High-fidelity tomographic imaging reconstruction for photopyroelectric thermal wave detection equipment

A. Yarai, K. Sakamoto and T. Nakanishi

Department of Electrical Engineering and Electronics, Faculty of Engineering, Osaka Sangyo University, Daito, Osaka, Japan

Abstract This paper describes a high-fidelity tomographic imaging reconstruction method for photopyroelectric thermal wave detection equipment. The high-fidelity is achieved through a high signal-to-noise ratio detection technique and through a new calculation algorithm. A very-small-diameter detection metal probe tip can be used due to the high signal-to-noise ratio detection technique, increasing the spatial resolution. The calculation algorithm which considers thermal wave transmission paths along with defects achieves the high-fidelity tomographic imaging reconstruction.

1. INTRODUCTION

A new photopyroelectric tomographic imaging technique has recently been developed^{[1]-[3]}. This technique adopts a thermal wave detection method, whose key components are a photopyroelectric film having an electrode on one side and a capacitive coupled remote metal tip (i.e. noncontacting) capable of sampling the local thermal wave field value. Therefore, this technique is effective in non-destructively evaluating the sub-surface features of solids. It has, however, serious difficulty with high-fidelity tomographic imaging reconstruction due to a very low signal-to-noise ratio (very low detected signal amplitude, on the order of nV~10nV). Moreover, a serious problem exists with position discrepancies of reconstructed sub-surface defects from the real positions.

This paper shows that high-fidelity tomographic imaging reconstruction is possible with (1) a high signal-to-noise ratio and high spatial resolution, and (2) a new calculation algorithm. Note that (1) is achieved with (a) a film of high pyroelectric coefficient, (b) a very-high-power laser diode, (c) a very-small-diameter metal probe tip and (d) ultra-low-noise pre- and 2nd-stage amplifiers. Note that (2) basically uses the one-dimensional heat-flow equation which considers thermal wave transmission paths along with defects.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for the tomographic scans (both the excitation laser and the probe tip are scanned independently). In order to avoid thermal perturbation while the probe tip is being scanned, a gap is set between the probe tip and the pyroelectric film. By attaching an ultra-low-noise FET amplifier directly to the probe tip, a very low input capacitance of 5pF is obtained, suppressing a decrease in the signal voltage^[5]. It should be noted that in our equipment (i.e. capacitive coupled pyroelectric detector), an 85- μ m-thick LiTaO₃ (Hamamatsu Photonics Co., Ltd.) pyroelectric film, which has a five-fold larger figure of merit than a 30- μ m-thick PVDF (polyvinylidene fluoride; KF piezo film, Kureha Chemical Industry Co., Ltd.) film, and a high power laser diode (wavelength: 840 nm, power: 970 mW) as an excitation heating source can be used. The beam is focused to an approximately 20- μ m-diameter spot on the sample. Consequently, a signal-to-noise ratio of at least 100-times that in previous works [3][4] can be expected, as well as a small-sized experimental setup.

When an LiTaO_3 pyroelectric film was used, however, it was found that not enough measurement reproducibility could be obtained, probably due to the influence of humidity^[6]. Therefore, it was necessary to control the humidity very carefully when the LiTaO_3 film was used. This problem has not yet been completely resolved.

3. TOMOGRAPHIC MEASUREMENT

The measurement sample used was a 2.0-mm-thick and 15-mm-square aluminum plate with a 1.0-mm-diameter drilled out hole at its center (between the top and bottom surfaces) and with a thin layer of black paint on the top surface. The gap mentioned above was set at 0.1 mm. The diameters of the metal (brass) probe tips were varied from 0.2mm~0.8mm. These parameters were selected quantitatively by finite element method (FEM) analysis^[5]. The excitation beam was amplitude modulated in the frequency range of 10~100Hz with a laser diode driver. Scan spans for the excitation laser and the probe tip scanned independently, were set at 4.0 mm. Scan steps were 0.1 mm.

4. THERMAL WAVE BYPASS TRANSMISSION

We calculated the bypass transmission effect of a thermal wave with the one-dimensional heat-flow equation. Figure 2 shows the theoretical and experimentally detected phase lag values. The calculation conditions were as follows. 1) a 0.4-mm-diameter metal probe tip was fixed at the bottom surface of the test sample, and set at the hole center. 2) The thermal wave transmission distance x was calculated; the flow was along the hole, between the laser irradiated position on the top surface and the metal probe tip position. In the figure, the origin is defined as that on the top surface, which corresponds to the point where the probe tip is fixed and the edge of the probe tip. 3) The phase lag value was calculated by using x . Here, the modulation frequency is 50 Hz.

The figure shows that these experimental phase data closely match the calculated curve of a 1.6-mm-diameter probe tip, which is 4-fold that of a 0.4-mm-diameter probe tip. The reason for this is the fringing effect of electric field lines for the probe tip^[5]. The correspondence between the theoretical (probe tip diameter is 1.6 mm) and experimental values (probe tip diameter is 0.4 mm) shows that the calculation condition whereby heat flow along the hole is proper (bypass transmission). A slight discrepancy, however, can yet be seen between the theoretical curve calculated with the one-dimensional heat-flow equation (probe tip diameter is 1.6 mm) and the experimental data (probe tip diameter is 0.4 mm). The reason for this is assumed that the one-dimensional heat-flow equation can not be adopted completely especially at the area adjacent to the hole boundary.

5. TOMOGRAPHIC RECONSTRUCTION ALGORITHM

As mentioned above, we have developed a new calculation algorithm which considers thermal wave transmission paths along with defects to be imaged. The one-dimensional heat-flow equation for this algorithm is solved as follows. (1) A cross-sectional area that includes a defect to be tomographically imaged is divided into picture pixel matrix. (2) The thermal transmission distance x is calculated between every laser and probe tip position along with the defect, by using the detected phase signals. Phase datum is used instead of amplitude datum because it is less susceptible to mechanical gap alignment errors and to configuration changes on the sample surface. (3) Values for F ($F=x/d$) are calculated, where d is the direct

Fig. 1 Photopyroelectric thermal wave tomographic imaging system

1: Sample, 2: Pyro film, 3: Probe tip, 4: Ultra-low noise pre-amp., 5: X-Y pulse motor stage, 6: High power laser diode, 7: Focusing lens, 8: Function generator, 9: Laser diode driver, 10: Lock-in amp., 11: 2nd stage amp., 12: Personal computer, 13: Pulse motor controller

Fig. 2 Theoretical and experimental detected phase lag values

distance between the laser position and the probe tip position. An F value represents the bypass transmission ratio of a thermal wave. (4) For every pixel, all F values obtained using all phase data relating to the pixel (meaning data obtained when the direct path from a laser position to a probe tip crosses the pixel) are added. (5) Every pixel is classified into "1" or "0" according to the summed F values (a value larger than a certain threshold level is classified as "1"). In this method, it is easy to find a reasonable threshold level.

A tomographic image reconstructed with this method, however, may suffer from image distortion and/or position errors. To overcome these problems, we extended the algorithm as follows. It was found that the errors occurred due to the ununiformity in the calculation (the adding mentioned above) times for every pixel. To correct this problem, each pixel was further divided 10 times (only for the top and bottom directions) and only for the calculation.

Figure 3 illustrates the adding times of locations nearby a center position for a sample with no defect before and after this additional division. With this new calculation algorithm, the image distortion and position errors, which had been serious problems, were significantly reduced.

6. RECONSTRUCTED TOMOGRAPHIC IMAGE

Owing to the techniques mentioned above, a very-small-diameter probe tip of 0.2 mm diameter could be used, drastically increasing the spatial resolution. Figure 4 shows the modulation frequency dependence of the position deviation quantity (the positions deviate to the bottom direction), with and without the correction shown is the previous section. Figure 5 shows the modulation frequency dependence of the image fidelity factor, with and without the correction. As shown in the figure, the circle obtained had an almost complete shape, where the image fidelity factor was calculated to be 93 % when the modulation frequency is 50 Hz. Here, the image fidelity factor is defined to be the ratio of 1) the white area obtained from the real data within the original complete circle, over 2) the area of the original complete circle. It was found that this new algorithm considerably corrects both the position deviation quantity and the image distortion of defects [3]-[4].

Figures 6 shows a phase datum for a probe tip of 0.2 mm, and Fig. 7 shows reconstructed tomographic images for a probe tip of 0.2 mm or 0.6 mm, when the modulation frequency is 50 Hz. It is shown that the spatial resolution of the former is well improved compared with that of the latter.

Fig. 3 Adding times of locations nearby a center position for a sample with no defect

Fig. 4 Modulation frequency dependence of the position deviation quantity

Fig. 5 Modulation frequency dependence of the image fidelity factor

Fig. 6 Phase datum
modulation frequency: 50 Hz
probe tip diameter: 0.2 mm

Fig. 7 Phase reconstruction images
probe tip diameter: (a) 0.2 mm
(b) 0.6 mm

7. CONCLUSION

Owing to the high signal-to-noise ratio detection technique, high resolution detection has been achieved, drastically increasing the spatial resolution. We have developed a new reconstruction calculation algorithm which considers thermal wave transmission paths along with defects. Although this calculation algorithm is simple, a high-fidelity tomographic image could be obtained.

This work can be expected to yield significant tomographic reconstruction capabilities, even for thin solid materials with near-surface defects. An array of probe tips for parallel data collection is now being developed^[7] to decrease the data collection time.

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