From photothermal radiometry to lock-in thermography methods

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Abstract. This thermal wave conference dates back to 1979 when it was held for the first time in Ames/Iowa. All participants have this area still in mind, maybe not only due to the landscape but also to the cheerleader courses held parallel to our sessions on the same campus. So after 30 years time has come to review some thermal wave developments that started back in 1979 and to see how they affected other fields, e.g. NDE. This paper traces the origin of lock-in thermography back to the roots which is essentially to show how initially two different areas (thermal waves and thermography) merged partially together to become a powerful tool for modern NDE.

1. Thermal waves: Back to history
In 1822 Fourier dealt with the water supply system of Paris: The question was in which minimum depth the tubes should be put in order not to freeze in winter. On the other hand, without modern machinery it was important to avoid unnecessary depth. So he had to optimize carefully, and the result was the differential equation for heat and its depth dependent solution for daily and annual temperature modulation [1]. There he found that the solutions can be derived separately for each frequency and superposed. He became famous for the superposition named after him.

In 1863 Angstrom published a paper [2] where he described an experimental method to determine thermal diffusivity: He launched thermal waves into one side of a metal rod and monitored temperature oscillation at two locations with two thermometers (Fig.1). From the measured phase shift and the known distance he determined thermal diffusion length and theremofrom thermal diffusivity. This setup contains the main idea that we use still nowadays, only the equipment for periodical heating and thermal wave detection has become more sophisticated (and expensive).

The next step where thermal waves became important was G. Bell’s discovery of the photoacoustic effect in 1881 [3]. What he initially looked for was much different, but luckily his assistant Mr. Tainter made a mistake (forgot to close the switch) and realized its importance: Sound was emitted by the resistor when it absorbed modulated light (sunshine, not laser).
The setup in Fig.2 is what it could look like nowadays. After the photoacoustic effect had been found it was optimized and resulted in a simplified “photoacoustic” setup. Bell was convinced that this discovery was his best, and also Roentgen went into this field but stopped his work after he discovered “his” radiation. Unfortunately the effect was not at all understood in terms of thermal waves, and activities stopped after a few years.

Activities restarted much later due to Rosencwaig and Gersho’s theory [4] and Pao’s book [5]. Then imaging started where local signals were plotted during scans. Initially, samples had to be put into microphone cells and a modulated laser beam scanned across the sample surface. Unfortunately, sample size was limited by the size of the small microphone cell, and piezoelectric detection required mechanical coupling of the sample. On this background “photothermal radiometry” developed by Nordal and Kanstad in 1979 [6] was a major step forward for thermal wave imaging techniques since it was easily applicable to any kind of sample. The basic idea is that thermal infrared emission is modulated in a thermal wave, hence the signal of an infrared detector analysed at the modulation frequency of the light source extracts the thermal wave effect (Fig. 3).

The device doing this is the famous lock-in-amplifier which is essentially a narrow band filter whose frequency is fed in by a reference signal allowing also phase sensitive detection indicating finally the phase shift between optical excitation and infrared detector signal. At the same time it had been found that signal phase is better for thermal wave imaging (more range than amplitude, insensitive to surface absorption features) [7, 8]. The state of the art in thermal wave imaging in 1980 is described in Ash’s book [9].
2. Drawbacks of photothermal radiometry

Though photothermal imaging is well suited for all kinds of applications, its basic drawback became obvious when defects had to be imaged that were hidden deeper underneath the surface: As modulation frequency and depth range are linked to each other \([7,8]\), the low frequency required for deep defects needs some time for the thermal wave to propagate back and forth (thermal waves are highly dispersive).

Therefore the time required for imaging is proportional to the square of the required depth range. In a point-by-point raster mode one image may take hours even at poor resolution, like the one of a fingerprint (Fig. 4) deposited on the polymer substrate before it was covered by spraying paint on top of it [10].

![Figure 3](image3.png)

**Figure 3.** Photothermal radiometry [6]: Local remote measurement of thermal wave induced temperature modulation (amplitude and phase from lock-in amplifier). Image generated during point-by-point measurement one after each other.slow scan at low frequencies.

![Figure 4](image4.png)

**Figure 4.** Photothermal imaging of a fingerprint on polymer substrate underneath paint sprayed on afterwards [10].

The only way out is to measure at many (better all pixels) at the same time. The one element IR detector needs then to be replaced by an IR camera to monitor all sample points, a modulated lamp illuminates the whole surface, but one cannot use one lock-in amplifier per pixel (Fig. 5).
3. Solution: lock-in-thermography with optical excitation

The solution to this problem dates back to 1976 [11-14]. The operational function of the lock-in-amplifier can be simulated by Fourier transformation at the frequency of optical intensity modulation. This is achieved by continuously recording thermographic images while the illumination is modulated. This way a stack of images is obtained which is Fourier transformed at each pixel so that local amplitude and phase are obtained, an information extracting procedure that finally results in one amplitude image and one phase image with the advantages known from photothermal radiometry. Of course there is still the relation between depth range and thermal wave frequency, but the total measuring time for this “lock-in-thermography” (Fig. 6) is only the time required for one pixel in photothermal imaging. The evaluation process takes nowadays much less time than the measurement itself. Most of this thermal wave work escaped the attention of the ICPPP community since it is presented at thermography conferences, e.g. QIRT (“Quantitative Infrared Thermography”) being held since 1992.

One early example where a tail cone of an aircraft was inspected using optically excited lock-in-thermography (OLT) is shown in Fig. 7 [15]. Of course there are many more since meanwhile lock-in-

![Figure 5](image5.png)

**Figure 5.** Image generation with photothermal point-by-point imaging (left) and its spatially multiplexed version “lock-in-thermography” (right). [10].

![Figure 6](image6.png)

**Figure 6.** Setup for optically excited lock-in-thermography (OLT).
thermography systems are commercially available that are integrated in production lines and maintenance systems for industrial quality management purposes. Inspection time depends on required depth range (seconds to some minutes).

4. Other ways of thermal wave imaging based on the lock-in-principle

A good answer fits to more than just one question; therefore the potential of variations is of interest.

4.1. Variations of lock-in thermography

The way how heat is deposited may be varied, and one option is mechanical heating by using the hysteresis effect which converts elastic vibration into heat. As defects are an area of mechanical weakness, there are e.g. stress concentrations or cracks which cause excessive heat generation when the sample is coupled to a powerful ultrasound transducer [16]. If the power is modulated, the temperature of the defect is modulated as well so the defect is turned into a thermal wave transmitter. In this “ultrasound lock-in thermography” (ULT) dating back to 1992 [17, 18] defect-selective imaging is achieved where again the phase image is more robust and related to depth. It should be mentioned that depth range is not a basic limit like in thermal wave interference based phothermal radiometry [7] but limited only by noise. A comparative example for lock-in-thermography performed on the sample sample using optical or ultrasonic excitation is shown in Fig. 8. ULT shows selectively the areas of friction in defects (also friction between sample and floor at the bottom) while intact features are suppressed.

Figure 7. Example for inspection of an airplane: Phase angle image of tail cone made out of carbon fibre reinforced polymer (CFRP) [15]. Obviously bulkheads and stringers are well attached.
For metallic and other conductive materials like CFRP inductive heating is feasible [19] providing in the modulated operation thermal wave excitation and phase angle imaging. The method is applicable for imaging of stringer disbonds and of impact damage in CFRP [20]. The area to be covered using this method (“Induction lock-in thermography”, ILT) is confined to the size of large inductive coils.

4.2. Burst excitation

Another refinement to be mentioned is excitation by burst which is in between lock-in- and pulsed techniques [21]. Pulses with their short duration (typically some ms) have a frequency spectrum with a very small content in the low frequencies regime required for NDE at a large depth range. A burst with a duration of seconds has a low frequency spectrum allowing for analysis at various frequencies and thereby for depth profiling from just one measurement.

4.3. Lock-in principle applied to other ways of thermal wave imaging

While in all methods described till now thermal wave detection was based on modulated thermal infrared emission like initially in photothermal detection, it should be mentiones that thermal expansion going along with the thermal wave is also suited for imaging. The technique has been used in 1981 for scanned imaging [22] and has been extended by transferring the lock-in-principle from thermography to interferometric imaging [23]. An example is based on lock-in-shearography is presented in Fig.7.

5. Conclusion

In the last three decades, imaging based on thermal waves and their interaction with defects has developed from an initially mainly basic research oriented topic dealing with thermal wave interference effects in samples to its robust industrial applicability. Luckily there were two other other developments at the same time that made this progress possible. One is the development going on in infrared thermography starting with low sensitivity and slow devices to the present focal plane arrays with their many pixels and sensitivities in the range of some mK. The second field is computers that can deal with stacks of 3000 images (each with several MB pixels in it) in such a short time that the user of the equipment is almost unaware of the many operations (e.g. Fourier transformation at each pixel, phase calculation, image setup) going on behind the screen.

What will a review deal with in another three decades? Everything just faster and cheaper? Physics sets a clear final speed limit based on the relation between depth range and thermal wave frequency which is a limit given by the speed of diffusive thermal waves that is known to be low. Computers will certainly become more powerful, but they are presently not the bottle neck.

One topic of increasing interest is data analysis in terms of defect characterisation in modern materials which are highly complicated. The broad spectrum will require the combination of various NDE methods and intelligent data fusion in order not only to image defects (which is the present stage) but also to decide rapidly about their relevance, e.g. whether your plane may take off today or better not.
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