# Defect-selective imaging of aerospace structures with elastic-wave-activated thermography

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## ABSTRACT

Aerospace structures are subjected to variable loads over long periods with rapid changes of conditions (e.g. humidity, temperature). Therefore the materials and components made out of them may suffer from aging and deterioration, especially since the weight of such structures is an important quantity. On the other hand, any failure of a component may cause costs that exceed by many orders of magnitude the cost of the component itself. On this background it is important to identify defects reliably and early enough during production or maintenance inspections in order to avoid catastrophic failure. This is the general and important task of nondestructive evaluation. We present a method where thermal effects are selectively activated in defects so that defects reveal themselves selectively even in the presence of complicated intact features. The mechanism involved is local friction or hysteresis which turns a variably loaded defect into a heat source which is identified by thermography. Loading is achieved by an elastic wave or oscillation with a suitable time dependence. The method is presented together with results obtained on aerospace structures.

**Keywords:** Non destructive testing, defect selective imaging, thermal wave imaging, lockin thermography, phase angle thermography, elastic wave thermography, ultrasound lockin thermography, ultrasound burst thermography

## 1. INTRODUCTION

Waves propagating in structures undergo modifications that are due to the interaction between the wave and the material. The kind of wave determines which physical quantity of the material is involved. Therefore images obtained by evaluation of wave propagation display the inspected component in the specific light of certain physical properties. In the case of ultrasound which is a classic tool for nondestructive inspection, these properties are the local elastic constants and density. Therefrom result the velocities and their local changes and - finally - wave reflections (“echoes”) that identify hidden features of density or elastic properties.

### 1.1 Thermal waves and optical lockin thermography

This idea is applicable as well to the thermal wave concept which is the description of how a temperature modulation propagates in a material[1], they have been used for material characterization very early[2] where the disadvantage was the cumbersome generation and detection of the thermal wave. The photothermal technique was a major step forward since it allowed to deposit energy in a remote way (absorption of intensity modulated light) and to analyse the resulting temperature pattern also remotely using infrared radiometry[3]. It has been used for imaging of hidden features where the depth range depends on thermal diffusion length $\mu = ( 2k/\omega\rho c)^{1/2}$ (k denotes thermal conductivity, ρ density and c specific heat, respectively) so that depth profiling is possible via the modulation frequency ω [4,5]. In fact, μ is the depth range if one uses the amplitude of the thermal wave for imaging while it is almost twice that if one uses the phase of the thermal wave[6-9]. In addition the phase angle image has the advantage that it is not sensitive to optical or infrared surface features[10]. However, the major disadvantage of this scanning photothermal radiometry was its slow imaging capability since serial pixel-by-pixel generation of the thermal wave image requires about one modulation period at each pixel.

The situation was improved after the infrared point detector had been replaced by thermographic equipment and the laser by a powerful lamp[11-14] so that even large scale structures could be inspected remotely within a short time[15]. The basic idea is that the thermal wave is simultaneously generated and detected on the whole sample surface. Images obtained using this “lockin thermography” display all features that interact with thermal waves, e.g. boundaries and surfaces. The quantities involved are essentially the geometry and the material parameters that affect μ . It is essential to keep in mind how the signal is generated: The optical radiation is modulated, it generates at the absorbing sample surface a temperature modulation. Therefore the surface acts as a thermal wave transmitter from where the heavily damped thermal wave[4,5] propagates into the inspected sample where it is reflected at hidden boundaries so that it is superposed on the surface to the

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original wave. Addition of the vector amplitudes results in a modification of magnitude and phase by which the hidden thermal boundary is detected if it is not out of depth range mentioned above.

This principle of optical lockin thermography (OLT) is displayed in fig.1. Its application to structures displays all thermal features regardless of whether they are defects or not. To interpret such images one needs to know what the intact structure looks like and then to watch out for deviations caused by defects. Of course an image processing equipment can handle this problem, but then a reference image is required which shows what the intact structure looks like. It would be much safer if the method responded selectively to defects and displayed only them.

### 1.2 Thermography based on absorption of elastic waves

This can be done. The essential idea is that one can replace absorption of optical radiation in the surface by absorption of elastic waves in mechanically lossy areas since these are correlated with defects.

The thermal effects caused by strain are as well known since some time: Besides the hysteresis effect where the hysteresis area in the stress/strain diagram denotes the energy density or the resulting heat density deposited irreversibly during each strain cycle[16, 17]), there is the reversible thermo-elastic effect[18] which is being used for stress pattern analysis by thermal emission (SPATE[20]). The two effects can be separated from each other by the strain dependence of the signal[21]. It has been shown by Migogna et al.[22] that the injection of high power elastic wave pulses results in efficient selective heating of cracks and other defects which reveal themselves by their heating up when they absorb elastic wave energy. The high frequency (ultrasound instead of sonic excitation) used by these authors improves the heating since more hysteresis loops are generated per time, therefore power density of heating is linear in the elastic wave frequency. Instead of this pulsed or transient operation one can modulate the injected elastic wave power to turn the heat generating defects into thermal wave sources whose activity is monitored on the surface by the Lockin thermography system which is tuned to the modulation frequency[23-26]. This signal generation in “Ultrasound lockin thermography “ (ULT) is compared in fig. 1 to OLT. As there is no thermal wave interference involved, source depth is linear in signal phase and depth range in ULT is only limited by noise. So it can be enhanced by injecting more power while depth range limitation in OLT is not given by optical power.

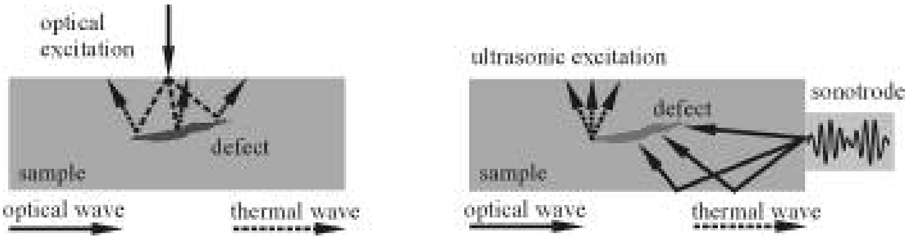


Figure 1: Principle of ptical (OLT, left) and ultrasound lockin thermography (ULT, right) [24].

## 2. EXPERIMENTAL ARRANGEMENT

The conversion of this basic principle to hardware is displayed in fig.2: The transducer with an electrical output up to 2 kW operates at a carrier of 20 kHz and above. The output shape can either be sinusoidal for lockin-operation, pulsed[24, 27], or in a burst mode to derive phase angle images from a Fourier analysis which are more meaningful than just a timegram since they are much less affected by inhomogeneous power distribution[28]. This principle has been applied previously to thermography with optical excitation (“burst phase thermography”[29, 30]). It provides frequency dependent phase angle images which make depth interpretation much easier[31] since the high frequency phase image contains information an near-surface depths (e.g. open cracks) and vice versa.

Figure 2: Experimental arrangement of lockin thermography with ultrasonic excitation[24].

The elastic wave emitted from the transducer attached to the sample propagates in the sample where it undergoes reflections and mode conversions until it finally interacts in a suitable mode and direction with areas of significantly enhanced loss angles where it disappears (e.g. in a crack) while it generates heat. This is similar to the way how optical absorption occurs in a multi-pass cell.

Due to the relevance of nondestructive inspection for safety-relevant structures we applied this technique to various components of aircraft or space vehicles. The materials were advanced non-metals that will be described below together with the results obtained using this defect-selective technique. Concerning results obtained on metal structures (where rivets, screws and bolts are involved) are the subject of another presentation at this conference[32].

## 3. RESULTS

### 3.1 Stringer 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 3. Where the results of OLT and ULT are compared. While OLT displays the whole structure where the small effect of the defect readily escapes attention, a small white spot in the ULT image indicates a crack and a delamination in the stringer underneath the intact CFRP-skin.

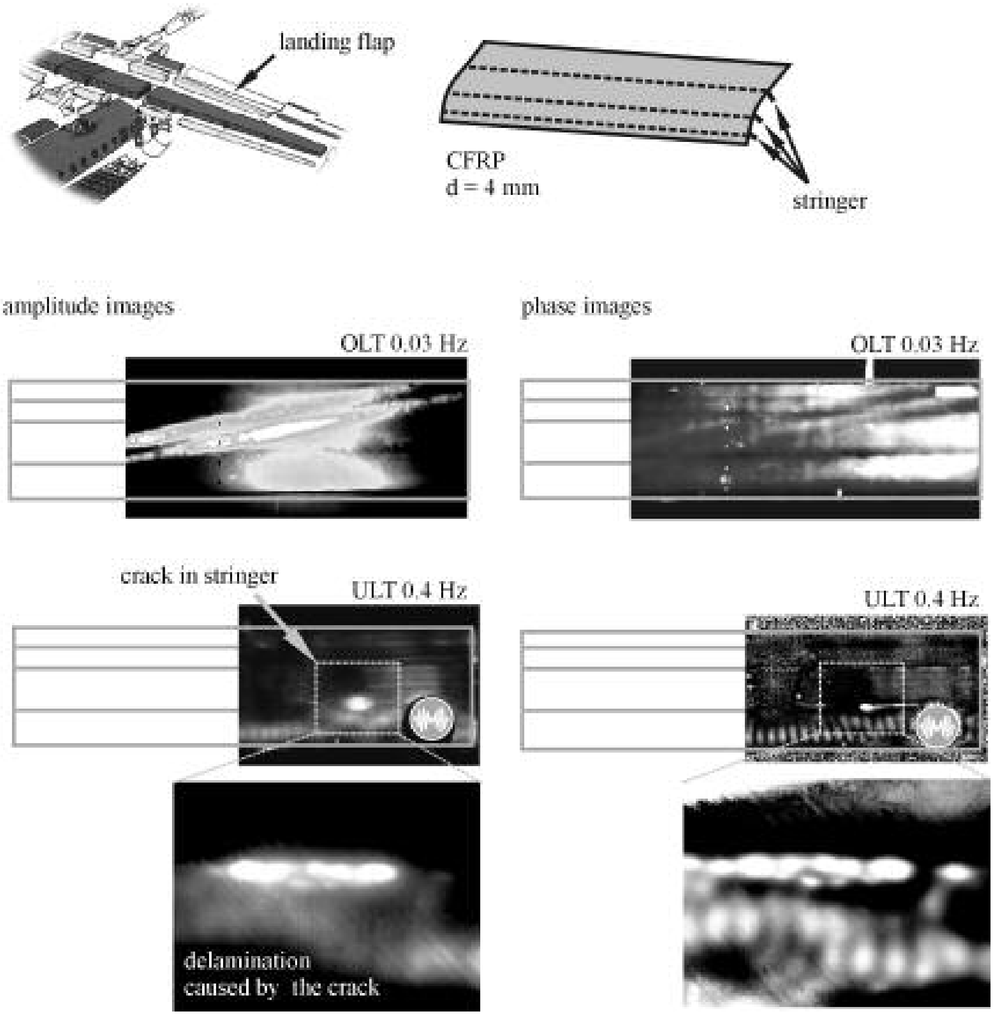


Figure 3: Crack and Delamination in stringer of a landing flap (CFRP). A comparison between OLT and ULT.

Another example is the component investigated previously[15, 24] (fig. 4). 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.

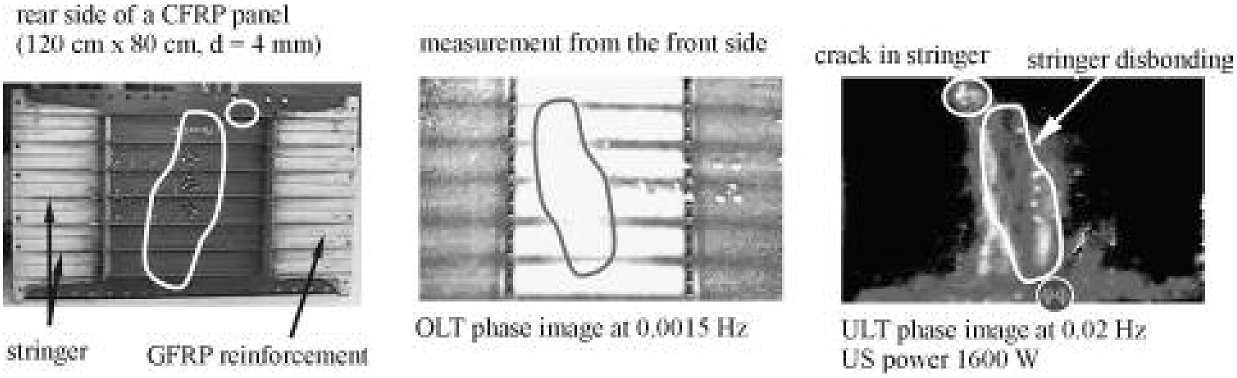


Figure 4: Stringer disbonding and cracks in an aircraft panel. OLT (left) and ULT (right).

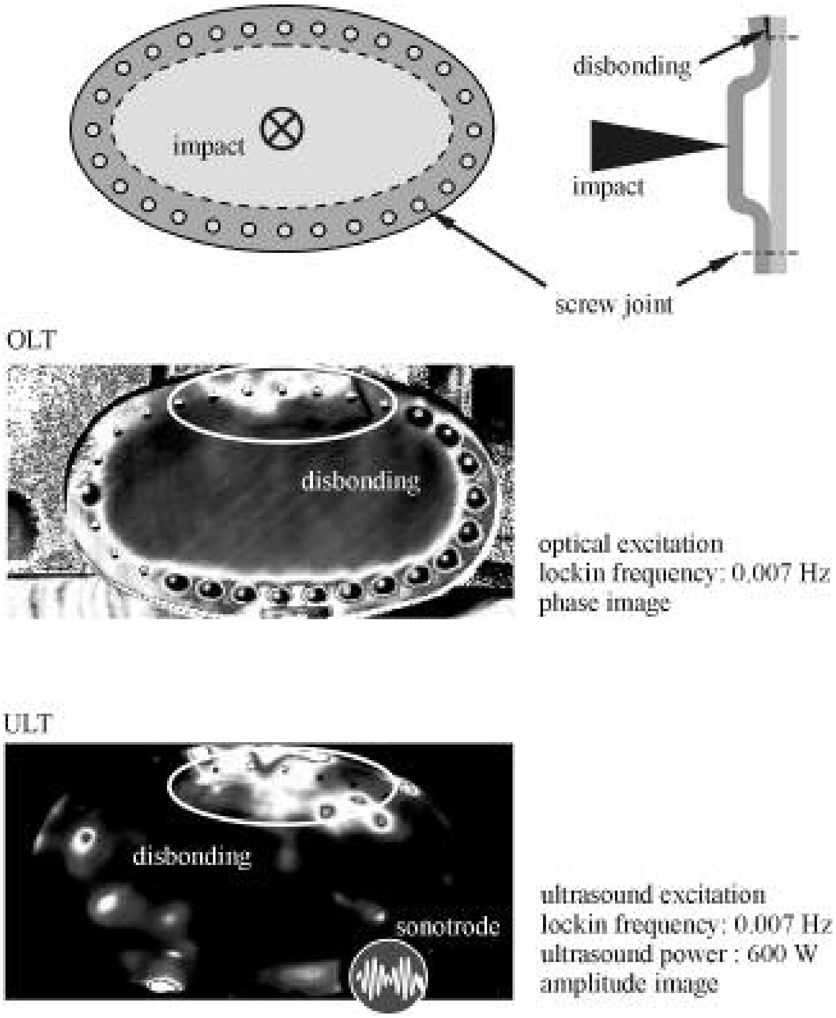
### 3.2 Access hole

The cover of a maintenance access hole (fig. 5) had an impact and the question was whether damage had been induced to the rivets around the impact. The result of OLT is consistent with the known structure, but not all screws look the same. The ULT image makes the damage visible which is not confined to the areas where it is expected from the OLT image. This is another example for the reliability of elastic wave stimulated thermography.

### 3.3 Carbon fiber reinforced silicon carbide

Re-entry vehicles undergo rapid temperature changes where the material needs to withstand high temperatures. The same requirement holds for the 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. The result are boundaries and potentially also cracks which is a source of trouble when the material is used. Such material had been inspected both with ULT and OLT (fig. 6). 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 the question is obvious 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).

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 (figure 7) under such conditions in a very fast and reliable way.



optical excitation
lockin frequency: 0.007 Hz
phase image

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

Figure 5: Access hole for aircraft maintenance.

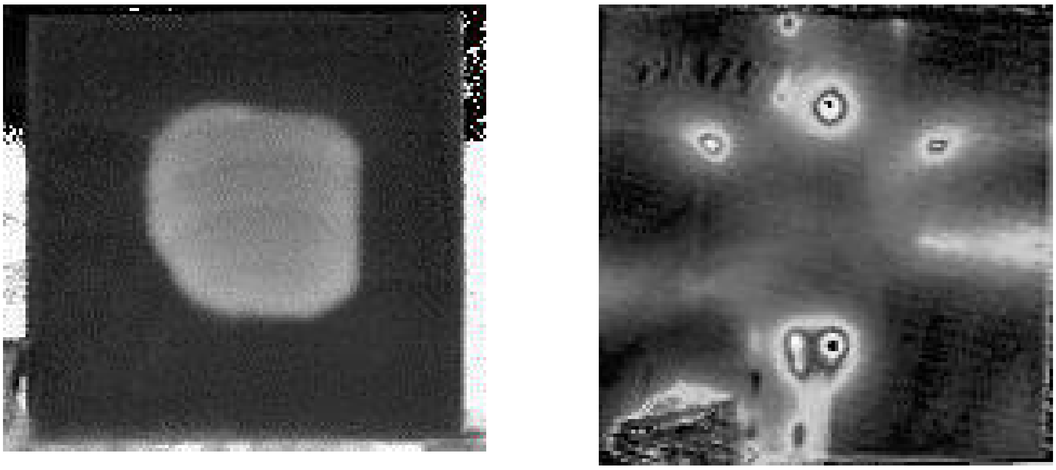


Figure 6: Phase images of a C/C-SiC sample at 0.03 Hz. OLT (left) and ULT (right).

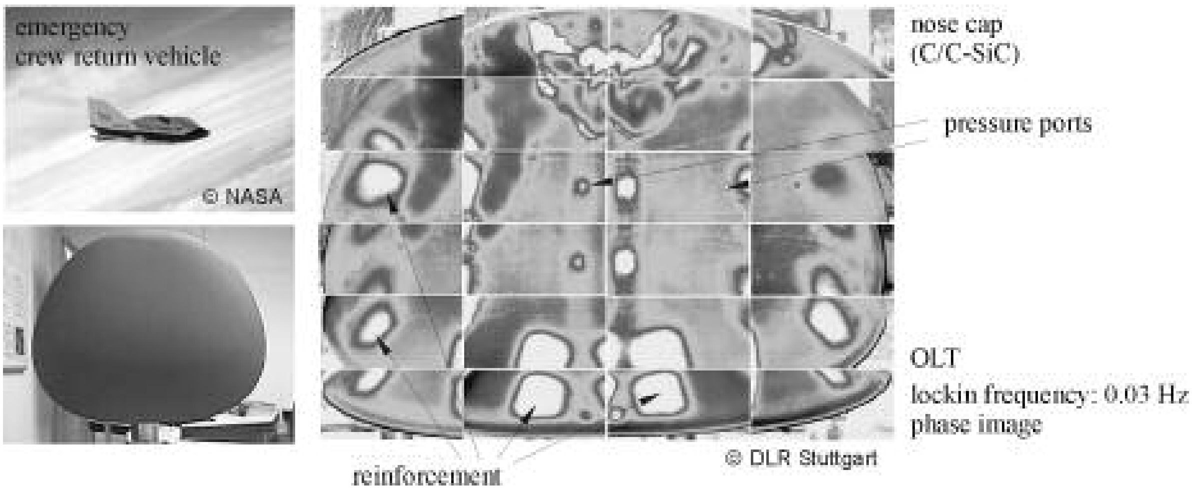


Figure 7: Phase image of a C/C-SiC nose cap of an emergency crew return vehicle.

## 4. CONCLUSION

We have shown how defect-selective imaging using ultrasound stimulated thermography (ULT) works. The method provides reliable results in a short time and displays only relevant features, as is indicated by the results obtained on safety-relevant aerospace structures. If one needs to know where these features are located with respect to the structure, one may use additionally the information provided by OLT performed using the same camera which is then synchronized to light modulation instead to sound modulation. Results obtained with phase angle images derived from burst excitation are highly promising since they provide additionally depth information in one shot while the signal to noise ratio is better than with pulsed techniques since many images are involved in data evaluation. The problem that still needs to be solved is acoustic coupling of high power ultrasound into the sample.

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