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Applications of phase sensitive thermography for nondestructive evaluation

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Abstract:

The technique of thermal wave thermography combines advantages of both conventional thermal wave measurement and thermography using a commercial IR camera. This technique allows for shorter imaging time and depth profiling. Non-uniformity of heating area and optical surface structures can be suppressed in phase images. Several examples show the potential applications of thermal wave thermography in the field of non-destructive testing.

1. Introduction

The advantage of thermography where the temperature field is monitored with an infrared camera is its fast imaging capability. However, depth range is not defined. Furthermore thermal and optical/infrared structures are superposed in the thermographic image.

In thermal wave techniques phase and magnitude of the local dynamic thermal response are measured. The phase of the modulated infrared emission is independent of optical/infrared surface structures. But a large depth range requires measurements at low modulation frequencies. Imaging with a point-by-point raster scan is very slow. Various techniques have been developed to obtain the information in a short time [1,2]. The aim of this paper is to use "thermal wave thermography" as a combination of these two separate fields and to provide a fast thermal wave measurement technique.

2. Principle of thermal wave thermography.

The principle of lockin thermography is described in Fig. 1. The sinusoidal thermal input may result from the modulation of a light beam, electrical current, gas temperature, or mechanical vibration source etc.. As a result a thermal wave is generated in the whole sample simultaneously. Each pixel on the whole sample surface is monitored sequentially using a thermographic scanner. During each modulation period four successive thermographic images are recorded. To perform local digital Fourier analysis four data points may be used in the case of sinusoidal modulation. This allows for very simple mathematical treatment where the phase φ and magnitude A of the local thermal wave can be determined at all pixels.

$$\varphi(x_1) = \arctg \frac{S_3(x_1) - S_1(x_1)}{S_4(x_1) - S_2(x_1)}$$

$$A(x_1) = \sqrt{[S_3(x_1) - S_1(x_1)]^2 + [S_4(x_1) - S_2(x_1)]^2}$$

The average of the primary images S_1 to S_4 is the thermographic image which is strongly affected by local optical absorption and infrared emission coefficients, local thermal properties, and local optical illumination. However, in the phase image the surface structures are suppressed to reveal only thermal structure in the sample [3]. Fig. 2 shows the general setup of lockin thermography. A thermal wave is generated at the same time in the whole sample using a sine wave thermal source at low modulation frequency. The IR image capture and external thermal source are synchronized with a computer system. Some image processing functions are performed to provide phase and magnitude images.

Fig. 1.
Input intensity $I(x)$, scan $x(t)$, and pixel x_1
with reconstructed local thermal wave $S(x_1,t)$.

Fig. 2.
Experimental setup for lockin
thermography

3. Applications

The capabilities of depth profiling and suppression of optical surface structures are investigated which are typical for thermal waves. Fig. 3 presents results obtained on the thermal structure in a CFRP (carbon fiber reinforced polymer) sample with lockin thermography using a modulated optical input. The phase image at the modulation frequency 0.24 Hz reveals the rear surface slot up to a depth which is larger than at 0.96 Hz. The magnitude images are strongly affected by the inhomogeneity of illumination.

Fig. 3. CFRP sample with a slant slot on the rear side (0.24 Hz and 0.96 Hz)

The phase image of a metal weld sample at 0.2 Hz is shown in Fig. 4 where the weld structure and previously heated zone can be seen clearly. The sample has homogeneous thickness due to grinding after welding. Fig. 5 is an example of resistive heating with modulated current instead of modulated illumination. The object under inspection was a resistive wire bent to a S-like shape and hidden in wood-metal. While thermography cannot reveal this shape, it is well seen both with phase and magnitude where resolution is better at high frequencies. Thermal wave excitation is homogeneous in this case.

weld seam

Fig. 4.
(left) Phase image of welding
seam in flat metal plate at 0.2 Hz.

Fig. 5.
(below) Example of resistive ac
heating at 0.4 Hz and 4 Hz. Primary images
indicated by S₁ to S₄

S₁

S₂

S₃

S₄

ϕ

A

0.4 Hz

4 Hz

When the optical absorption of the sample is weak, a gas flow of modulated temperature might be an alternative for thermal wave generation (similar to Angstrom's method using modulated temperature of liquids [4]). Fig. 6 shows the results obtained at 0.1 Hz on veneered wood with different sizes of subsurface defects and layer thicknesses ranging from 0.5 mm to 2.5 mm (sample kindly provided by Mr. K. Koppenhöfer and Mr. B. Ritter, trade school Schwäbisch-Hall). Defects under the thicker layer of veneer cannot be found because of the limited depth range of the thermal wave.

Fig. 6.
Defects in veneered wood.
Temperature modulated gas flow at 0.1Hz.

Fig. 7.
Polymer sample (PBT) with a hole
under oscillating load at 1 Hz.

Loss angle heat induced under oscillating load is another modulated thermal input of interest for material testing [5]. The phase image in Fig.7 reveals the hole located 1 mm beneath the surface. The magnitude image is the same as in a standard SPATE measurement to show the stress distribution near the hole [6].

4. Conclusion

Several examples were described for application of lockin thermography which combines standard thermography and thermal wave technique. Advantages are much shorter imaging time than in usual thermal wave methods. Its depth profiling capability and suppression of surface optical structures to reveal only subsurface thermal structure will be very important for many industrial applications. Compared to pulse thermography, there is no need of powerful lamps, no sample overheating due to deposition of high energy in a short time, and no need of high dynamic range to follow strong temperature changes.

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