PULSE-ECHO THERMAL WAVE IMAGING

L.D. Favro, Xiaoyan Han, Yingxia Wang,
P.K. Kuo and R.L. Thomas
Department of Physics and Institute for Manufacturing Research
Wayne State University, Detroit, MI 48202, USA

INTRODUCTION

We present calculations which describe the three-dimensional reflection of thermal wave pulses from planar sub-surface defects. We also present the results of confirming experiments for the case of subsurface flat-bottomed holes with various depths and lateral dimensions.

CALCULATIONS

We have shown elsewhere [1-3] that when a planar thermal wave pulse encounters an arbitrarily shaped, strongly reflecting planar subsurface defect at a depth, ℓ, the contrast from the reflected wave (the thermal wave echo) at the surface is given approximately by

$$T(\mathbf{r},t) - T_0(0,t) = \frac{-1}{2\pi} \frac{1}{(4\pi\alpha t)^{1/2}} \frac{\partial}{\partial z} \iint_{\text{defect}} dx'dy' \sum_{m=-\infty}^{\infty} \left. \frac{e^{-\frac{[r_m + z]^2}{4\alpha t}}}{r_m} \right|_{z=\ell} , \qquad (1)$$

where

$$r_m = [(x - x')^2 + (y - y')^2 + (2m + 1)^2 \ell^2]^{1/2} .$$

In Eq. (1), α is the thermal diffusivity of the material, and t is the time after the flash at which the image is acquired. The summation over the index, m, takes into account multiple reflections of the thermal wave pulse between the subsurface scatterer and the surface of the material. Such reflections are increasingly important when the lateral dimensions of the subsurface scatterer become large.

Figure 1 shows a schematic diagram of a flat-bottomed hole specimen used to test the predictions of Eq. (1). The specimen has six holes milled into the rear surface of the sample. The flat bottoms of these holes are 1 - 5 mm beneath the painted front surface. The small square areas indicated in Fig. 1 show the regions for which the temperature was measured as a function of time to acquire experimental contrast curves to compare with the predictions of Eq. (1).

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 14
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1995

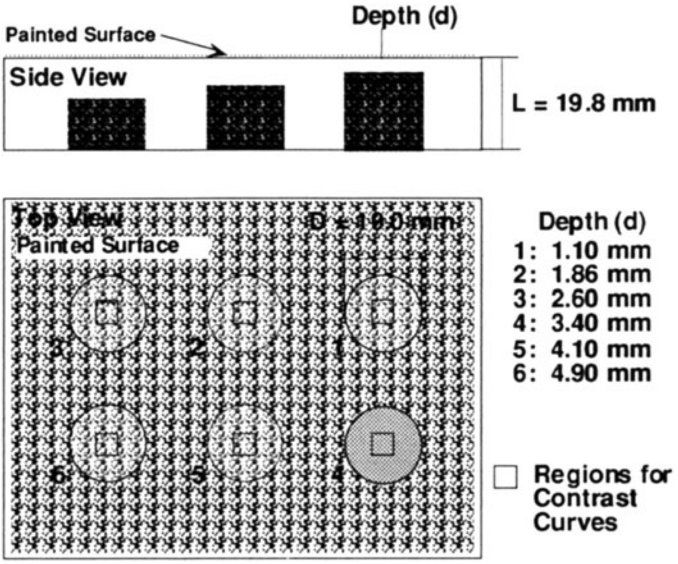

Fig. 1 Schematic diagram of a flat-bottomed hole specimen used to test the predictions of Eq. (1).

In Fig. 2 we show the predictions of Eq. (1) for the thermal wave echo amplitude at a surface location directly over the flat bottom holes having the dimensions shown in Fig. 1. Figure 3 shows the results of the corresponding experimental measurements of echo amplitude, using a Santa Barbara Focal Plane Camera, with a 128 x 128 pixel InSb focal plane array, operating at a frame rate of 244 Hz. Notice the successively later peak amplitude times, as well as the successively later arrival times of the leading edges of the echoes. We will show, both theoretically and experimentally, below that the peak times are dependent on the lateral size of the defect, whereas the position of the leading edge is almost totally independent of lateral size.

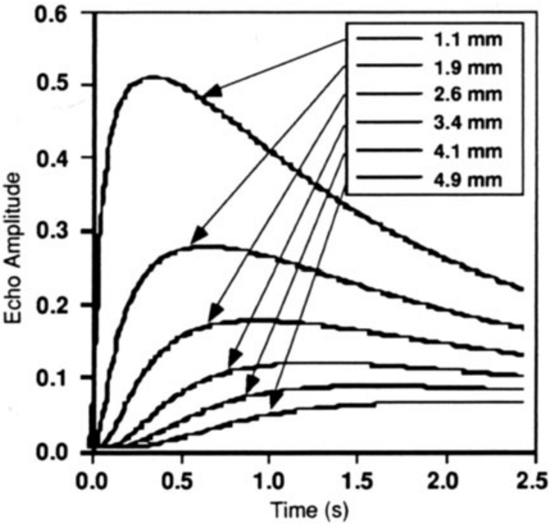

Fig. 2 Predictions of Eq. (1) for the thermal wave echo amplitude at a surface location directly over the flat bottom holes having the dimensions shown in Fig. 1.

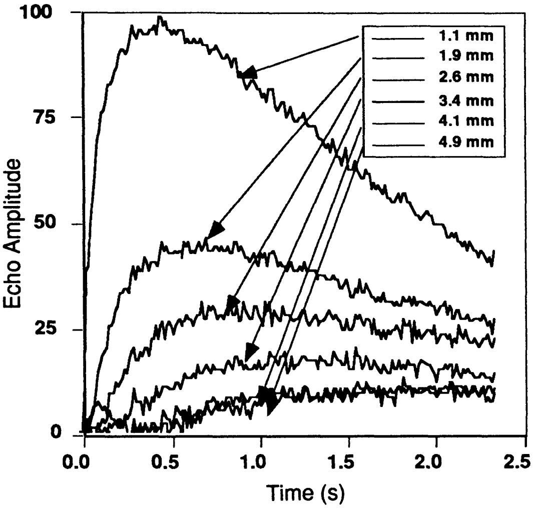

Fig. 3 Results of the experimental measurements of echo amplitude corresponding to the predictions shown in Fig. 2.

Comparing Figs. 2 and 3, it can seen that the agreement is quite good, both in terms of the shifting of the peaks and in the time for the arrival of the leading edges of the echoes. However, it appears that the nominal depths of some of the holes are not quite accurate. Notice that the signals from the two deepest holes in Fig. 3 are essentially identical, indicating that the actual depths are nearly equal. Also, the shallowest hole appears to be slightly closer to the surface than the nominal depth since the signal level is slightly higher than predicted by the theory. This is not surprising, since the depth sensitivity is greatest for the shallowest hole, so that a small deviation from the nominal depth causes a large deviation in the signal amplitude.

Figure 4 shows a schematic diagram of a flat-bottomed hole specimen used to test the predictions of Eq. (1) for holes having the same depth but varying lateral sizes. Figure 5 shows the theoretical predictions corresponding to this sample, and Figure 6 shows the experimental curves. It can be seen from both Fig. 5 and Fig. 6 that the peak times vary with the hole radius, whereas the leading edge of the pulse does not. This suggests using an algorithm which detects the leading edge [4,5] in order to best achieve depth discrimination. These conclusions agree with those of Lau et al. [4], Krapez et al [5], and Ringermacher [5].

CONCLUSIONS

Wave optics techniques have been shown to provide a fruitful approach to understanding the underlying physics of thermal wave phenomena, and also provide a simple technique for getting quantitative analysis of pulse-echo thermal wave imaging.

ACKNOWLEDGMENTS

This work is sponsored by the FAA-Center for Aviation Systems Reliability, operated by Iowa State University and supported by the Federal Aviation Administration Technical Center in Atlantic City, New Jersey, under grant number 93-G-018, by AFOSR, under Grant No. F49620-93-1-0428, and by the Institute for Manufacturing Research.

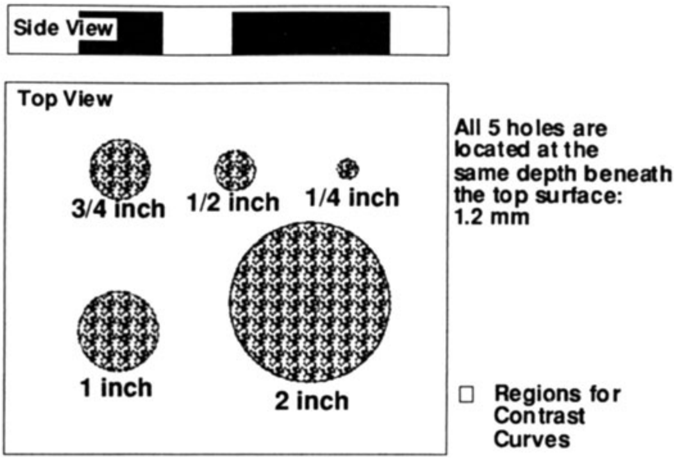

Fig. 4 Schematic diagram of a flat-bottomed hole specimen used to test the predictions of Eq. (1) for holes having the same depth but varying lateral sizes.

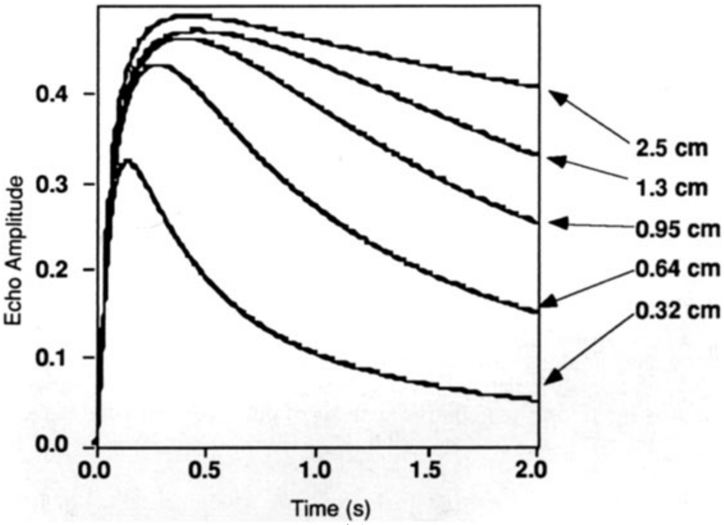

Fig. 5 Theoretical predictions corresponding to the sample shown schematically in Fig. 4.

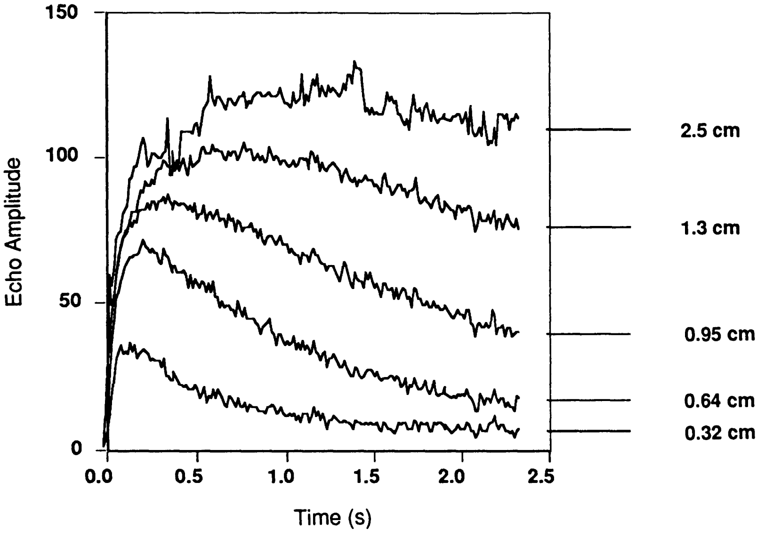

Fig. 6 Experimental measurements corresponding to the sample shown schematically in Fig. 4.

REFERENCES

1. R.L. Thomas, J.J. Pouch, Y.H. Wong, L.D. Favro, P.K. Kuo, and A. Rosencwaig, J. Appl. Phys. 51, 1152 (1980).
2. L.D. Favro, D. Crowther, P.K. Kuo, and R.L. Thomas, Proc. SPIE Thermosense XV Orlando, FL, April 12-16, 1993, Vol 1993, pp. 138-141 (1993).
3. D.J. Crowther, L.D. Favro, P.K. Kuo and R.L. Thomas, J. Appl. Phys., Vol. 74, pp. 5828- 5834 (1993).
4. S.K. Lau, D.P. Almond, and P.M. Patel, Springer Series in Optical Sciences, Vol 69, Photoacoustic and Photothermal Phenomena III, Ed. D. Bicanic, Springer-Verlag Berlin, Heidelberg (1992), pp. 522-524.
5. J.C. Krapez, D. Balageas, A.A. Deom, and F. LePoutre, Abstract for the Rev. Prog. QNDE, Aug. 1-6, 1993, Brunswick, Maine, p. 130.
6. H.I. Ringermacher, W.A. Veronei, F.A. Reed, T.J. Batzinger, I. Perez and W.R. Scott, Abstract for the Rev. Prog. QNDE, Aug. 1-6, 1993, Brunswick, Maine, p. 173.