01 May 2016

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Recommended Citation

J. D. Pribe et al., "Toward DMD Illuminated Spatial-Temporal Modulated Thermography," *Proceedings of the SPIE Defense + Commercial Sensing (DCS) (2016, Baltimore, MD)*, vol. 9861, SPIE, May 2016.
The definitive version is available at https://doi.org/10.1117/12.2223859

Toward DMD illuminated spatial-temporal modulated thermography

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ABSTRACT

This paper reports on a system using a Digital Micromirror Device (DMD) to modulate a near-infrared laser source spatially and temporally. The DMD can produce an arbitrary heat source varying both spatially and temporally over the target. When the thermal response of the target surface is recorded using a thermal imager, this provides new possibilities in subsurface defect detection, partially with regard to features whose orientation does not allow them to be resolved using conventional thermographic inspection techniques. In this respect it is similar to conventional focused spot detection approaches; however, the DMD allows the signal to be frequency/phase multiplexed which provides for simultaneous interrogation over a large area. The parallel nature of the process permits a longer inspection time at each point which has signal-to-noise benefits. Preliminary experiments demonstrating the multiplexing approach are presented using a low-cost thermal imager. A NIR laser is spatially and temporary modulated to generated multiple thermal line sources on the surface of a composite circuit board. The infrared response is demodulated point-by-point at each drive frequency. This permits the thermal response from each line source to be resolved individually. Beyond damage detection the approach also has applications to system identification. Initial limitations due to the test setup are discussed along with future system improvements.

Keywords: Active Thermography, Nondestructive Evaluation, Digital Micromirror Device (DMD), Defect Detection, Laser Modulation

1. INTRODUCTION

Thermography (radiometric imaging to map surface temperature) is a widely used technique for non-destructive testing. Generally, an infrared (IR) imager is used to monitor the surface temperature of a target and identify discontinuities caused by uneven thermal conduction. Active thermography involves illuminating the target with a known heat flux to provide more accurate detection of defects. It has been widely studied and demonstrated for identifying features that impede the flow of heat away from the surface. A typical example is the detection of delamination defects in composites. Several temporal modulation schemes have been studied intensively; notably a single short pulse and a sinusoidal modulation, known as pulse and lock-in thermography, respectively. Both involve uniform spatial illumination of the target.

In lock-in thermography, a temporally modulated light source heats a target. Thermal waves then propagate through the target perpendicular to its surface. Defects parallel to the surface reflect some of the incident light back to the surface, producing a temperature difference and shifting the phase of the light wave at the surface. An IR camera can then be used to record the temperature at the surface and identify defects. This effect has been used to study, for example, delaminations, impact damage, and fatigue cracks in aerospace materials[1].

A problem arises for defects that are perpendicular to the target surface, which may elude detection with the traditional approach. This is because neither lock-in nor pulse thermography generates a thermal gradient tangential to the surface.

A rule detecting these types of defects with pulse thermography was defined by Maldague[2]: the smallest detectable defect has a radius that is "at least one to two times its depth under the surface." Several attempts have been made to improve on this. Initially, studies investigated extending pulse thermography, typically by scanning a pulsing laser across the target surface and analyzing the lateral heat diffusion from each pulse[3-4].

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Thermosense: Thermal Infrared Applications XXXVIII, edited by Joseph N. Zalameda, Paolo Bison, Proc. of SPIE
Vol. 9861, 98610Z · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2223859

In terms of lock-in thermography, Lugin[5] created lateral thermal flows by exciting a target for a long enough period of time that thermal waves reflected from the back surface. This technique essentially used the same principle as traditional lock-in thermography to detect defects but with the waves propagating laterally across the surface rather than through the target. Pech-May et. al.[6] developed a model for characterizing perpendicular cracks using a single Gaussian spot or line excitation. Finally, Thiel et. al.[7] used two line sources modulated at the same frequency but with a phase shift of π radians in order to detect perpendicular cracks in between the two sources. These two line sources were projected onto the target using a DMD.

In this paper, we propose expanding the concept of using the DMD to spatially and temporally modulate the heat flux on a surface. In general the target can be modulated by a large combination of different point or line sources that control the expansion of spherical or cylindrical thermal waves in the substrate. By modulating these sources at different frequencies the sources are multiplexed and can demodulated in frequency space during post processing of the time history of the surface. This avoids the requirement of moving the illumination around the surface during an experiment and permits longer time histories to be recorded (because the entire surface is sampled simultaneously). Deviations from the expected diffusion response from the source can be used to detect damage such as cracks. Alternatively because the amplitude and phase response are material dependent, the same technique can be used to identify the materials and classify a structure beyond its surface reflectivity.

2. MODELING

A two-dimensional finite difference model was created in MATLAB to first simulate the lateral heat diffusion in FR-4 from a single modulated source with a nearby crack. This solves the heat diffusion equation:

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial x^2} = \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

The lateral boundaries are insulated while convection (h=5 W/m^2·K) is applied to the top and bottom surfaces along with the time and position dependent heat flux due to the heat source. Figure 1 shows the temperature results 20s that illustrate heat diffusing vertically and laterally from a uniform 2 Hz source and a 2 Hz line source (50 µm wide).

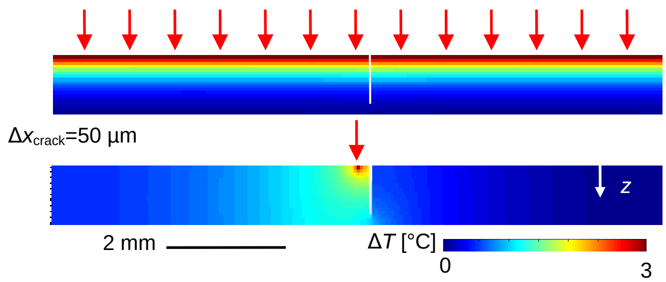

Figure 1. Top: heat diffusion from a uniform 2 Hz source exciting the entire target surface. Bottom: heat diffusion from a 2 Hz line source exciting the middle of the target surface.

The uniform 2 Hz source simulates a traditional lock-in thermography approach, which, as expected, is blind to the perpendicular crack. In the simulation of the 2 Hz line source, however, the crack clearly impedes the lateral thermal diffusion. Amplitude and phase plots of these simulations are shown in Figure 2.

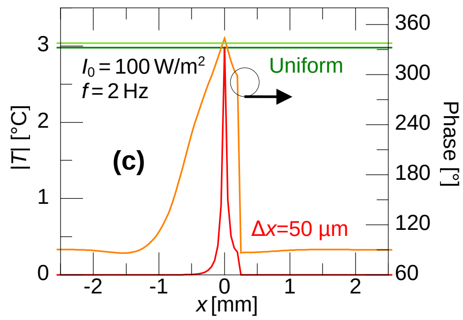

Figure 2. Simulated amplitude and phase at 2 Hz of uniform illumination and line source from Figure 3. A discontinuity (noted by the circles) is visible at the crack location in both amplitude and phase of the line source.

Similar to conventional lock-in thermography, the phase image for the line source is the most useful since the phase roll-off is much wider than the amplitude response as the thermal wave diffuses through the target[8]. This result from the line source supports the work of Pech-May et. al.[6]. Meanwhile, as expected, the vertical crack did not cause any discontinuities in the target response to the uniform 2 Hz excitation.

To establish a framework for our study, the response of FR-4 under excitation from line sources at 2, 2.1, 2.2, 2.3, and 2.4 Hz was also simulated. A 3-D plot showing the temperature amplitude at each frequency is shown in Figure 3.

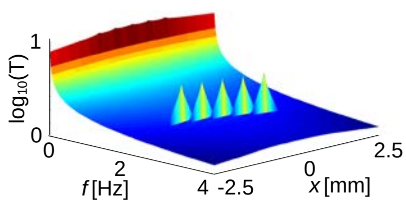

Figure 3. Simulated amplitude plot of FR-4 under excitation from 5 line sources. The line sources rise in frequency from left to right along the x dimension. The DC offset is due to transient heating of the target.

Figure 4 provides another visualization of the same simulation. In Figure 4, the amplitude and phase at each frequency are plotted with respect to the x direction.

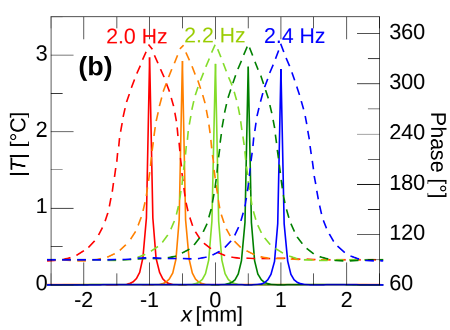

Figure 4. Simulated amplitude and phase at the drive frequencies from Figure 3.

Figures 3 and 4 both indicate that each line source has its own region of influence that can be analyzed by demodulating the target response at the known drive frequencies. A wide variety of patterns with line sources at difference frequencies can be created to interrogate various targets, and, based on these simulation results, individual frequencies can be "reused" as long as the second line source at the same frequency is sufficiently far away from the first. The experiment procedure described below attempted to replicate this result with 5 separate sources on a piece of FR-4.

3. METHODS

3.1 Experimental Setup

In the experiment, a 30 W Coherent Duo FAP (λ_0=810 nm) laser beam was homogenized by passing through a light pipe. The homogenized beam was then imaged onto the DLP chip of a Dell 1209 projector. The DLP mirrors were configured by the image or video on a computer connected to the projector. For this demonstration a movie generated in MATLAB of the source was played through the projector to image it onto the target. The surface temperature of the target is monitored using a DRS Tamarisk 320 uncooled infrared imager. This camera is not radiometrically calibrated which is acceptable as long as the response is linear due to the fact that the technique does not require absolute temperature measurements. A diagram of this setup is shown in Figure 5.

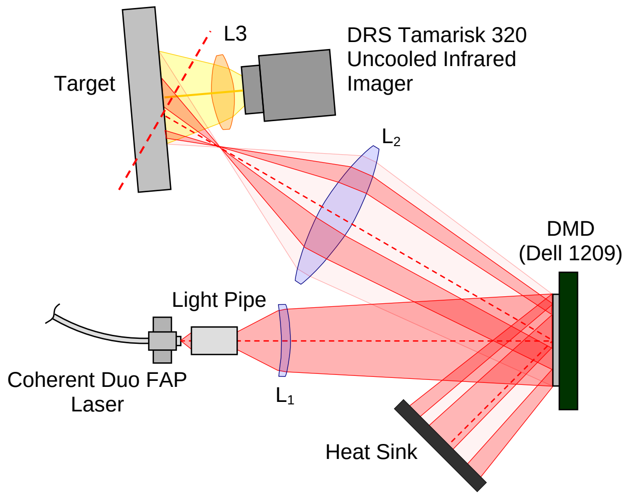

Figure 5. Experimental setup schematic. Outside of this setup, a computer is connected to the DMD projector. Additionally, the target is mounted on a stage.

A picture of this setup is shown in Figure 6.

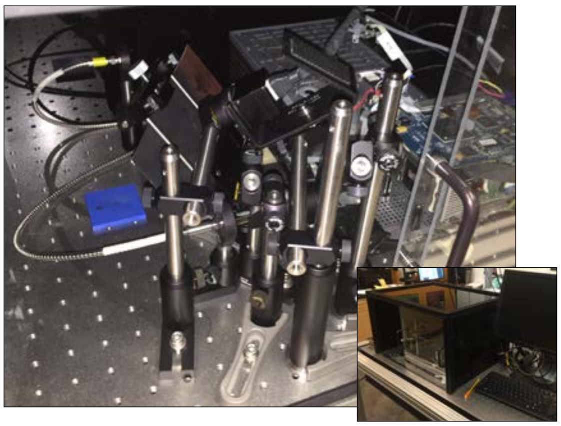

Figure 6. Picture of experimental setup. The inset shows the box containing the entire setup and the desktop computer used to control the laser and the DMD. A second computer was used to control the IR camera.

This setup allows the illumination at multiple points on the target to be varied individually at different frequencies depending on the video that is being played on the computer screen. An experiment can then be run for an extended period and the pixels demodulated at the various drive frequencies.

3.2 Procedure and Data Analysis

The laser in the experiment was controlled by a LabVIEW program that both set the laser power and turned it on and off. Several video files of sinusoidally modulated rectangles created using MATLAB were loaded into a PowerPoint presentation on the computer that interfaced with the DMD projector. The target was a piece of copper-plated FR-4 with the bare FR4 face facing the thermal imager (see in Fig. 6). Note that the FR4 was spray painted black to maximize emissivity.

On the data collection side, the IR camera recorded at a rate of 30 frames per second, meaning that we could record sources modulated at up to 3 Hz without significant distortion problems. Additionally, the camera recorded a 320×240 pixel video, which corresponded to an 8×6-mm area on the target. The video recorded by the camera was processed using MATLAB. Prior to demodulating the target response, however, the temperature data in each column (i.e. the y direction) at each time step was averaged to reduce noise. This was possible because the line sources and the resulting lateral thermal diffusion were assumed to be uniform. Finally, the MATLAB program produced amplitude and phase plots at each drive frequency.

4. RESULTS

The results were found using a pristine target in order to demonstrate the demodulation process. Improvements to the experimental setup need to be made prior to running tests with simulated defects, for reasons described in the following section. A raw camera image prior to the start of the test of the five line sources used is shown in Figure 7.

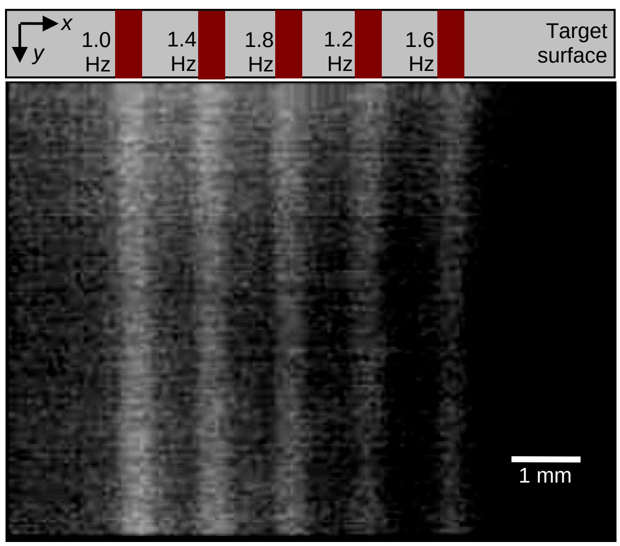

Figure 7. Raw IR camera image of line sources.

Video was recorded for 2 minutes and 30 seconds at the standard camera frame rate of 30 Hz. Line sources at frequencies of 1, 1.2, 1.4, 1.6, and 1.8 Hz were projected onto the target as shown in Figure 7. The amplitude and phase response at each frequency are shown in Figure 8.

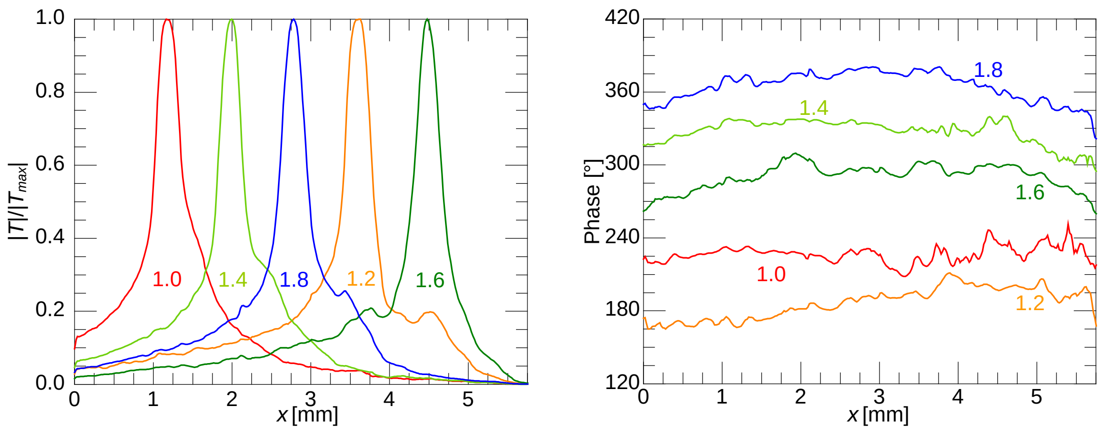

Figure 8. Results from demodulating the response of the target surface. Left: normalized amplitude vs. x position. Right: phase vs. x position. In both plots, the frequencies (in Hz) of the line sources are listed next to the corresponding traces.

The amplitude traces indicate that, as expected, the response at each frequency was independent of the others, demonstrating thermal superposition. However, the decay on either side of each amplitude peak is not symmetrical. This can be attributed to misalignment in the system (i.e. between the laser and the DMD projector and between the DMD and the target), resulting in non-uniform illumination including ghost images of the targets slightly offset from the original target.

The phase roll-off does not agree with Figure 4. This is because the simulation response is for a near-line source as opposed to the much wider line sources in Fig. 7 (nearly 500 µm, 50% duty cycle). This results in superposition of the phase response over the wider line sources, which serves to wash out the phase response. Figure 9 shows a two dimension demodulation example where two university logos where imaged at different frequencies (2.0 and 2.2 Hz) onto the same FR4 substrate. The amplitude response allows the two logos to be distinguished. The blurriness is from a combination of focusing errors and the effects of thermal diffusion allowing the image to spread.

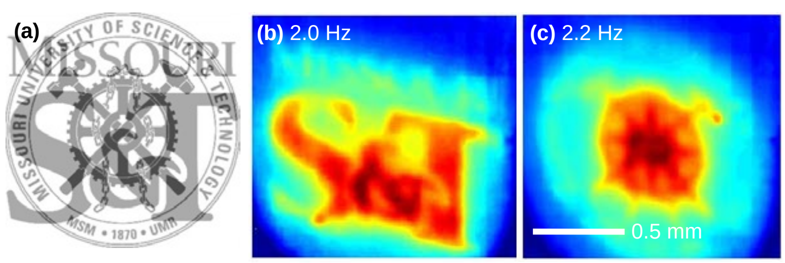

Figure 9. Result of projecting (a) two university logos simultaneously projected onto FR4, the logos were modulated at different frequencies. The images were obtained by demodulating a movie recorded by the thermal camera at (a) 2 and (b) 2.2 Hz respectively.

There are several issues with the setup shown in Figs. 5 and 6. Specifically, we could not confirm that the response of the thermal imager is linear with respect to temperature and light reflected from the DMD is not precisely focused onto the target. Both the DMD plane and the target are significantly rotated with respect to the optical axis of the imaging lens (L_2). This configuration was selected on the basis of convenience when aligning the laser source to the DMD but leads to significant aberrations of the imaged source. This can be corrected by illuminating the DMD in a more conventional beam path shown in Fig. 10. The addition of a spatial filter in the Fourier plane of the collection lens (L_2) also removes diffractive ghost images on the target. A key disadvantage for proper imaging is the target must be canted to allow observation with the focused thermal camera. This can be resolved using a beam splitter to make both the illumination and observation axes normal to the surface at the expense of reducing the illumination efficiency.

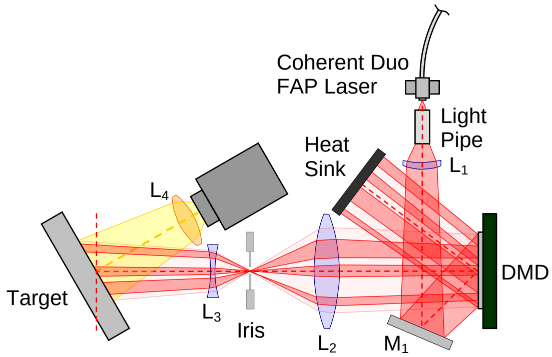

Figure 10. Corrected setup with DMD normal to illumination optical axis.

5. CONCLUSION

The objective of this study was to demonstrate a spatial and temporal modulation scheme, using light sources at several different frequencies, could be used to locate defects perpendicular to the surface of a target. In agreement with theory, simulations and experiments demonstrate that the response of the target can be demodulated, and the thermal diffusion due to the sources at each drive frequency can be individually analyzed. This has exciting potential for thermographic inspection and the DMD modulated approach remains promising. Future work will improve the physical setup to minimize aberrations in the illumination. Other demodulation approaches are also being explored, because only a finite number of frequencies are included in the illumination (frequencies can be recycled after a finite space of ~3 mm for the FR4 target used in the study) a least-squares approach will be computationally less expensive than the FFT.

ACKNOWLEDGEMENTS

Support from the Missouri S&T Intelligent Systems Center is gratefully acknowledged. The DRS Tamarisk Camera was donated by as part of the DRS Student Imaging Competition (Dr. George Skidmore).

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