OPTICALLY GENERATED THERMAL WAVES FOR NON-DESTRUCTIVE MATERIAL PROBING AND IMAGING

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Résumé - Le contrôle non destructif et la réalisation d'images à l'aide d'ondes thermiques engendrées optiquement se montrent particulièrement intéressants. On montrera des exemples de la méthode et quelques unes de ses applications.

Abstract - Material probing and imaging with optically generated thermal waves is of broad interest for non-destructive evaluation. Examples are presented for the method and some of its applications.

1. Introduction

This article is supposed to be tutorial. Therefore it cannot be a complete review of what has been done and of what is going on. The conference papers are better and more representative samples to show the state of the art. The intention of the article is to indicate some of the basic ideas.

Nowadays we are quite well aware of the fact that many different topics dealt with at this conference have one feature in common: it is all thermal waves that are generated by absorption of modulated photon or particle beams and detected by various techniques thereby resulting in different names. What can these waves be used for? One broad field - historically the first - is spectroscopy where one observes what happens to the detector signal as the energy of the photons (or the light wavelength) changes. Another one that attracts more and more attention is material inspection where one is interested to see how the thermal wave detector signal can be used to monitor material properties as a function of process parameters (e.g. temperature, time ...) or of sample coordinates.

The idea to use thermal waves for material probing is not new. In fact more than a century ago Ångström designed the setup drawn schematically in Fig.1. By switching back and forth between hot steam and cold water he generated a thermal wave: "Periodical changes of temperature (are) transmitted across the bar ... Maxima and minima occur later with greater distance from the points of heating" /1/. From the phase difference measured with two thermometers a certain distance apart he determined the thermal diffusivity of solids.

Therefore it seems that the essential advantage of a dynamical measurement and the significance of phase have been understood very early, also the importance of thermal wave analysis for material characterization - before the optoacoustic effect was found in 1881 /2/. Then it took nearly a century to understand that the optoacoustic effect can only be interpreted in terms of thermal waves /3/. Now we have the question whether optical generation of thermal waves is enough reason to start work in material inspection again.

Fig.1:
Early thermal
wave experiment
(1863, /1/)

Indeed, there are some good arguments. First of all, optical remote energy deposition removes all problems of mechanical thermal contact. The laser provides an excellent thermal wave source with variable geometry (including a point source) and a large range of modulation frequency. Also thermal wave detection sensitivity has improved to 10^{-5} K/Hz^{1/2} or better even in remote detection. And one more argument is that modern materials present questions we did not know before.

2. Non-scanning material inspection

In some applications one is not interested in spatially resolved measurements. All one wants to see is whether thermal waves can be used to characterize a certain material or a process. The experimental procedure is then rather simple: a thermal wave is generated at a known phase and frequency. It is analyzed (with a microphone or a more modern detection method) after it has propagated through the sample or after it is reflected to the front surface, therefrom one can monitor geometry or thermal properties. The principle is similar to what Ångström did. Examples are listed briefly, details are found in the references.

An early application of optically generated waves for material inspection was thickness measurement of polymer coatings on metal by observing how the phase angle changes as a function of modulation frequency /4/. It is now possible to measure the thickness of a 50 μ m coating on 0.5 mm metal with a resolution of 0.5 μ m without touching the sample /5/. Also it is of interest for industrial applications to monitor materials during or after processing. An example is metal adhesive the curing of which is observed in a remote and non-destructive way using photothermal detection /5/. Other examples are hardening of steel/6/, imbedded glass fibres in polymers /5/, and molecular and

fibre orientation effects in polymers /5,7/. Though nothing is known presently about thermal wave in-line quality control in manufacturing processes, the results indicate that this kind of inspection is possible and useful.

3. Scanned material inspection

In these applications one is interested to correlate local changes of the thermal wave signal with known structures. The idea is to use later on the observed signal for characterization of unknown structures.

Magnitude or phase of signal is monitored as a function of coordinate. It does not make much difference whether one scans along one coordinate only or in a raster fashion across a certain area. In the latter case one makes a map of the locally obtained signal and calls it an image. The basic arrangement is shown in Fig. 2. Localisation of

Fig.2: Block diagram.
Beam scan and sample
scan used alternatively

the process is achieved by focusing the light beam in such a way that one has essentially a thermal wave point source (the historical reason is that imaging started when only microphone or piezoelectric detection was used where thermal wave integrals are obtained. With spatially resolved photothermal detection methods one could also use an extended source). As only the relative motion of the optical beam with respect to the sample is relevant, beam scan and sample scan are both possible. Beam scan is easier and faster, also it can be modulated for local derivative measurements /8/. Sample scan, however, is necessary when the orientation of the detector with respect to the source is important to avoid image distortion. That is the situation for piezoelectric detection and a scan field that is not much smaller than the detector area /9/, and for localized detection. The scan electronics provide the information on the x, y coordinates where the signal was obtained. They are combined with the output of the detector (microphone, piezoceramics, photothermal devices..) to give on an oscilloscope a perspective line drawing, a halftone image, or a combination of both.

These possibilities are illustrated in Fig. 3 as a matrix. The upper

Fig.3:
Half-tone images,
perspective line
drawings, and their
combinations.

row contains line drawings, the left column is the halftone image of the signal (top) or its derivative (bottom) obtained by electronic filtering. All images were generated from one single scan across an integrated circuit (about $300 \times 400 \mu\text{m}^2$) at 2.KHz modulation frequency and piezoelectric detection. The dashed line in Fig. 2 indicates a beam splitter that allows for optical inspection or an optical scanned reference image of reflected radiation. First photoacoustic scans were performed on ceramic material where surface cracks were detected and also evidence was found of subsurface structure /10/. As both optical absorption and thermal properties affect the signal /3/, an image obtained with optically generated thermal waves can show optical and thermal structures. The latter ones are those one is interested in. To eliminate effects of optical structure, scans were made across metal samples with a homogeneous surface and holes hidden underneath. These thermal structures were identified from the signal even after the holes had been refilled /11,12/. The obvious sensitivity to boundaries could be demonstrated on regions of deformation in metal /13/.

Next step after structure detection is interpretation. First of all one has to separate thermal from superposed optical structures. It could be shown that images obtained by mapping the signal phase are independent of optical surface structure /14/. Also it is possible to obtain

three-dimensional information: as range is correlated to thermal diffusion length, depth profiling of subsurface structures can be performed by imaging at different modulation frequencies /9/.

Besides depth range another point of interest is resolution. It has been demonstrated that not only the focus size of the laser beam is important, but also thermal diffusion length. Therefore thermal wave microscopy requires modulation frequencies that are beyond the range of microphones in the case of metals and semiconductors /14,15/.

Various methods of image processing have been suggested, e.g. electronic filtering and local beam modulation /8,16/. Also Fourier transform methods were applied to thermal wave imaging by Wong /17/.

Imaging described till now was performed with microphone or piezoceramic detection. This simple and powerful opto-(or photo-)acoustic technique has the disadvantage of requiring physical contact with the sample. However, if one does not insist in acoustic detection there are methods that in principle do about the same job without touching the sample. These methods will be mentioned briefly now.

Photo-displacement imaging is based on modulated thermal expansion: Optical heating induces expansion and buckling of the illuminated surface area. Remote optical detection of the periodical displacement is performed using a laser beam interferometer. Imaging with this technique has been demonstrated /18/. It should be noted that the same detection principle works also on a microscopic scale with current-induced thermal waves /19/.

The thermal wave at the sample surface is coupled to a thermal wave propagating into the gas near the sample thereby causing a modulation of the refraction index gradient and a deflection of a sensing laser beam /20/. This thermal wave laser probe technique has been used by several authors for imaging /21-24/.

A different approach to the detection of temperature oscillation in a thermal wave has been suggested by Nordal and Kanstad /25/ who also demonstrated imaging /26/. As this method is based on infrared thermal emission it tends to be mixed up with thermography which uses a similar detection. The important difference is that photothermal detection of a thermal wave is an active modulation method providing phase information and temperature amplitudes, while thermography as a passive analysis has nothing to do with thermal waves. However, in some applications it is useful to combine both techniques. Such a setup will be discussed in more detail now to clarify the basic ideas. Only detection of the transmitted thermal wave at the rear surface of an opaque solid will be considered /27/, but all conclusions are the same for front surface detection. The light wave (dashed line in Fig. 4) with

Fig.4:
Conversion
processes
involved in
photothermal
detection

the modulation frequency ω produces a thermal wave (solid line) the frequency of which is also ω . When the temperature modulation arrives at the rear surface it causes a modulation of infrared thermal radiation S (dotted line) emitted from the rear surface according to the Stefan-Boltzmann law:

$$\Delta S = 4 \cdot \epsilon \cdot \sigma \cdot \bar{T}^3 \cdot \Delta T$$

where ϵ is the infrared emission coefficient, $\sigma = 5.67 \cdot 10^{-8} \text{ W/K}^4 \text{ m}^2$, and $\bar{T}$ the mean value of temperature of the rear surface element. One must keep in mind that $\bar{T}$ is not room temperature but the static coordinate dependent temperature one would find if a non-modulated light source with the same average power and the same focus illuminated the sample. So $\bar{T}$ is the solution of a steady heat flow equation, while ΔT is the solution of the time dependent heat flow equation. In a thermographic experiment the total thermal emission

$$S = \epsilon \cdot \sigma \cdot \bar{T}^4$$

from a surface element is measured, thereby giving the static temperature distribution.

An experiment was performed where both techniques are combined (Fig. 5a):

Fig.5: Double modulation
for spatially resolved
observation of thermal
wave and temperature.

The light is modulated by M1 at the frequency ω_1 , the optical focus is a point source from which a thermal wave propagates to arrive at the rear surface where it is observed spatially resolved (spot size about 0.3 mm) by a focused infrared detector coupled to lockin 1. Its output gives magnitude and phase of ΔT . By shifting the detector along x (or by shifting the optical spot) one scans across the thermal wave and measures how ΔT changes with increasing distance from the point source /28/. If modulator M2 is inserted additionally and operated at a different frequency ω_2 , one observes the detector signal shown in Fig. 5b where the thermographic part is modulated at the carrier frequency ω_2 while the thermal wave signal is the weak amplitude modulation. So the infrared detector does two jobs at the same time while it uses the same optics to look at the same sample spot. The signal is fed into two lockins tuned to ω_1 and ω_2 , respectively, thereby giving the complex quantity ΔT and simultaneously mean temperature $\bar{T}$ in the same 0.3 mm spot.

As an application Fig. 6 shows magnitude ΔT and mean temperature T

Fig.6:

Profile of magnitude A of thermal wave ΔT compared to profile of mean temperature $\bar{T}$ in a spatially resolved scan with setup of Fig.5.

of a thermal wave observed at the rear surface of a 0.2 mm thick steel plate at 20 Hz and 1.6 W average laser power. The DC-part of temperature opposite to the source is 13K above room temperature while thermal wave magnitude is smaller by more than an order of magnitude. However, with increasing distance from the center, the decrease in ΔT is much steeper than in $\bar{T}$. The thermal wave signal is a well localised oscillation superposed to a broad and smoothly curved profile of mean

temperature. That is the reason why thermal wave scanning is so much better than thermography for subsurface structure observation. The technique of observing simultaneously the thermal wave and the temperature in it has been found very useful for photothermal inspection of polymers where significant temperature increase must be avoided. In these experiments remote temperature observation was made in the laser focus on the front surface /5/.

Phase and magnitude of the thermal wave in Fig.5 can be distorted by subsurface obstacles (e.g. holes) /28/, and from this wave front distortion it should be possible to reconstruct the object in a way similar to optical holography. Thereby one could solve in an elegant way the problem of thermal wave image interpretation in terms of defect geometry and its location within the sample. The present situation is at a lower level as will be discussed for thermal wave transmission imaging. Wave front deformation (both for magnitude and phase) is strongest when detector and source are opposite to each other with the obstacle in between. Therefore most imaging experiments with transmitted thermal waves have been performed by moving the sample in a raster fashion between stationary source and detector spots /27/. The essential result is that the magnitude part $A(x,y)$ contains structure of optical surface absorption and of rear surface infrared emissivity. Therefore features of an optical image and of a thermal image are superposed to the thermal wave image. The phase angle image, however, has the advantage of ignoring structures of optical surface absorption, infrared emission coefficients, and background of local average temperature. Thus only true thermal structures are shown. Also resolution is better than with the integral detection methods of opto-(or photo-) acoustics /28/. However, there is a disadvantage of this arrangement: depth information is lost, one obtains only the projection of internal structures like on a x-ray image /28/. A straightforward way around this problem has been published recently: With a point source and point detection one can use the stereoscopic effect /29/. Accuracy of depth localization is then better than 0.1 mm for a 0.4 mm diameter hole in a 2.2 mm thick aluminum sample.

4. Conclusion

From results published until now it seems that analysis with heavily damped thermal waves is a "near-surface method": front surface inspection is limited in depth to about twice the frequency dependent thermal diffusion length which means some mm for metal. Only this layer can be monitored, independent of how thick a sample is. Rear surface analysis of transmitted thermal waves can be performed if

a sample is not much thicker than this layer. The method has practical advantages, but 1 cm thickness is about the upper limit for metal inspection. Accuracy is better for thin samples which are difficult to analyze with ultrasonic methods. In these situations thermal waves should compete successfully with ultrasonic waves, especially when detection techniques are used that do not require physical contact with the sample.

Thermal wave imaging has been performed mostly on model samples (like holes drilled into metal) in order to test the methods. Results were also obtained on realistic samples like surface layers (coatings, hardened steel, integrated circuits...) or thin samples like foils or plates where one can determine the thickness, the effect of manufacturing process, or the quality of welding.

The experimental equipment needed is not simple or cheap, especially for the remote methods. It is not at all sure whether one day we will have a small black box that makes a thermal wave image of a sample.

But the various experimental arrangements we have now in the laboratories are a real challenge since they provide us with answers to questions most of which we do not yet know.

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