

Displacement detection techniques

for thermal wave

non-destructive testing

Techniques de détection d'ondes thermiques par déplacements de surface

pour tests non destructifs



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Yves MARTIN poursuit ses études en vue d'un doctorat en instrumentation physique et optique. Ses travaux concernent la microscopie par photo-déplacements, et font appel à des ondes thermiques et des interféromètres à rayon laser pour la mesure de micro-déplacement.



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SUMMARY

The use of thermal waves for non-destructive testing is developing rapidly. The means used for detecting the thermal waves include acoustic transducers, infrared radiation sensors, and laser detection of the surface heated gas—the mirage technique. A further alternative, which has proven to have an unsurpassed sensitivity, is the use of a laser interferometer, to detect the surface movement of the object—the displacement detection technique—the main theme of this paper.

The most frequently used source of thermal waves is a modulated laser beam. The configuration which we have adopted for this “photo-displacement” technique is a GaAs semiconductor modulator laser to perform the heating function, and a HeNe Bragg-cell interferometer for detection. The attainable resolution obtained with this method is enhanced by the circumstance that both the heating and the detector laser beams can be focused to a diffraction-limited spot. We will show that the detection of even closed surface-breaking cracks can be optimized by arranging for a small displacement, of a few microns, between these two spots. Results on a subsurface defect and on surface breaking-cracks are presented.

Another technique is introduced—Joule displacement—where thermal waves are generated by resistive heating.

KEY WORDS

Interferometer, thermal wave, non-destructive testing.

RÉSUMÉ

L'utilisation d'ondes thermiques est de plus en plus répandue dans les tests non destructifs de matériaux. Parmi les méthodes de détection des ondes thermiques, on peut citer des transducteurs acoustiques, des capteurs sensibles aux rayons infrarouges, et la technique utilisant l'effet mirage. Une autre méthode, décrite dans ce rapport et dont la sensibilité s'est révélée excellente, consiste en la détection du mouvement de la surface de l'objet testé par l'intermédiaire d'un interféromètre à rayon laser : la technique de détection de déplacements.

La source d'ondes thermiques la plus fréquemment utilisée est un faisceau laser modulé. La configuration que nous avons adoptée dans cette technique de « photodéplacement » comprend, comme source de chauffage, un laser à semi-conducteur AsGa modulé, et pour la détection, un interféromètre hétérodyne utilisant un laser HèNé. L'utilisation de deux faisceaux laser focalisés à l'échelle du micron permet d'atteindre une excellente résolution spatiale. Nous montrerons que la détection de fêlures de surface peut-être optimisée en séparant les deux faisceaux focalisés de quelques microns. Des résultats concernant des défauts sous-jacents et de surface seront présentés.

Une autre technique sera introduite — la technique de déplacement Joule — dans laquelle les ondes thermiques sont générées par dissipation d'énergie électrique.

MOTS CLÉS

Interféromètre, onde thermique, tests non destructifs.

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2. Subsurface hole detection

The first approach considered in our work is based on the photo-displacement technique previously described [3, 4]. A focused modulated semiconductor laser generates thermal waves on the surface of a solid; a focused laser interferometric probe measures the periodic surface displacement resulting from the thermal expansion. A near-surface discontinuity such as a subsurface hole modifies the propagation of a thermal wave, an effect which is observed through the resulting change in surface displacement. Figure 1 shows the photo-displacement signal recorded when

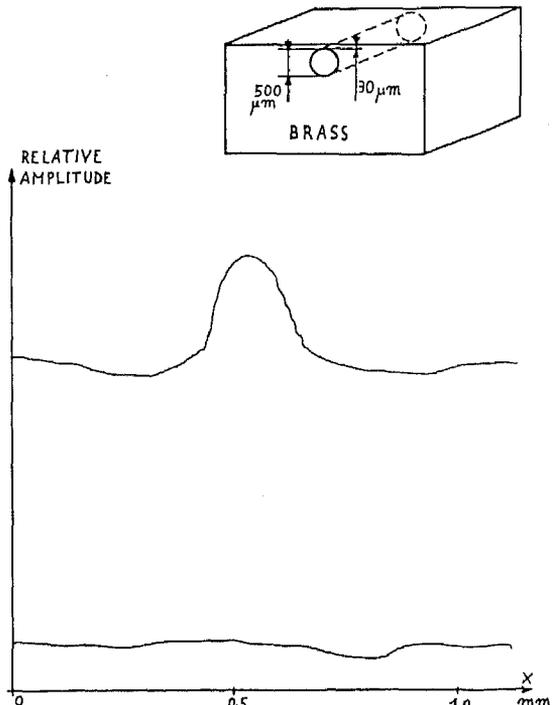


Fig. 1. — Photo-displacement scan over a hole in a brass block.

1. Introduction

The scattering of ultrasonic waves has been applied to the characterisation of materials and to the detection of defects. Recently, thermal waves found a renewed interest for the non-destructive examination of surface [1] and near-surface regions [2] of opaque materials. The wavelength of thermal waves measured in millimeters is typically of the order of $f^{-1/2}$, where f is the frequency in Hertz. At a few kilohertz the wavelength is of the order of ten microns — allowing microscopic examinations. The thermal waves are rapidly attenuated, which is at the same time a limitation, but with the peripheral advantage that multireflection effects are minimized.

the two laser beams are concentric and scanned simultaneously over a block of brass containing a hole. The bottom trace is the record when the semiconductor laser was switched off. The spot sizes of the heating and probing lasers were estimated to 8 and 5 μm respectively. The average heating power incident on the object surface was around 2.5 mW, which gave rise of an AC surface displacement of the order of 0.1 \AA at the thermal frequency of 10 kHz. The sensitivity of the probe is better than 10^{-3} \AA ; it provided a signal/noise ratio larger than 20 dB in 1 Hz bandwidth. It is seen that the hole is clearly imaged.

2.1. A ONE-DIMENSIONAL INVESTIGATION

A first attempt to explain the experimental diagram involves a simple one-dimension theory [5]. The hole would be described as a serie of slices of varying thickness, as shown in Figure 2. Each slice could then

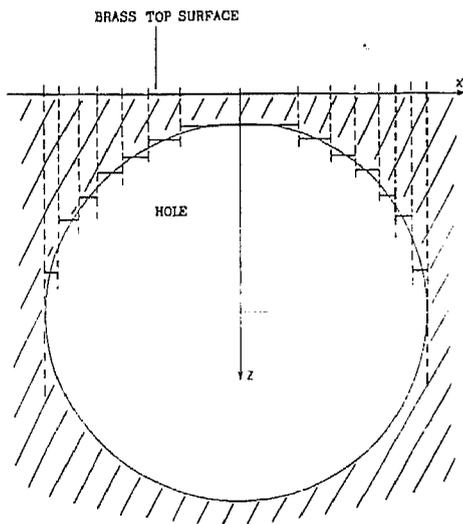


Fig. 2. — Decomposition of the sub-surface hole in slabs of varying thicknesses, to be described by a one-dimension theory.

be treated as a one dimensional problem of an infinite slice of thickness l , uniformly heated over its top surface.

The temperature T at the depth z is given from the diffusion equation:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\beta} \frac{\partial T}{\partial z} = 0,$$

where β is the thermal diffusivity.

The solution contains two terms, being the propagation along $\pm z$:

$$(3.4) \quad T = (U e^{\sigma z} + V e^{-\sigma z}) e^{j\omega t},$$

where $\sigma \equiv (l + j)/\mu$, $\mu \equiv [2\beta/\omega]^{1/2}$. μ is the thermal diffusion length and U and V are complex constants.

The boundary conditions are the energy flux $p_0 e^{j\omega t}$ at $x=0$, and zero at $x=l$, which determines the values

of U and V :

$$U = \frac{P}{k\sigma(e^{2\sigma l} - 1)}, \quad V = \frac{P}{k\sigma(1 - e^{-2\sigma l})},$$

where k is the thermal conductivity.

The surface displacement results exclusively from the quasistatic bulk expansion. One finds it by multiplying the temperature by the expansion coefficient α , integrating over the thickness l , and extracting the real part of the complex result:

$$d = \text{Re} \left[\alpha \int_0^l T dz \right] = \frac{\alpha\beta P_0}{k\omega} \cos(\omega t - \pi/2).$$

We find the surprising result that the thermo-displacement remains constant for all value of the thickness l ; neither the amplitude nor the phase of d depend on l . This result can be understood in the following way: for a thin sheet, the smaller expansion due to a smaller thickness is compensated by the larger temperature amplitude in the medium.

This calculation is based on the assumption of a static lower surface—as if it were backed by a rigid layer. For a sheet of thickness comparable to the thermal diffusion length, this assumption is valid. In the limiting case of a very thin sheet loosely suspended, the temperature will be uniformly distributed across the sheet. The expansion will have identical effects on both sides and the observed surface displacement will be reduced by a factor of two. But in any case, this model can not describe the experimental signal increase observed over the hole of the brass block.

2.2. THE SPHERICAL WAVE MODEL

Clearly, a multidimensional theory is necessary to explain the experimental results. Noting that the heating source is focused, we have calculated a solution for the thermal wave distribution in the solid by applying a three-dimension spherical wave model. The model is a modification of the point source function. It has been shown [6] that when the heating source is considered to be a point source in infinite or semi-infinite space, with harmonic variation and under steady state conditions, the temperature takes the form:

$$T(r, t) = \frac{A}{r} \exp(-\sigma r) \exp(j\omega t),$$

where r is the distance from the source to the observation point, and A a constant. The idealization of a point source gives a good account of the temperature distribution due to a highly focused laser beam, at some distance from the source. Yet, it predicts a temperature which increases without bound for progressively smaller values of r . We wish to retain the form for the solution, but remedy the non-physical behaviour for small values of r . To do so, we shall make two approximations in the immediate vicinity of the heat source:

- (i) Instead of a $1/r$ dependence, we impose a Gaussian dependence;
- (ii) We maintain the spherical symmetry.

Figure 3 shows the situation. For a radius $r < r_0$, where r_0 is a parameter to be determined, the temperature follows a Gaussian law. For $r > r_0$, the temperature distribution is taken as that for a point source. We determine the size of the Gaussian, its amplitude and the radius r_0 of the junction by applying three conditions:

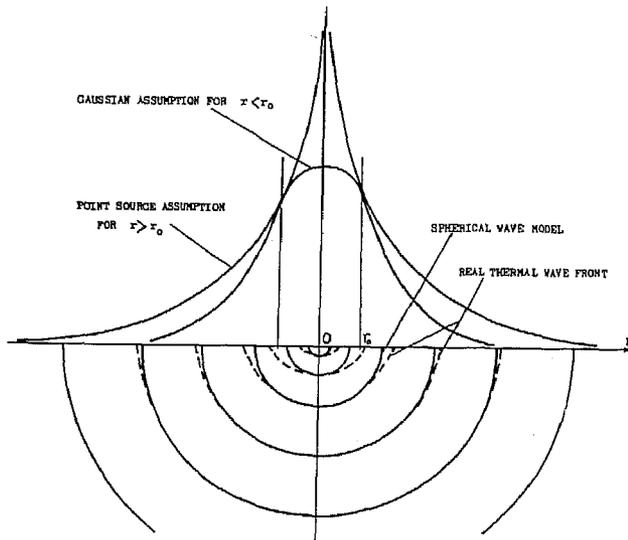


Fig. 3. — Model for the determination of a thermal wave generated by a focused laser.

- (a) The heating laser beam will in general have a Gaussian intensity distribution, given by $\exp-(r/a)^2$. We assume that the temperature distribution for $r=r_0$ is also a Gaussian, having the same waist radius, a .
- (b) At $r=r_0$, we match the point source distribution to the Gaussian distribution. The matching consists of equating both the temperatures and the radial derivatives of the temperature distributions.
- (c) We equate the total power flux across $r=r_0$, to the incident absorbed power, P_0 .

This model is of course highly intuitive. Yet, it does appear to grasp the main features of the problem. Perhaps its worst feature is that it underestimates the lateral spread of the temperature distribution. However for a highly focused heating beam, the model gives a good value of the thermal distribution outside the heating spot region.

We write the temperature equations in the two regions as:

For $r > r_0$:

$$(1) \quad T = \frac{A}{r} \exp[-\sigma r] \exp(j\omega t).$$

For $r < r_0$:

$$(2) \quad T = B \exp(-r^2/2a^2) \exp(-jr/\mu) \exp(j\omega t).$$

From the three conditions, we deduce r_0 , A , and B , when $a < \mu$:

$$r_0 = a, \quad A = \frac{P_0 \exp[\sigma a]}{2\pi k(1 + \sigma a)},$$

$$B = \frac{P_0 \exp(1/2) + j(a/\mu)}{2\pi ka(1 + \sigma a)}.$$

This model is applied to determine the incident and reflected thermal wave from the subsurface hole. Many reflections of the thermal wave occur between the hole and the top surface. However, they become rapidly negligible because of the highly damped nature of the thermal wave, and only the two first

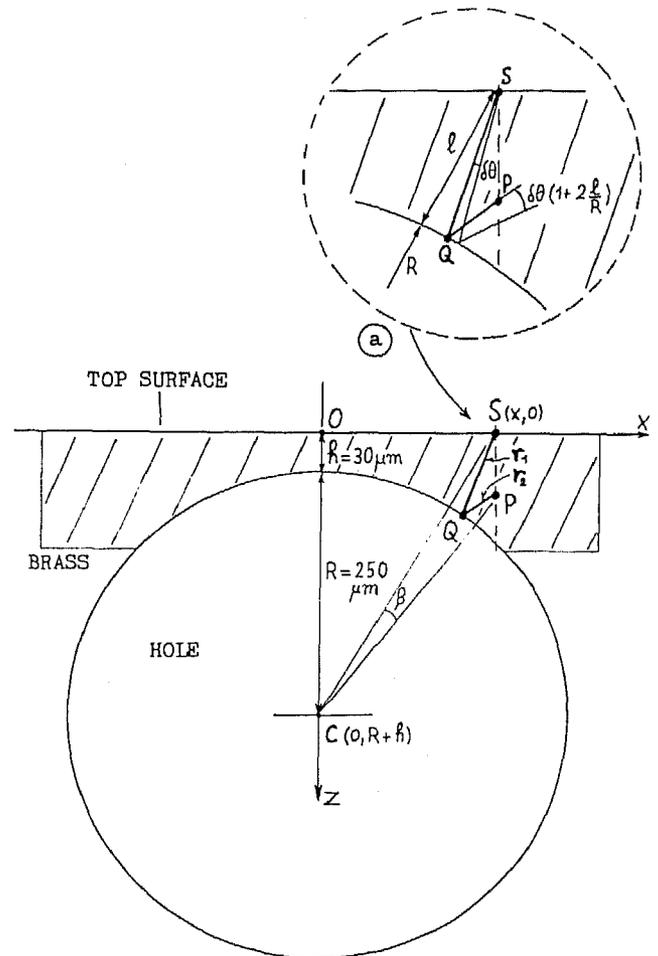


Fig. 4. — Determination of the first reflected thermal wave.

reflections are considered. The Fermat principle of the minimum path length r_m is used to calculate the reflected wave fronts. This calculation neglects the diffraction effects which are weak in the region investigated (dashed on Figure 4), since the size of the subsurface hole is much larger than the thermal diffusion length. The path length r_m from S to P on Figure 4 where $r_m = r_1 + r_2$, is computed as a function of R , h , x and z , and is inserted in equation (1) or (2) to find the temperature. However, one must take

account of the spreading effect of the hole (fig. 4 a). For the approximation $\beta \ll 1$, the incident energy in an angle $\delta\theta$ is reflected into the angle $\delta\theta (1+2l/R)$; thus, to ensure conservation of energy, one has to correct the temperature by a factor $(1+2(lr_2/Rr_m))^{-1}$.

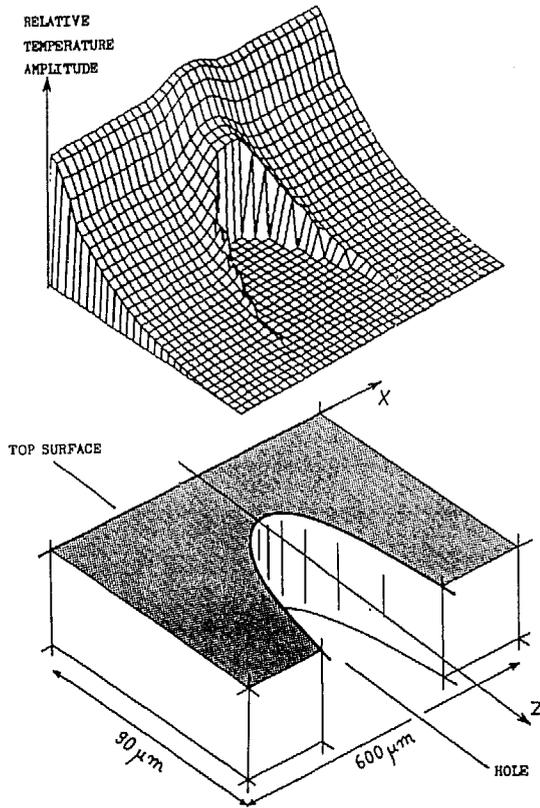


Fig. 5. — Computed temperature amplitude in the brass block, in the area near the subsurface hole (the Z-axis is expanded).

For each position of the heating laser S, one determines the temperature at all the points P on the vertical line under S. Figure 5 shows the diagram of the computed temperature amplitude at each point P, when the source is scanned over the hole. The scale over the Z axis is expanded. We notice the increase of the temperature amplitude on the top of the hole and on its sides due to the thermal wave reflection.

In section 2.1, we effected a simple integration of the complex temperature over the z direction, multiplied by the expansion coefficient α , in order to find the surface displacement. Such an integration in the present situation yields again the result of a constant surface displacement across the surface: the two-dimensional interaction of the temperature with the hole cannot alone describe the experimental results. The rigorous calculation of the surface displacement should involve solving the Navier-Stokes equation, subject to the condition that there is no normal component to the stress at the boundaries of the slab:

$$(1 - 2\nu) \nabla_u^2 + \nabla(\nabla \cdot u) = 2(1 + \nu) \alpha \nabla T,$$

where u, v, T are the displacement vector, the Poisson ratio, and the temperature change from equilibrium value, respectively. This equation takes account of the elastic constraints which are responsible for the measured displacement.

We shall deduce an approximation to the surface displacement from the temperature distribution of the diagram 5 by applying a more intuitive idea: the contribution to the surface displacement of a heated region decreases with its depth under the surface. This observation lead us to modify the simple z-axis integration previously mentioned. We shall weight the contribution of a heated region at abscissa z by a decreasing function F of the form:

$$F = (1 + z/a)^{-1},$$

with a being a constant. By optimizing the value of the constant a, we obtain the computed displacement of Figure 6: we observe a distribution similar to that

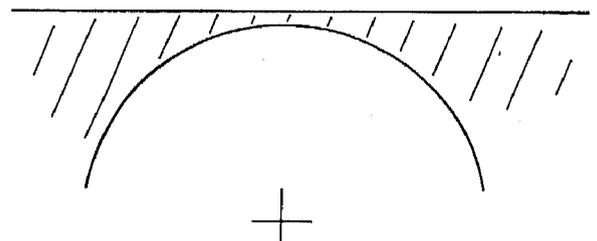
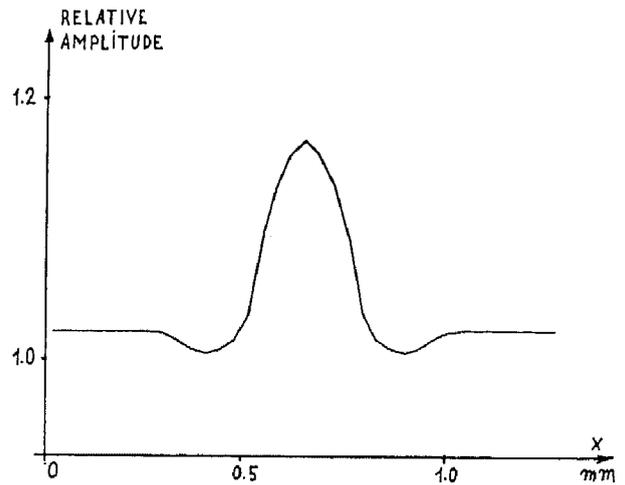


Fig. 6. — Computed photo-displacement scan over the hole.

observed experimentally. The corresponding value of the constant a is 5 micrometers: the function F decreases by a factor two within the thermal diffusion length, which is satisfying physically. Further investigation would include a more precise determination of the function F. This approximated method could then be applied to evaluate the surface displacement signal produced by more general subsurface defects, when the temperature distribution is calculated.

3. Imaging of Micro-cracks

In the photo-displacement technique, both the thermal wave generator and the laser probe detector use tightly focused laser beams; both are able to operate on a microscopic scale. The laser probe spot can coincide with that of the heating laser beam. It can, however, also be displaced from it, and this turns out to offer an increased detection sensitivity. Figure 7 shows how this idea is implemented. The object is scanned under the two beams, which are

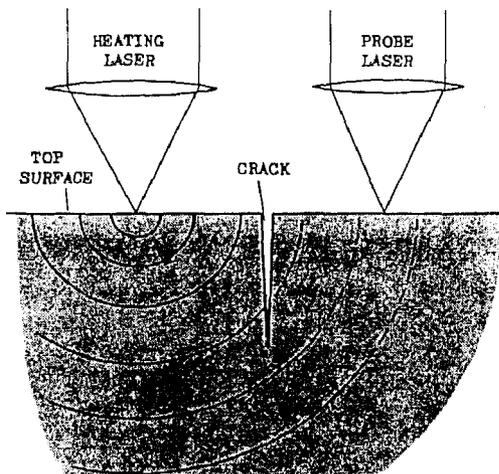


Fig. 7. — Detection of a vertical crack by photo-displacement.

kept stationary. When the crack passes between the two beams, the laser probe records a significant signal change. In our experiment, both SC laser and probe beams are focused onto the surface by means of the same lens. A slight angle between the beams before entering the lens leads to two spots, at different positions on the focal plan. It is thereby possible accurately to control the spot separation from zero to 50 μm .

3.1. EXPERIMENTAL RESULTS

We explored the capability of the system using glass samples with closed cracks. The cracks were simply obtained by an impact technique. From optical observations, it appears that the width between the two sides of the crack is well below one micron. We covered the top surface of the glass with a Cr layer of 300 \AA , which is sufficient to eliminate any optical contrast. Figure 8 shows the block of glass containing a vertical crack and a typical image formed by the photo-displacement signal, when the SC laser and the probe beam are separated by 20 μm in a direction perpendicular to the direction of the crack at the glass surface («configuration 1»). We observe:

(i) A large amplitude decrease when the crack is located between the two spots; this can reach 90% of the initial signal. It shows that the transmission coefficient for the thermal wave through the crack is small ($<10\%$).

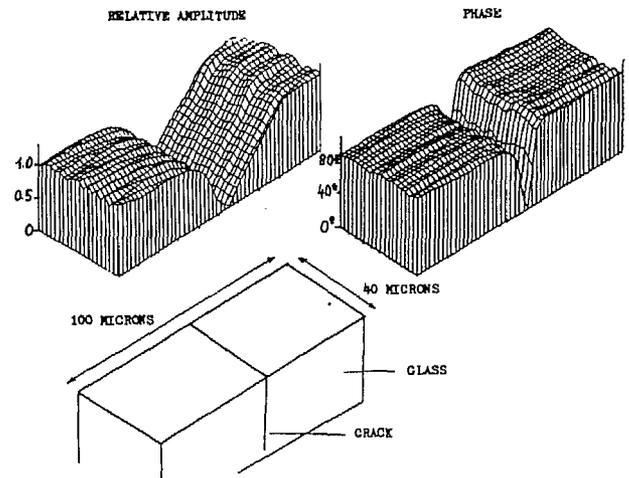


Fig. 8. — Photo-displacement imaging of a closed crack in glass.

(ii) A sharp phase change, precisely when the probe is positioned over the crack. This can be used accurately to locate the crack.

A "configuration 2" was investigated, where the direction defined by the two spots is parallel to the crack. Here, part of the thermal wave will be reflected from the crack and affect the detected signal. The crack is scanned under the two beams which are kept stationary. Similar amplitude and phase decreases are observed as in "configuration 1", but with magnitudes which are generally smaller.

3.2. THEORY

In order to explain these results, we applied the spherical wave model to determine the reflected and transmitted waves from the crack. These waves are spherical waves when the crack is assumed vertical, of infinite depth, and of negligible width. The displacement was found from the one-dimension approximation, by integrating the vertical temperature distribution. Figure 9 displays the computed amplitude and

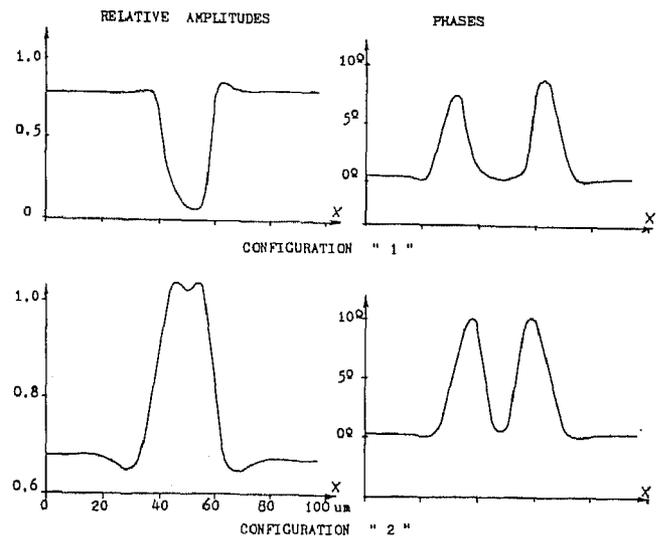


Fig. 9. — Theoretical distribution of the photo-displacement signal over a crack, assuming a one-dimensional expansion effect.

phase, corresponding to the two experimental situations, where we have taken the thermal transmission and reflection coefficients to be respectively 10 and 90%.

4. Discussion

The only agreement between the computed and experimental results concerns the amplitude signal in "configuration 1". Both results reveal the amplitude decreases when the crack is between the heating and probe spots. The other three theoretical results show a dramatic discrepancy with the experimental results — which requires explanation.

Whilst the theory is approximate, it must be reasonably accurate in its portrayal of the three-dimensional temperature distribution. Indeed, the increase of amplitude in "configuration 2" reflects the intuitive idea of the wave reflection. However, the calculation of the surface displacement is very much one-dimensional in nature. One concludes that the observed surface displacement variation comes from the two — or three-dimensional nature of the elastic response to the temperature distribution rather than from the temperature distribution itself. It marks the difference between the photo-displacement technique and other techniques, such as photo-thermal radiometry or photoacoustics where the detection provides information, mainly as a result of thermal wave interactions [7]. Again, a rigorous treatment of the problem would involve the solving of the Navier-Stokes equation.

5. Joule displacement microscopy

In the case where there is a suitable metallic track on the surface — as for example in microelectronic circuits, one can use the Joule heating of an ac current in the track, to launch the thermal waves — Joule displacement imaging. The method enables one to image current densities in thin metal tracks [5] and

energy dissipations at the surface of semiconductors [8]. The method has also proven to be particularly valuable as a means for investigating electromigration effects in metals [9]. It involves the detection of local changes to electric resistivity with a sensitivity which allows the electromigration process to be observed well before the occurrence of a catastrophic failure.

6. Conclusion

The displacement detection techniques have proven to be tools for nondestructive testing which operate on a microscopic scale. They involve both thermal wave interactions and elastic deformations. They are suitable for the detection of subsurface defects, as well as of surface breaking cracks, where the elastic deformations play a predominant role. Their high sensitivity allows the detection of cracks of width smaller than a micron; they also enable a precise characterization of conducting thin films.

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