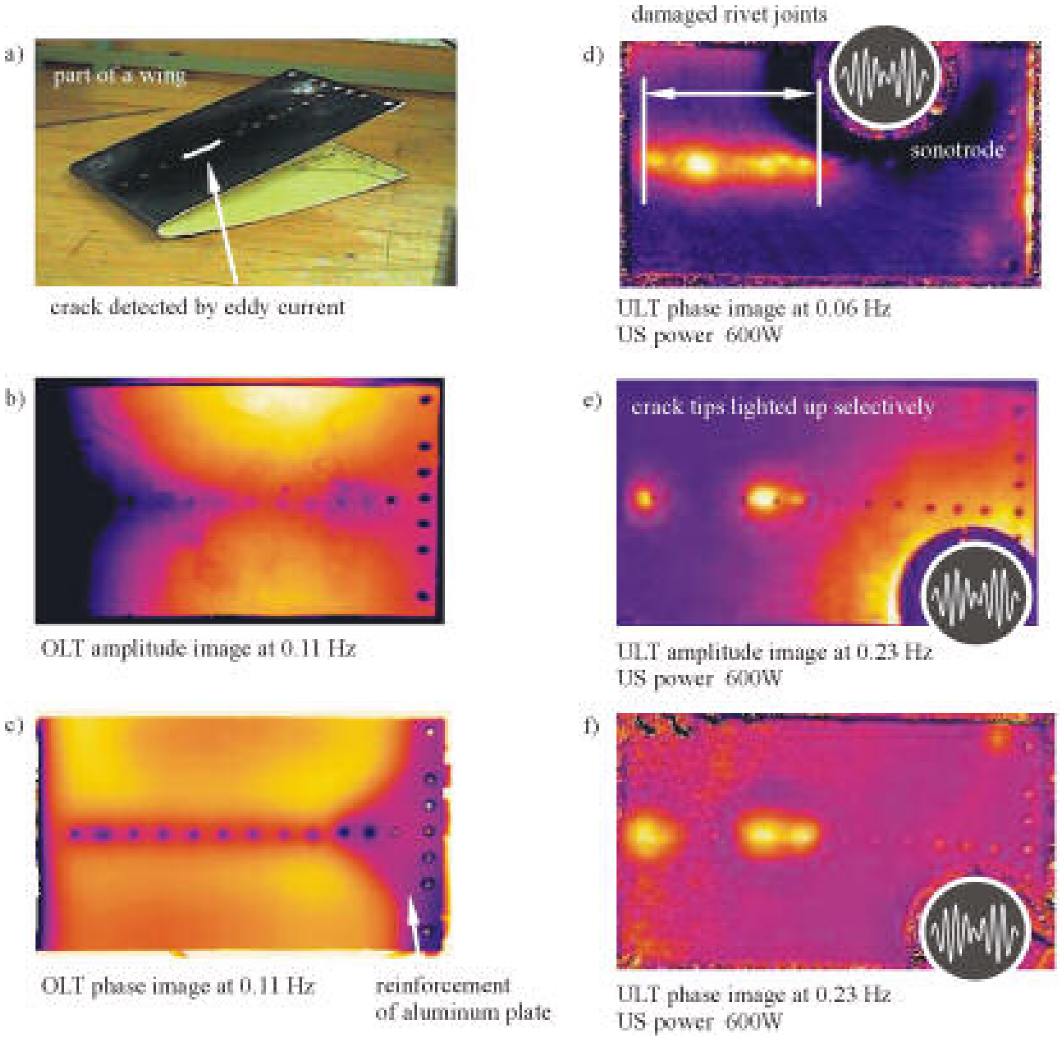


Figure 12: Crack along a row of rivets.

SUMMARY

The examples show that acoustically generated thermal waves are applicable for non-destructive inspection of aerospace structures where one can detect impact, delamination, cracks, and hidden corrosion. The advantage of selective defect heating is obvious: besides highlighting of defects the energy is used in a very efficient way since it is not wasted for heating of uninteresting intact areas. This makes ULT well suited for non-destructive testing in the quality control of safety relevant structures, e.g. in aerospace applications.

The problem that still needs to be solved is the injection of high power ultrasound. While optical excitation of thermal waves allows for inspection of several square meters, we are presently limited to areas of about 1 square meter with acoustic generation of thermal waves.

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