

Lockin-Thermography: Principles, NDE-applications, and trends

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Abstract

A review is given about Lockin-Thermography, about its photoacoustic and photothermal roots, about the principle and modern applications for nondestructive testing using different kinds of options.

1. What is Lockin-Thermography?

As Lockin-Thermography is based on thermal waves, a short excursion to this kind of waves and some remarks on the way they were used seems to be appropriate. Some indications about promising futural developments are provided as well.

1.1. Basics of thermal waves

When Fourier was involved in planning the water supply tubing for Paris, he was concerned with the problem how deep the tubes should be buried in the soil to prevent freezing in winter. So he dealt with the periodical temperature cycles on the surface and how deep they extend into the soil. He found out that the process is described by a linear differential equation whose solution is a highly attenuated wave where thermal diffusivity μ is the only parameter involved [1]. In order to solve the linear differential equation for non-sinusoidal boundary condition (daily and annual temperature cycle), he decomposed it into a sum of sine functions and superposed the solutions. Fourier became famous for developing the mathematical principle of solution which is broadly applicable.

His solution is the "thermal wave" that describes the deviation T of temperature from its local average,

$$T(x,t) = T_0 e^{-x/\mu} e^{i(\omega t - x/\mu)}$$

where the "thermal diffusion length" μ is defined as

$$\mu = \sqrt{\frac{2\lambda}{\omega\rho c}}$$

with thermal conductivity λ , density ρ , specific heat c , and angular modulation frequency ω . This dependence on depth and time displays the strong damping and also the phase shift with increasing depth.

Hence phase velocity is given by

$$v = \omega\mu \sim \sqrt{\omega}$$

Obviously higher frequencies propagate faster which means that thermal waves are dispersive. The consequence is that a temperature pulse starting from the surface changes its shape while it propagates into the material. As only sine waves maintain their shape, in the following we deal only with them while Vavilov's review at this conference reports on pulsed excitation.

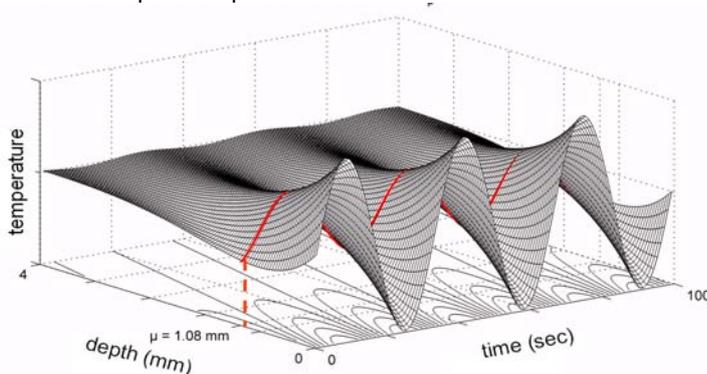


Fig. 1. Temporal and spatial behaviour of a one-dimensional thermal wave of 0.03 Hz propagating in Polyvinylchloride (PVC). From thermal diffusivity $\alpha = 0.0011 \text{ cm}^2/\text{s}$ results a phase velocity of $v_{Ph} = 0.2036 \text{ mm/s}$ at this frequency [2].

1.2. Photothermal radiometry

The basic principle of modern thermal wave applications is much the same as in 1863 when Angstrom applied it to measure the thermal diffusivity of a metal rod by launching a temperature modulation at one end and measuring the phase difference between two points located at different distances from the source [3].

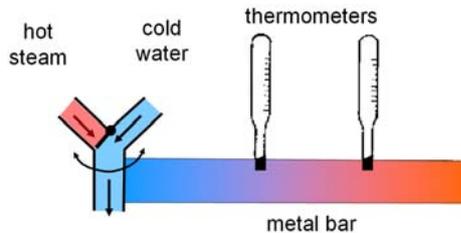


Fig. 2. Measurement of thermal wave phase velocity and therefrom thermal diffusivity: Angstrom switched a valve to generate a temperature modulation whose propagation was monitored at two locations with thermometers.

Interestingly, next time when thermal waves were involved they were not recognized: There were various efforts to describe the photoacoustic (also named optoacoustic) effect observed initially by Bell [4] where absorption of modulated radiation resulted in audible sound, but only much later experimental work and theoretical description in terms of thermal waves started [5-10]. The revival of thermal wave experiments used the absorption of modulated light provided by lamps, lasers, or other electromagnetic sources while detection was performed e.g. by microphones responding to the modulated air pressure, or by piezoelectric detectors where signal depended on the depth integral of the thermal wave.

Remote thermal wave generation and remote detection by evaluating the modulated infrared thermal radiation that is caused by the thermal wave induced temperature modulation (some people still think that thermal waves and thermal radiation are the same) has been used in 1979 [11]. This arrangement (figure 3) allowed for remote point detection of the thermal wave field and its defect induced changes even under vacuum conditions. Its principle is essential for understanding Lockin-Thermography since in both cases a small modulation of temperature needs to be detected in the presence of a much stronger background signal.

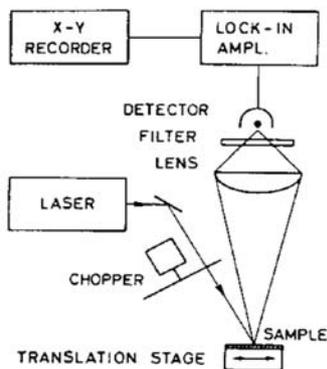


Fig. 3. Early photothermal detection of thermal waves [11]: The intensity of a laser beam is modulated so that it heats the sample periodically. The resulting surface temperature modulation is monitored via the modulation of thermal radiation going along with it, and this small effect is detected by an infrared detector whose noisy signal output is analysed by a lock-in amplifier that provides amplitude and phase of the local temperature modulation.

In this single ended arrangement (where thermal wave generation and detection are located on the same side of the sample) information on the inside of the object comes to the front surface only if the thermal wave propagating into the inside is backreflected to the surface where it is superposed to the initial wave thereby affecting both magnitude and phase of it by interference. Hence a defect is detected by thermal wave reflection at its thermal boundary. As thermal waves are highly attenuated, interference effects can be observed at the surface only if the defect to be found is close enough to it: it turns out that depth range for defect detection is about thermal diffusion length if signal magnitude is monitored and almost twice of this range if phase is used [12-15]. Therefore defects deep underneath the surface require low modulation frequencies.

Though photothermal radiometry was found to be easily applicable and highly sensitive for e.g. characterisation of hidden boundaries, coating inspection, and thickness measurements of wet paint, this technique turned out to be too slow for industrial applications when many data points are required, like in scanned raster imaging: the one-channel arrangement of figure 3 allowed only for sequential point-by-point measurements with a time duration at each point ("pixel") given by the required depth range. At a modulation frequency in the range of 1 Hz or less (that is required e.g. for structural inspection) an unacceptable duration of many hours might result.

On this background it was clear that the thermal wave measurement data should not be taken one after the other but parallel to each other, so that total inspection time would be the same as for just one pixel. In order to avoid that the number of pixels requires the same number of lockin analysators, we need to understand how they work.

1.3. What is a Lockin amplifier?

Like in most of the thermal wave setups used before (and in most other measurement techniques), the signal to noise ratio is the decisive quantity that determines how small a defect or any other feature can be to be still detectable. As thermal wave excitation is basically limited either by source power or by the sample, any further improvement of detectability can be achieved only by noise reduction. In the simplest case this can be done by averaging the results of repeated measurements where the noise goes down by the square root of repetitions. The repetition corresponds to an averaging time and this means essentially reduction of noise bandwidth (this argument is well known to people who are familiar with signal processing). The narrower the bandwidth, the less noise and the better the signal to noise ratio. So the detector output can just be fed into a narrowband amplifier. Unfortunately, a very small bandwidth may cause oscillations of the system, and this is the situation where the lockin principle is extremely helpful.

The experimental arrangement of “photothermal radiometry” (figure 3) and most photoacoustic applications included a lockin amplifier that related the modulated reference input (connected to the modulator) to its signal input. In the sixties of last century, the lockin-amplifier (also “Lockin analyser”) consisted of a mechanical relay operated by the reference voltage: the input signal was reversed periodically at the modulation frequency (at that time limited by the inertia of the relay) so that only the signal component at the modulation frequency was rectified. The output of this “phase sensitive rectifier” was integrated by an RC-circuitry providing the integration time constant which is proportional to inverse filter bandwidth. Modern lockin devices use basically the same principle. This way a weak signal could be extracted even if a much higher noise dominated the total output of the infrared detector so that the signal to noise ratio could be as bad as 10^{-5} at the Lockin input. In terms of signal processing, the activity of the lockin-amplifier corresponds to spectral filtering at the excitation frequency where the filter bandwidth is related to the time constant (or the averaging time) of the lockin amplifier. This way a very weak signal could be extracted from a noise up to a million times higher. Of course the background of this successful procedure is that the initially large bandwidth of noise contribution is reduced so that the signal to noise ratio is correspondingly improved by the square root of this bandwidth reduction. This is the key idea for the principle of Lockin-Thermography. In terms of modern data analysis, the lockin principle means simply Fourier analysis at the modulation frequency where again the reference is the computer generated modulation.

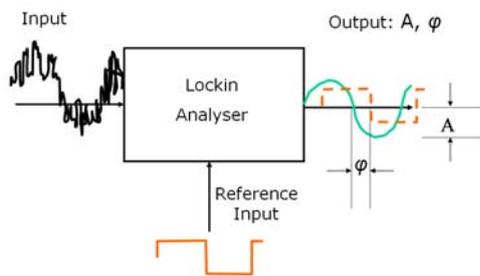


Fig. 4. Noise suppression in a periodical signal in an effect-modulated experiment: The lockin-amplifier reduces the noise by narrow band filtering of its input signal at the externally provided reference which is the modulation. The output provides magnitude and phase of the hidden sinusoidal component. Therefore the function of the lockin-amplifier corresponds to a Fourier transformation of the signal at the modulation frequency. In the drawing, the superposed noise shown in the input signal noise is not typical, in reality it could be higher by orders of magnitude.

1.4. Multichannel photothermal radiometry: Lockin-Thermography

The solution to this problem of time consuming sequential pointwise measurements was a multi-channel arrangement with an infrared camera whose detector array replaced the single detector element while a modulated powerful lamp generated the thermal wave not in just one point, but all over the surface (figure 5). As for the hardware lockin, it was clear that it needed to be replaced by the mathematical procedure applied to the time dependent signal at each pixel. Hence it has been suggested already in 1976 to record a stack of thermographic images while the inspected sample was periodically illuminated, and then to extract from this stack both local amplitude and phase of the modulated thermal response [16]. Since the lockin-principle is simulated at each pixel by digital Fourier transformation (DFT) though the hardware device itself is no longer needed, the term “lockin thermography” has become popular which is a coded description of a complicated procedure. The outcome is the compact information known from photoacoustics: One image displays local thermal wave phase, the other one amplitude. Such images have been generated as soon as powerful enough computers were available [17-19], and with progress of computer performance the complicated mathematics involved are done almost in real time. This way the information contained in a stack of several thousand thermographic images taken at video frequency while illumination goes on and off, is squeezed out so that just two images are obtained: One of local amplitude and one of phase. Fourier mathematics of the image stack finds the needle in the haystack since it removes the hay mathematically. The higher the stack of images, the narrower the noise filter and the better the signal to noise ratio. The phase image has the advantage of more depth and of being almost insensitive to optical surface features and inhomogeneous illumination, as had been found before [12,20].

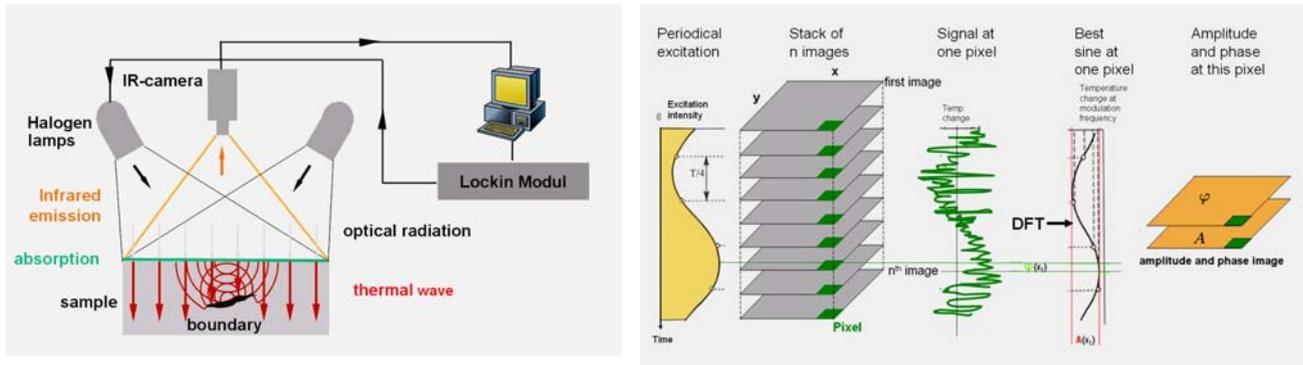


Fig. 5. Lockin-Thermography: Basic setup (left) and mathematical principle to derive amplitude A and phase image φ from thermographic image stack taken during one modulation cycle (right)

This way modern Lockin-Thermography has become a convenient tool for fast and remote non-destructive testing of hidden thermal boundaries. Examples for areas of application are inspection of:

- Layers (thickness and lack of adhesion), delaminations,
- impact damage,
- hardening and fatigue/deterioration,
- rivets and screws,
- bonding of plates and foils

2. Optically excited Lockin-Thermography (OLT)

The technique directly derived from photothermal radiometry is shown in figure 6 (left). Halogen lamps are efficient optical sources with an upper modulation frequency limit of about 1 Hz. Hence their use is best e.g. for structural inspection when depth probing in the mm range is needed like in many aerospace structures or in modern light weight vehicles.

In such structures the outer skin -often carbon fiber reinforced polymers (CFRP)- is reinforced at the rear surface by stringers to provide structural stiffness. Their function depends critically on their adhesion. Unlike metals, such materials do not generate bumps when they are locally overloaded. Hence it is essential to monitor from the outside stringer disbond caused by excessive load. In terms of thermal waves, we look for the change of boundaries and changes of thermal wave reflection like in the following example showing the setup in the lab where an aircraft CFRP-panel (figure 6) is inspected that had been damaged in a torsional test (sample kindly provided by P. Kaechele, Dornier).

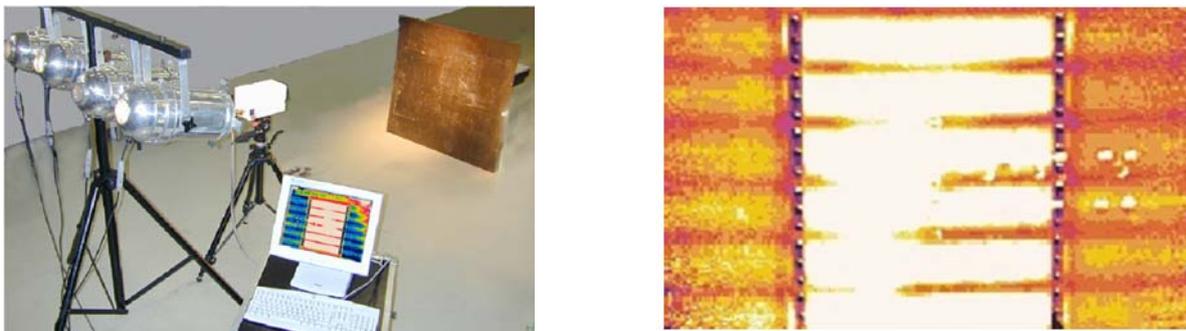


Fig. 6. OLT at work in the lab: Four powerful lamps illuminate the front surface of a 0.7m^2 CFRP plate with rear surface stringers that disbonded partially, as indicated by locally missing horizontal lines. Vertical rectangular areas at right and left edges are rear surface reinforcements for the bending test [21].

In figure 6, OLT results obtained on the CFRP-tailcone of a Do 328 aircraft are displayed together with the factory drawing of the same area. Structure of stringers and bulkheads is clearly seen, they are obviously in the whole component in good contact with the outer shell.

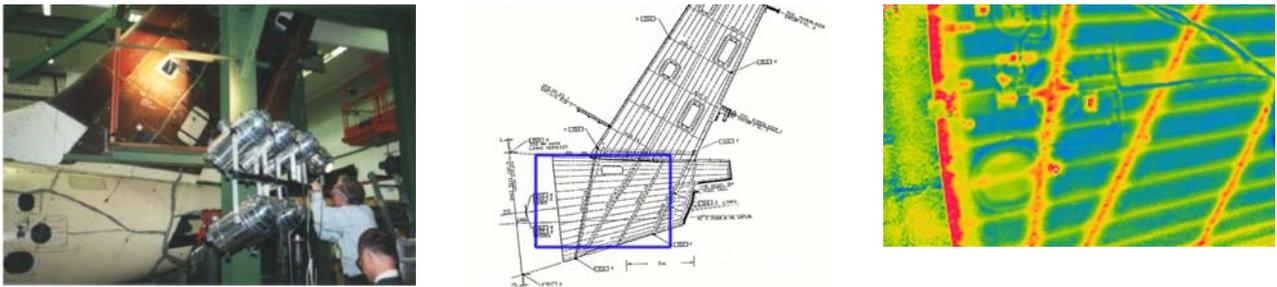


Fig. 7. OLT at work on an aircraft in the hangar (left): Examination of CFRP tailcone of Dornier Do 328. Factory drawing (middle) and phase angle image (right) [21].

As OLT is obviously sensitive to thermal contact, the method is well suited to examine how well screws or rivets are tightened like in figure 8 where maximum phase angle close to the screw is related to compressive force [22].

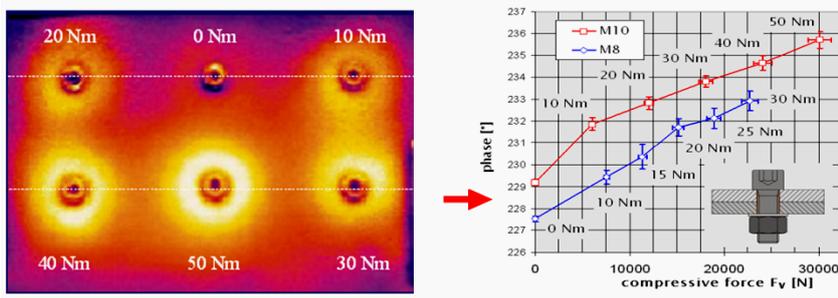


Fig. 8. OLT phase image of six screws (tightened at different torque levels) that press two metal plates together. Phase angle curves taken along the two dashed lines displayed maxima whose height depends on torque level [22].

3. Ultrasound excited Lockin-Thermography (ULT)

Thermal wave experiments always depend on heat deposition. Traditionally, absorption of electromagnetic radiation is being used for remote thermal wave generation. In that case the result is a thermal wave reflection image displaying all boundaries regardless of their quality. Hence the image is always a superposition of intact structural features and of those that are induced by defects. In fact they might look quite innocent and almost hidden so that interpretation is not straightforward. Therefore it is meaningful to use properties for imaging that are specific for defects, similarly to crack detection with a fluorescence liquid, but here defect selective thermal properties are required.

The most obvious property of a defect is its mechanical weakness, otherwise it would not be a defect. Weakness means that the stress/strain-diagram is locally changed so that the curve has a different shape or has hysteretical effects due to internal friction when loose boundaries in a crack move parallel and in contact with each other and generate heat. Such effects have been investigated initially by ultrasonic pulses and thermography [23,24] and later with modulated ultrasound as a source for Lockin-Thermography [25], a technique often called “Ultrasound Lockin-Thermography” (ULT). Strong ultrasound at typically 20 kHz is injected into the sample (figure 9) and generates heat at

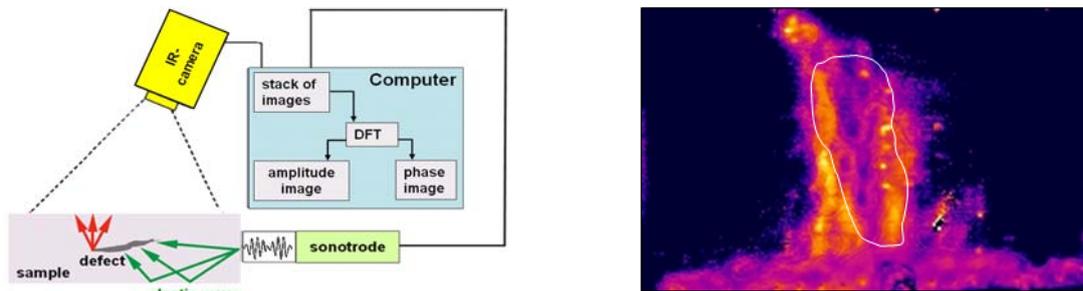


Fig. 9. Principle of ULT and image obtained on the same sample as in figure 6 [26].

frictional defects. Modulation of ultrasound amplitude causes modulation of defect induced heat generation thereby turning the defect into a thermal wave source whose emission is detected by the thermographic camera and subsequent image stack processing as described before. It is of interest to see that all intact features are suppressed like in dark-field microscopy and that modulated heat generation is strongest where stringers start to loose contact so that the product of compressive force and velocity of frictional rubbing of the crack has a maximum value. The bottom of the ULT image (figure 9, right) displays also a weak signal since the panel was standing and rubbing on the floor in the lab.

This observation that the vicinity of crack tips is most active in signal generation is confirmed by the result obtained on a fatigue crack in an aluminium aircraft component (figure 10) where the two bright spots indicate the ends of the crack. This is true for ductile materials while in ceramics the crack is an active thermal wave source along its whole length. This is an important difference for the interpretation of ULT images.

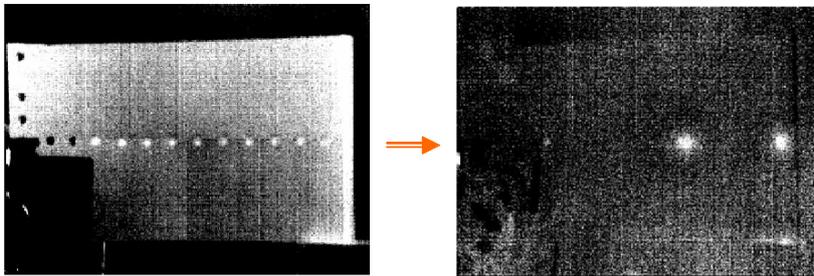


Fig. 10. ULT on the fatigue area between rivets of an aircraft component: One raw image of the image stack (left) showing the rivet row, and the phase image taken at 0.18 Hz (right) displaying the two crack tips where rubbing occurs. The crack area between the bright spots does not generate a signal since it is slightly opened.

In ULT of materials with low acoustic damping there might be local concentration of ultrasound intensity due to a standing wave pattern that dominates the result. As standing waves are resonance effects occurring only at certain frequencies, such patterns can be eliminated by frequency modulation of ultrasound in addition to the amplitude modulation used for the lockin technique [26]. An example is shown for a segment of a CFRP aircraft landing flap where a stringer had partially cracked (figure 11). The crack stands out clearly only in the right image, while it disappears in the OLT image due to the intact structure, and in the conventional ULT image due to the superposed standing wave pattern.



Fig. 11. Part of a CFRP landing flap of an aircraft: OLT phase angle at 0.03 Hz (left), ULT amplitude at 0.05 Hz and 20 kHz US frequency (middle) as compared to modulation of US frequency between 15 and 25 kHz to prevent standing waves (right) [26].

In addition to the lockin-technique requiring ultrasound modulation, additional research has been done on a pulse phase technique [27] which is essentially a long pulse whose frequency spectrum contains mostly the low frequencies needed for a large depth range. Therefore the image stack can be evaluated not only for one frequency, but for a whole spectrum with different depth ranges. Such investigations have also been successfully performed on longer acoustic pulses (“burst phase thermography”) [28].

In spite of the successes it should be mentioned that the bottleneck for ULT is the mechanical input coupling and the related concentration of load on the sample. This aspect confines presently the area that can be inspected around the ultrasound source. It is presently about DIN A 3 size which is much smaller than what is possible with OLT.

4. Recent work and emerging developments

The technique of generating thermal waves and of detecting them after they interacted with hidden thermal features is of course applicable to different kinds of excitation (besides light and ultrasound) and also to different kinds of detection.

As an example, submillimetre waves have been used in 1980 for photoacoustic imaging [29]. At that time the source was big and difficult to handle, also there was not much interest in the submillimetre spectral range which is now named the Terahertz regime attracting suddenly a lot of attention. It might be of interest to reconsider applications.

Another part of the electromagnetic spectrum is the eddy current regime that is of interest not only for Lockin-Thermography of metals, but also of CFRP [30]. The potential of modulated eddy current heating for Lockin-Thermography has not yet been fully explored, there are still many open questions [31].

There is a promising development on the detector side: Already in 1981 thermal waves have been monitored by the thermal expansion going along with them [32]. Meanwhile there are more sophisticated optical techniques that allow for rapid imaging of tiny displacements. As a good answer fits to more than just one question, the situation was reconsidered and investigated how well Lockin-Thermography can be replaced by lockin-interferometric imaging of thermal waves. So the idea is to monitor the thermal wave not by its modulated thermal infrared emission but by the thermal bump going up and down during this slow temperature modulation (in our experiments again typically below 1 Hz). This bump has contributions from inside the sample, so it contains the depth integral of the local thermal wave and not only its surface value. Hence depth range should be larger, just like with piezoelectric detection [33]. The difficulty to be overcome is that interferometric images (e.g. ESPI or Shearography) provide primarily a fringe pattern that is modulated by the thermal wave. This fringe pattern needs to be converted to height modulation (“demodulation”). This is done for each image of the interferometric stack of images, so there is a lot of mathematics to be done before one has

the same situation as in figure 5 where the same kind of stack mathematics is applied providing local amplitude and phase of height modulation. The contrast mechanism involved in this kind of imaging [34] contains also mechanical properties like stiffness which is the quantity of interest in the detection of defects. Part of the results [35] was as expected: Depth range of thermal wave Lockin-Interferometry (OLI) is about 50 % larger than with Lockin-Thermography at the same frequency. Surprisingly, it is also more sensitive to impact damage since it is less affected by thermal effects of the rovings in CFRP panels (figure 12). Therefore the 4J impact is much more clearly detected with OLI. This new thermal wave imaging technique does not require an expensive thermographic camera but a much cheaper optical array with more pixels. So it might compete successfully with OLT and -as it works also with ultrasonic excitation- with ULT. However, this article should not go into details since this conference deals with thermographic techniques.

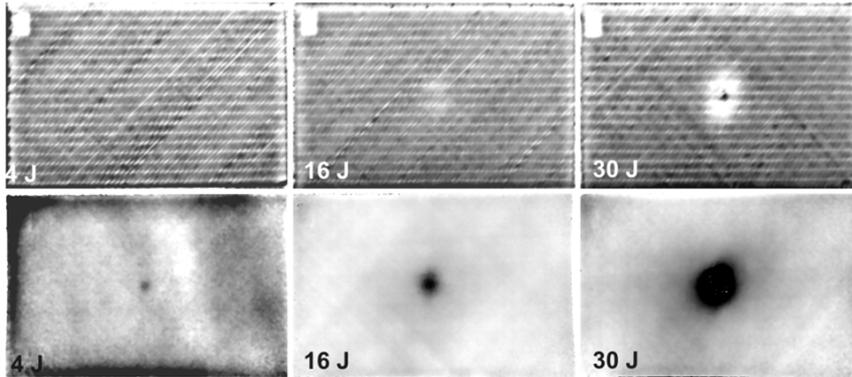


Fig. 12. Comparative imaging of impact damage in CFRP panels at 4J, 16J, and 30J. Top: OLT, bottom: OLI. Both are phase angle images taken at 0.1 Hz modulation frequency on the impact side of the plate. OLI was performed with the ESPI-Technique ("Electronic speckle pattern interferometry").

Another topic to be mentioned is automatical feature extraction by data fusion. The background is that visual defect detection in an image is sensitive to human interpretation and related unreliability. For safety relevant structures like in aerospace components, automatical inspection needs to be developed. Hence first steps have been performed to use such a technique for Lockin-Thermography data where two phase images are taken of the same sample area at different frequencies. For each pixel the obtained two data are plotted like coordinates in a map, so the two initial images result in a data cloud where certain sample features can be traced back to the sample. Spatial filtering of this cloud and back projection results in selectively highlighting certain sample properties [36].

The last topic is to improve resolution by spatially adapted optical illumination in order to reduce lateral heat flow. The idea is to install a feedback loop of imaging so that one image controls the illumination pattern on the sample for the next iteration step. The final result is a significant contrast enhancement and a better resolution [37].

5. Conclusion

Thermal wave imaging with different techniques is around since decades, but in the last years considerable progress has been made partly due to more sophisticated data analysis. So OLT and ULT have become important tools for fast and reliable NDE.

OLT uses lamps for optical thermal wave generation which confines modulation frequency so that application relevant modern lightweight structures can be inspected rather than thin layers where flash thermography might be the better option. The choice depends also on the thermal load to which the sample can be exposed during a high intensity pulse.

ULT is defect selective thereby allowing for a much easier interpretation of results and an enhanced probability of defect detection which is substantial for safety relevant structures. But presently the size of the inspection area is smaller than with optical excitation. However, the rapid development achieved in the last years together with ongoing developments is a good start for improvements in the near future.

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