THERMO-ACOUSTIC CELL (TAC): A DEVICE FOR THERMAL WAVE IMAGING AND DEPTH PROFILING

J. Saniie

Department of Electrical and Computer Engineering
Illinois Institute of Technology
Chicago, Illinois 60616

ABSTRACT

A simple device, a Thermo-Acoustic Cell (TAC), is described that can be used for thermal wave imaging, thermal diffusivity or for measuring the thickness of materials. The TAC is comprised of a thin window in which the periodic thermal waves resulting from the thermal interrogation of a sample (the sample being positioned on the window of the TAC) diffuse with minimal loss into the cell, generating acoustical signals. The TAC differs from a photoacoustic cell in that the cell window is opaque to photon and the sample is positioned on the window rather than inside the cell. Both the phase and magnitude of the acoustical signal within the cell are potentially useful for characterizing the sample. Preliminary experimental results indicate that the TAC is capable of characterizing the thermal properties of a broad range of materials and in several instances, at low modulation frequency, it demonstrated superior performance in comparison to the photoacoustic cell.

INTRODUCTION

Thermal characterization and imaging of materials has been demonstrated to have great potential in the field of nondestructive testing (as an example see [1]-[3]). Most thermal imaging procedures utilize either photoacoustics (gas cell detection), an optical probe beam (mirage effect), photothermal (IR detection), or piezoelectric photoacoustics (piezoelectric detection). As a complement to the existing thermal wave imaging systems, in this report we present a Thermo-Acoustic Cell (TAC). This device has the capability of visualizing features hidden below the surface, and is able to make thickness and thermal diffusivity measurements at low modulation frequency.

The cross section of a simple TAC is shown in Figure 1. In principle, the TAC is very similar to the photoacoustic cell except that the sample is positioned on the window instead of inside the cell. The cell window itself must be thermally thin and preferably opaque to photons.

The steps involved in generating the thermo-acoustic cell are shown in Figure 2. The modulated incident energy (e.g. laser) results in the periodic heating of the sample. The thermal wave is generated and propagated within the sample toward the cell window. This wave passes through the cell window becoming slightly attenuated. As the wave is diffused through the cell window, an acoustical signal is generated in the cell and is then detected by the microphon. The detected signal contains information pertaining to the thermal characteristics of the sample under investigation.

The experimental setup for thermo-acoustic imaging is very similar to that commonly used for imaging with photoacoustics. A typical thermo-acoustic detection system is shown in Figure 3. As shown in the figure, the modulated incident source is optical and can be a laser. Because of periodic heating of the sample, acoustical signals are generated in the cell and then detected

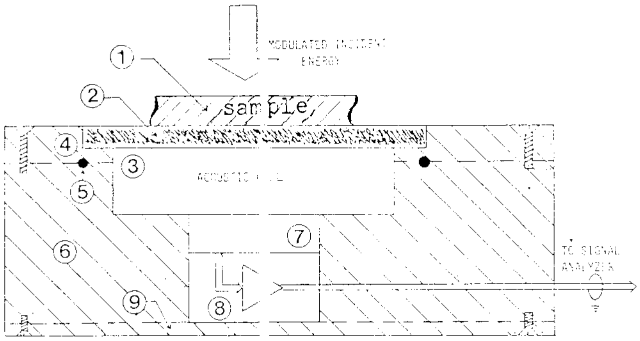


FIG. 1 Cross section of a thermo-acoustic cell (TAC), where (1) is the sample,(2) thermally thin window,(3) acoustic cell,(4) cell window holder (5) rubber o-ring pressure seal, (6) TAC housing (7) microphone, (8) pre-amplifier compartment, and (9) TAC base.

and preamplified. This signal is fed into a lock-in analyzer which provides the vector presentation (magnitude and phase) of the detected signal in reference to the modulated source. Both magnitude and phase can be used as parameters for thermal image formation. The entire scanning and optimization of the modulation frequency and incident energy can be automated through a microprocessor-based control system.

TAC DESIGN CONSIDERATION

In testing the sample, periodic heating of the specimen results in thermal waves which diffuse through the sample and cause periodic fluctuation of temperature within the sample. These thermal waves suffer attenuation and are delayed relative to the waves generated at the source (i.e. region of concentration of the modulated input energy). The attenuation and delay are governed by the distribution of the input energy, physical geometry and thermal properties of the sample under interrogation.

Consider the heat-diffusion equation [4] for temperature T:

$$\alpha\nabla^2 T = \frac{\partial T}{\partial t} \quad ; \quad \alpha = k/\rho C_p \qquad (1)$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ is the density and C_p is the specific heat. The solution to the above equation in the semi-infinite solid z > 0 (one dimensional solution in the direction of the detector) is:

$$T(z,t) = T_0 e^{-z/\beta}\, e^{j(\omega t - z/\beta)} \quad ; \quad \beta = (2\alpha/\omega)^{\frac{1}{2}} \qquad (2)$$

where β is the thermal diffusion length, ω is the modulation frequency of generated heat, and T_0 is the amplitude of the signal where z=0. Then, the amplitude and phase lag of the temperature are:

$$\text{AMPLITUDE:} \quad A = T_0 e^{-z/\beta} \qquad (3)$$

$$\text{PHASE:} \quad \phi = z/\beta \qquad (4)$$

In material evaluation, both of these parameters are measurable and each one provides information concerning the thermal characteristics and dimensions (shape, thickness, etc) of the sample.

It is important to point out that there exists an additional delay and attenuation which is introduced as a result of thermal wave diffusion through the window into the cell. For many practical applications this delay and attenuation is governed by equations (3) and (4) which are predictable

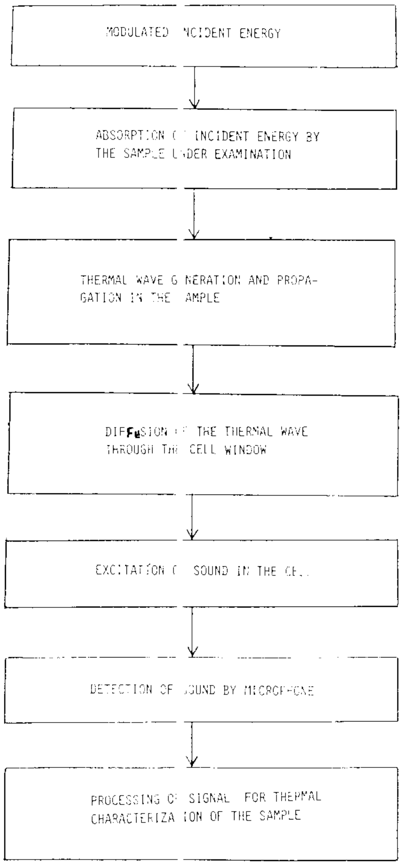


FIG. 2 Block diagram of the steps involved in the generation and processing of thermo- acoustic signal.

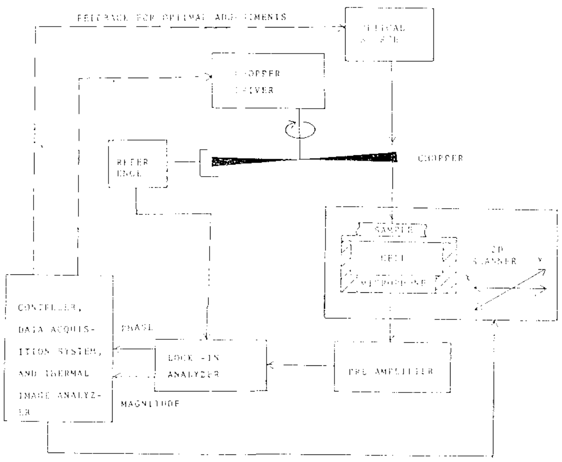


FIG. 3 Block diagram of a typical thermal - wave analyzer using thermo-acoustic cell.

quantities. Of further concern is the desirability to maintain minimal attenuation of the thermal wave. This can be accomplished by reducing the window thickness, or by selecting materials with high thermal diffusion length and/or reducing the modulation frequency. However, one must be aware that the reduction of attenuation can only be at the expense of the degradation of resolution, regional variations of phase delay caused by the window, and mechanical pulsation of the window itself.

An important problem in the design of the TAC are the dimensions and materials of the window. From the onset of this investigation, aluminum appeared to be a good choice of material since it has very high thermal diffusivity (0.82 cm^2/sec). Windows of 10 mm and 12 mm diameters and thicknesses of 0.2 mm and 0.3 mm were studied. Furthermore, for comparison purposes, windows of the same dimensions made of brass, which has thermal diffusivity (0.34 cm^2/sec) less than the value for aluminum, were examined.

Figure 4 shows the generated acoustical signal relative to the reference. This measurement was at a modulation frequency of 20 Hz. The time difference between the maximum of the signal and rising edge of the reference signal gives an indication of the signal delay which is caused in part by the thickness of window. Similarly, the intensity of the signal is governed by the absorbed incident energy and attenuation through the window. In the case of 0.3 mm thick aluminum window and modulation frequency of 20 Hz, the reduction in the signal intensity and introduction of phase lag are about 25% and 50 degrees respectively.

If the evaluation of the TAC is performed in a situation where the region of heating the cell's window is several diffusion lengths away from the boundary of the cell's wall, direct application of equations (3) and (4) provide good approximation in characterizing the signal. However, for the situation in which the imaging takes place near the boundary of the TAC's window, equations (3) and (4) are not applicable. Figure 5 demonstrates that the intensity and phase of the measured signal are dependent on the regional heating of the TAC's window. The diameter of the window is 10 mm, the thickness is 0.3 mm, the window is made of aluminum and the laser beam diameter is 1 mm. Trace (a) of Figure 5 is the measured signal in which the heating spot is near the boundary of the window. Trace (b) of Fig. 5 is the measured signal in which the heating region is at the center of the window.

(A)

(B)

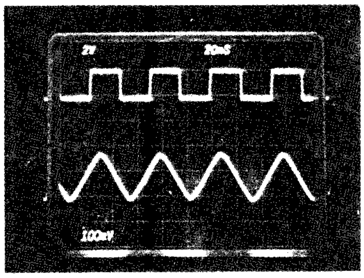


FIG. 4 Trace (A) is the reference signal. Trace (B) is tre acoustical signal. This signal has good signal to noise ratio and roughly a 90 degree phase difference relative to the risirg edge of the reference signal.

(A)

(B)

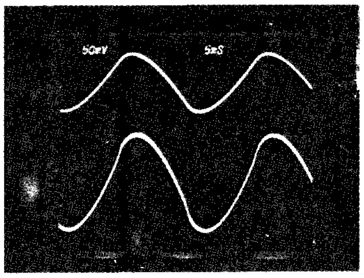


FIG. 5 Trace (A) is the measured signal in which The heatinf region is near the boundary of the windcw Trace (B) is the measured signmal in which the heating region is at the center of the window.

Prior to using the TAC in material imaging, it is necessary to obtain the regional variation of the phase and magnitude in the thermo-acoustic cell. Since variations in the intensity of the signal can be caused by various factors, the phase information is the more desirable parameter to be evaluated. We have investigated the phase variation experimentally for both aluminum and brass windows. Figure 6 shows the regional phase change of the cell as a function of the scanning position. The window is made of brass, the laser beam diameter is about 1 mm, and modulation frequencies are 20 Hz and 40 Hz. Comparison of the traces for the modulation frequency of 20 Hz and 40 Hz demonstrates that the range of constant delay is inversely related to the mcdulation frequency or thermal diffusior length of the window. Figure 7 shows a comparison of the variation in phase delays for 0.2 mm thick brass and aluminum. Since the thermal diffusivity of aluminum is larger than the value for the brass window, the variation of phase delay of aluminum is far more apparent. However, the thicker aluminum window results ir less variation in the phase delay. This is clearly shown in Figure 8 for modulation frequencies of both 20 Hz and 40 Hz.

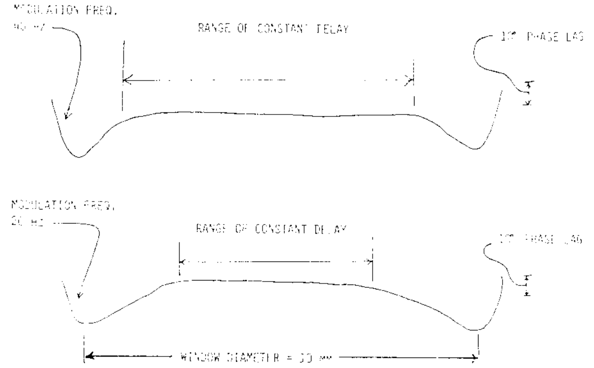


FIG. 6 Experimental evaluation of the regional characteristics of the TAC's window.

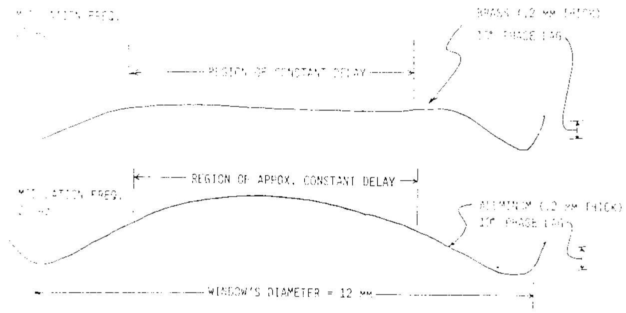
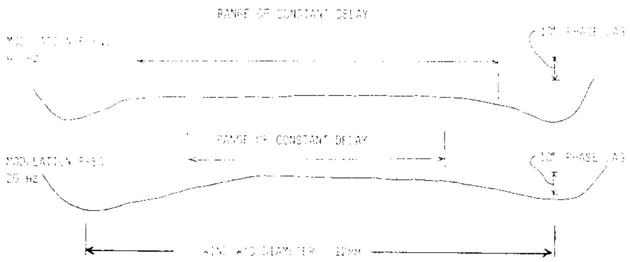


FIG. 7 The variation of the phase delay depends highly upon the thickness and the diffusion length.



Specification: The thickness of the window is .3mm and is made of aluminum. The diameter of the laser beam is about 1mm.

FIG. 8 The radial variation of the phase delay caused by the cell's window. Comparison of the traces for modulation frequency of 20 hz and 40 hz demonstrates that the range of constant delay is inversely proportional to the modulation frequency or the thermal diffusion length of the window.

RESULTS AND DISCUSSION

Both solids and optically semi-transparent materials were examined using the thermo-acoustic cell. The solids were positioned on top of the window with the use of a coupling gel. The thickness of the coupling gel is in a micron range and its overall thermal effects are negligible. A 2.0 mm thick aluminum sample with a flat bottom hole of 3.0 mm diameter and a depth of 0.4 mm were examined. Experimental results are shown in Figure 9. The modulation frequency is 20 Hz and the laser beam size is about 1 mm. Trace (a) is a direct scanning of the flat bottom hole. The significant drop in the phase lag (as much as 55 degrees) in the measurement represents the position and depth of the flat bottom hole. Trace (b) represents the phase lag of the signal obtained by scanning the flat bottom hole through a thin layer. The thin layer is a 0.3 mm thick aluminum. This setup presents a situation in which subsurface features are imaged thermally. In contrary to the outcome of the results shown in trace (a), the phase lag is larger since thermal waves diffused through air trapped in the hole and air has a smaller diffusion length than aluminum. Furthermore, the hole appears to be wider than its actual size. This is due to the integral response of the TAC which results in the degradation of lateral resolution. In fact this degradation becomes more pronounced as the distance between the source and internal features becomes larger. Inspection of trace (c), where the flat bottom hole is further away from the source, reveals a similar conclusion. Another experimental evaluation of resolution associated with the TAC was performed using a 2.0 mm thick

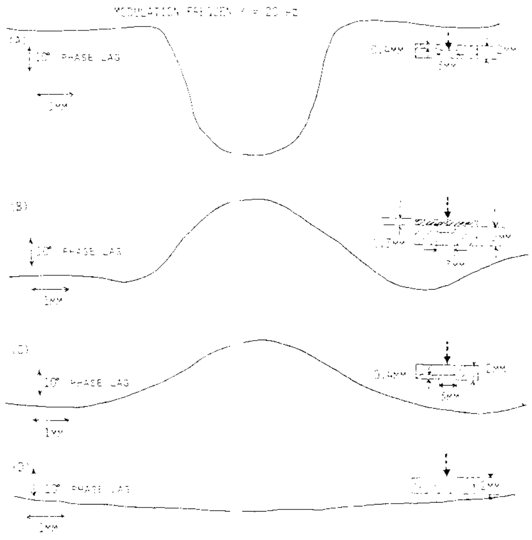


FIG. 9 Thermo-accustic imaging of a 2mm thin aluminum sample with and without a 3mm flat bot- tom hole. Modulation frequency is 20 hz for all measurements.

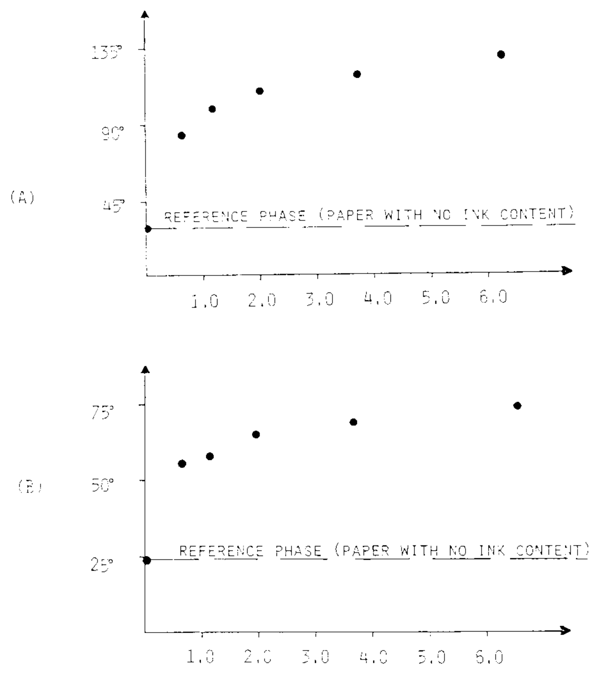


FIG. 12 Preliminary experimental measurements of the paper utilizing the thermo-acoustic cell. Plots represent the phase change as a function of ink content (g/m^2). Trace (B) The printed side of the paper is in contact with TAC's window. Trace (A) The unprinted side of the paper is in contact with the TAC's window.

In the concluding remark, TAC is a thermal detector, the design of which can be tailored and optimized to any particular application. For example, a very similar design was used [5] for photoacoustic spectroscopy of powders and liquids. The TAC performed best at low modulation frequency where the attenuation of thermal waves across the TAC's window were tolerable.

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