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Flash Thermography of Aerospace Composites

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Abstract

In the past decade, thermography has become a widely accepted inspection technique for both manufacturing and maintenance of aerospace composites. Optical flash thermography, where the sample surface is heated by a brief pulse of light, has emerged as the most widely implemented technique in the United States, as it is faster than step or modulated optical heating, and it facilitates quantitative measurement of thickness, depth or thermal diffusivity. For many polymer and ceramic matrix composite inspection applications, flash thermography has replaced traditional ultrasonic inspection. In part, the increased acceptance of flash thermography is the result of improved signal processing and analysis techniques. While early attempts at thermographic NDT were based on analysis of contrast in the post-heating image data sequence, modern systems treat each pixel as an independent time series, so that information about the state of a sample can be acquired from a single pixel, without the use of a reference standard. The Thermographic Signal Reconstruction (TSR) technique has been a particularly effective device for signal analysis. While the TSR signal itself provides only noise reduction, its first and second time derivatives provide a signature that is invariant to ambient conditions, surface preparation or input energy, and that reveal the presence of subsurface interfaces and their thermophysical properties.

1. Introduction

The use of Pulsed Thermography for Nondestructive Inspection (NDT) of composite materials has increased dramatically in the past decade. Applications range from maintenance of in-service aircraft to process control for the manufacture of large aerospace structures (e.g. the NASA Space Shuttle) (1,2). Today, Pulsed Thermography compares favorably to conventional inspection technologies in terms of its sensitivity and speed, while offering some advantages in terms of curvature tolerance and non-contact inspection. Modern systems are capable of subsurface defect detection, as well as materials characterization in both polymer and ceramic matrix composites, offering reliable measurement of sample thickness, defect depth and thermal diffusivity.

Early attempts at implementation of thermography were only capable of identifying gross defects that were readily detectable using simpler coin tap or visual inspection methods. As a result, the technology was only used as a qualitative adjunct to more mature technologies, such as ultrasound or radiography. The most frequently cited shortcoming of the technology was its subjective nature, i.e. interpretation of results depended heavily on the skill and experience of the inspector. The situation has improved dramatically with new approaches to signal processing, excitation and modeling, as well as improvements in IR camera technology and computer processing and data communication speed. The net result is that for many applications, thermography is now a viable stand-alone alternative to conventional inspection technologies.

1.1 Fundamentals Of Pulsed Thermography

In Pulsed Thermography, the surface of a sample is heated with a brief (typically, a few milliseconds), spatially uniform pulse of light from a xenon flash lamp array. An IR camera interfaced to a PC monitors the time dependent response of the sample surface temperature to the thermal impulse. In areas of the sample surface closest to a thermal discontinuity (e.g. a wall, layer boundary or unintentional defect), the transient flow of heat from the surface into the sample bulk is wholly or partially obstructed, thus causing a transient, local temperature increase at the surface. For a semi-infinite, defect free sample, the time-dependent surface temperature response to an instantaneous heat pulse is given by

$$T_{Surf}(t) - T_{Surf}(0) = \frac{Q}{\kappa\rho c\sqrt{\pi t}} \quad , \qquad (1$$

where Q is the input energy per unit area, κ the thermal conductivity, ρ the density and c the specific heat of the sample (3). A plot of the natural logarithm of both sides of Eq. 1 reveals a characteristic linear profile with slope –0.5 (Figure 1). As heat applied to the surface propagates into the sample and encounters a subsurface discontinuity, a pronounced deviation from linearity occurs. The time required for these deviations from ideal behavior to occur is a function of the depth of the interface, so that it is possible to measure the depth or thickness by measuring this thermal transit time. Conversely, if depth or thickness is known, the thermal diffusivity of the sample can be measured.

2. Thermographic Signal Reconstruction

Pulsed Thermography is most readily applicable to situations where the diameter of a subsurface defect is greater than its depth beneath the surface. As the defect aspect ratio approaches unity or less, the maximum temperature difference between a defect and the surrounding intact areas decreases, often to level comparable to the noise level of the IR camera, and is not detectable in the raw camera data. For these low aspect ratio applications, or for quantitative measurement of physical properties, additional signal processing is required. In these cases, the Thermographic Signal Reconstruction (TSR) method provides a significant degree of improvement in terms of sensitivity, reduction of blurring and depth range compared to contrast analysis. The technique acts as an amplifier of signals that deviate from typical cooling behavior, by exploiting the fact that the cooling of the surface by thermal diffusion yields a highly predictable and recognizable signal, regardless of the material involved (4-6). The TSR process generates an equation based

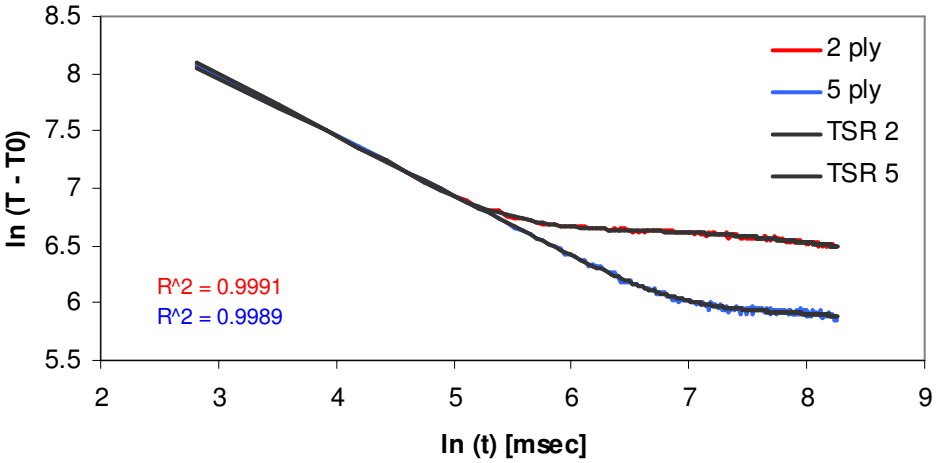

Figure 1: Raw and TSR logarithmic temperature – time evolution for 2 and 5 ply thick steps in a composite panel.

on a least squares fit of a low order polynomial to the logarithmic time history of each pixel. The result is a noise-reduced replica of the original time history.

In the TSR process, several hundred frames of raw data representing the time history of each pixel are reduced to a set of equations. The conversion process typically requires a few seconds. The fact that the TSR information is presented mathematically in a closed form allows advanced manipulation, such as differentiation, calculation of inflection points or FFT's to be performed quickly, and without adverse noise effects. The time derivatives of the logarithmic time history are particularly useful in discriminating between defective and intact points (Fig. 2). With the TSR method, pixels that deviate from linearity in their logarithmic time evolution are enhanced by differentiation, and easily identified by their derivative maxima and inflection points, compared to conventional parsing of the raw data. If the thermal diffusivity of the sample is known, the time at which the 2nd derivative peak occurs can be used to calculate the local wall thickness or flaw depth. Conversely, if the thickness of the sample (or depth of the flaw) is

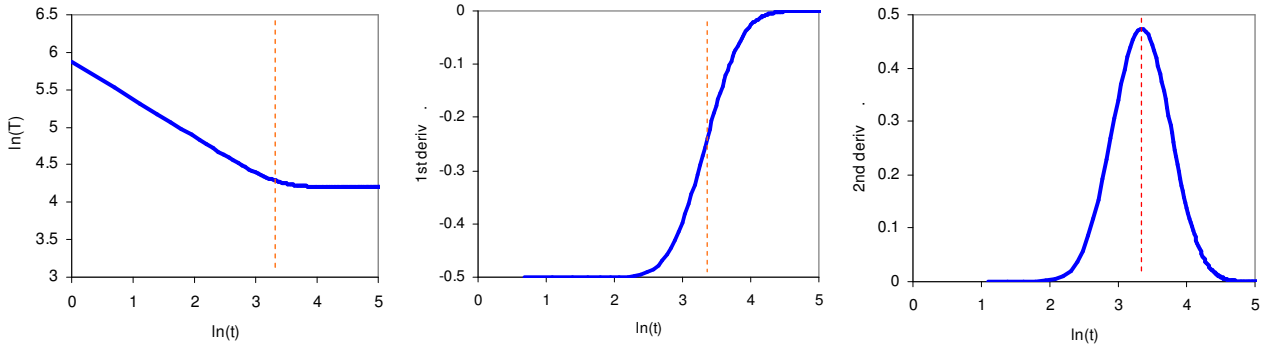

Figure 2: Comparison of logarithmic temperature-time, 1st and 2nd derivatives for a defect-free slab. The 2nd derivative maximum occurs at a time corresponding to the inflection point of the 1st derivative, and the initial departure from linearity in the log plot.

known, the same time can be used to calculate thermal diffusivity with an accuracy that is comparable to the widely used Parker flash method.

2.1 TSR Processing of Experimental Data

The effects of the TSR process on inspection results are shown in Figure 3, on a sample fabricated from 350°F cure carbon/epoxy, 3K-8 harness–satin weave prepreg. Carbon fibers were 33 MSI, AS4. The laminate consisted of a non-symmetrical $|0,90|_5$ ply stack, which was cured at 80 psi for 90 minutes. The resulting laminate was 0.129". Defects representative of voids and disbonds were fabricated from 2mm thick Rohacell® that was crushed to a thickness of .013 inches prior to placement in the laminate. The sizes of the simulated defects were one inch, one-half inch and one-quarter inch in diameter. These were placed in series under each consecutive ply of the laminate. One of the longitudinal sides of the laminate was stepped at each ply. The panel was inspected using a commercial Pulsed Thermography system (EchoTherm® – Thermal Wave Imaging, Inc.), using a 320 x 256 pixel InSb focal plane array camera operating at 60 Hz. The raw IR images show the near surface inserts and thinner steps, but features are blurred and deeper features are not detectable. Furthermore, there is little correlation between pixel intensity and defect depth. However, in the depth map that was created by applying the TSR process to the same data sequence, all inserts and steps are detected, and blurring has been significantly reduced. In particular, the smallest and deepest inserts (Figure 3, top row), which are undetectable in the original sequence, are apparent in the TSR map.

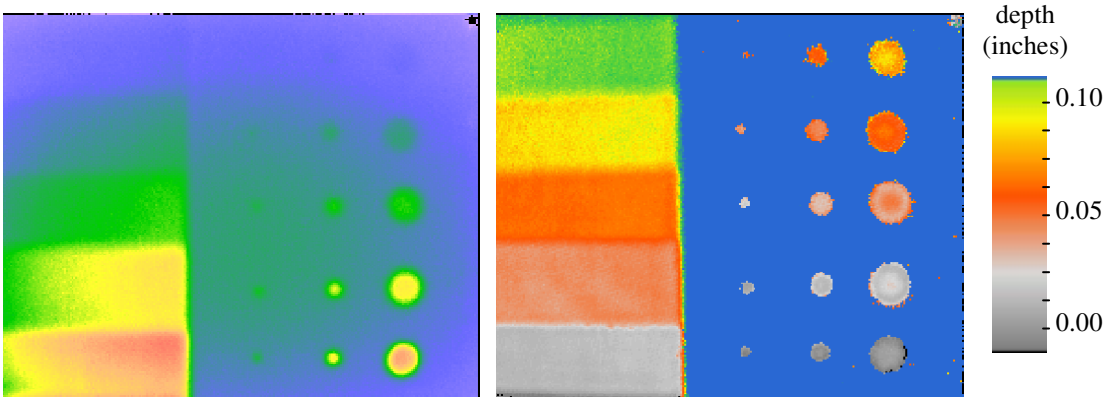

Figure 3. Thermographic images of a composite panel with Rohacell inserts between each ply layers. The inserts in each row are 0.25", 0.5" and 1" in diameter. (left) Raw IR image of the panel 1.6 seconds after flash heating. (right) Depth map created from reconstructed data.

2.2 Reduction of Image Artifacts for Low Emissivity Surfaces

In addition to increasing sensitivity to subsurface features compared to conventional contrast imaging, the use of the TSR derivatives allows inspection of low emissivity surfaces without requiring the surface preparation (e.g. application of black paint) that is often associated with thermography. The problem that normally occurs is due to the reflection of IR radiation

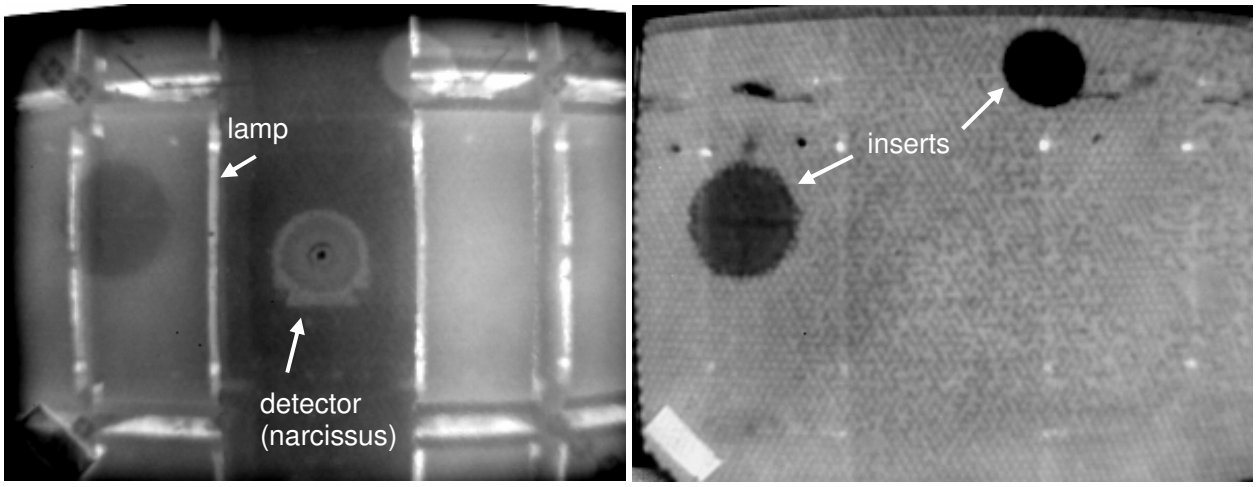

Figure 4. (left) IR image acquired 5 sec after flash heating, showing a 3-ply fiberglass panel with nomex core and both lamp and camera reflections from the low emissivity surface; (right) In the TSR 2nd derivative image of the same data set at the same time, the artifacts have been suppressed and the inserts are apparent.

emanating from the camera itself and the flash tubes and hardware off of the sample surface and into the detector. Often, the spurious reflected signal masks the emitted signal, thus preventing analysis in the low emissivity region. In such cases, the TSR derivatives significantly reduce the reflection artifact. Since the time scale of the cooling of the hardware is slow, compared to the time scale of diffusion cooling in most aerospace composites, the reflection artifact vanishes, or is greatly reduced in the TSR derivative image (Figure 4). Furthermore, features that do not appear in the raw image sequence and appear to be masked by the refection artifacts may appear prominently in the derivatives.

2.3 Parallel Processing and Analysis

In the TSR process, the raw data sequence is replaced by a noise-reduced replica, which may be subjected to subsequent processing operations, or analyzed directly. The original data set typically results in a large data structure or archival file (e.g. a 5-second sequence from a 60 Hz IR camera with 320 x 256 pixels yields a 49 MB data set), creating problems as large format focal plane array cameras gain popularity. However, the TSR replica of the original data only requires that the coefficients of the fit function for each pixel are stored (the 49 MB file size is reduced to 5 MB). As a result, a significant amount of data compression occurs, creating the opportunity to view, analyze and operate on multiple data sets simultaneously.

In actual inspection situations, this capability allows an inspector to define a large inspection area that will be interrogated in a series of acquisitions of smaller sub-areas. As the data is collected, each sub-area is added to the data set, so that on completion of data acquisition, the entire area may be viewed as a single entity, with the benefit of derivative analysis, artifact removal and in many cases, automated processing. The same capability also proves useful in manufacturing inspections, where batches of presumably identical samples are to be inspected for Quality Assurance. The entire batch can be processed and analyzed simultaneously, so that anomalous samples can be readily identified.

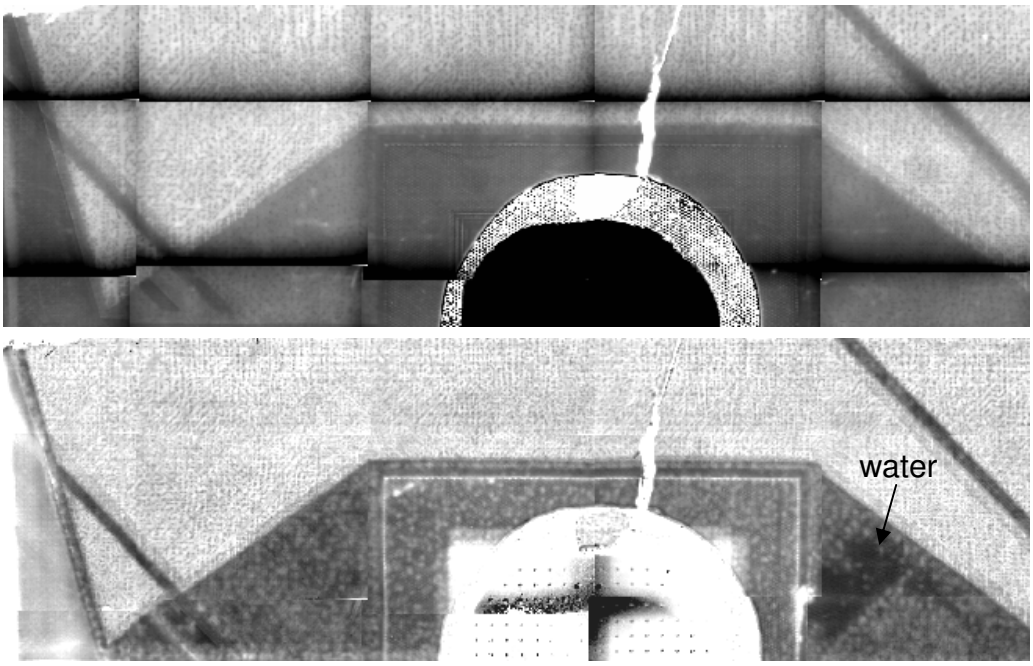

Figure 5. Multiple shot inspection of a 4 foot section of a composite aircraft spoiler. (Top) 15 shots show raw data from the image sequence at 1 sec after flash heating. Dark boundaries delineate the individual sub-areas. (Bottom) TSR 2nd derivative of the data set at 1 second after flash heating. Edge to edge matching is seamless and the boundaries have vanished. An indication of trapped water is also identified.

3. Conclusion

Analysis of flash thermography data using the TSR method offers a number of advantages in comparison to contrast analysis of raw data from the IR camera, or conventional averaging, subtraction or reference based schemes. Since the second derivative essentially indicates the time at which heat deposited at the surface encounters a subsurface interface, e.g. a wall, internal structure or an unintentional flaw, it can be used to characterize wall thickness, flaw depth or thermal diffusivity.

It is important to recognize the invariant aspects of the TSR derivatives. The basic shape of the second derivative of, say, a defect-free slab remains with adiabatic boundary conditions remains essentially unchanged regardless of the sample material, geometry or energy input (although noise considerations will come into play as the input energy approaches a small multiple of the camera noise level). Only the time scale of the derivative changes with material and thickness, while shape remains unchanged.

It is also noteworthy that the TSR approach is not based on contrast, and in fact, in many cases it allows one to infer information about a sample from a single pixel time history, without reference to a defect free sample. This is a marked departure from most approaches to active thermography, including sophisticated techniques such as lock-in, pulsed phase or principal

component analysis. In each of these techniques, one obtains data and then correlates it to the properties of a reference standard before attempting to evaluate a blind sample. Using TSR-based flash thermography, the reference step is not usually necessary, as the shape of the single pixel 2nd derivative will indicate whether the interrogated point describes a defect free interface and whether the thermal effusivity of 2nd (backing) layer is higher or lower than the 1st layer, or if the point represents a discrete subsurface flaw or feature. Recent advances in TSR processing have made true automated processing a reality (7-8). Since each pixel is treated as an independent entity, automation does not require creation or viewing of an image, or emulation of the human eye by machine vision techniques.

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