QUANTITATIVE CHARACTERIZATION OF THERMOGRAPHIC SEQUENCE DATA

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Abstract: Interpretation of image data sequences from active thermography systems has typically been based on analysis of temporal variations in the contrast of each pixel, relative to a real (or synthesized) defect-free reference point on the sample. Various schemes for quantitative analysis of contrast data have been developed, in which times for events such as maximum contrast or the maximum slope of the ascending contrast are identified and empirically correlated to physical characteristics such as depth or thermal diffusivity. The Thermographic Signal Reconstruction (TSR) method offers an effective alternative to contrast-based methods for quantitative measurement, as it significantly extends limits of detectability, and enables automated pass/fail processing. In the TSR method, a noise reduced replica of the time history of each pixel is expressed in series form, so that an entire data set, normally comprising several hundred frames, comprises only the coefficients of the series expansion for each pixel. The resulting series offers a significant improvement is signal to noise performance. However, the series is readily differentiated so that features may be detected based on the detection of inflection points or other characteristics of the pixel time history. The TSR process can be applied to an entire time sequence in order to create a single "fingerprint" image that facilitates comparison of samples to a defect free reference.

Introduction: The use of Pulsed Thermography for Nondestructive Inspection (NDI) has increased dramatically in the past few years. Applications range from maintenance of in-service aircraft to process control for the manufacture of large aerospace structures (1,2). For many applications, Pulsed Thermography compares favourably to conventional inspection technologies in terms of its sensitivity, speed, curvature tolerance and non-contact nature. Modern systems are capable of subsurface defect detection and materials characterization in both polymer and ceramic matrix composites, offering reliable measurement of sample thickness, defect depth and thermal diffusivity.

Despite the apparent benefits of Thermographic NDI, the technology was not widely accepted until recently. Early attempts at implementation were only capable of identifying gross defects that were detectable using simple coin tap or visual inspection methods. 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.

In the most widely used implementation of Pulsed Thermography, the surface of a sample is heated with a brief, spatially uniform pulse of light, and an IR camera interfaced to a PC is used to monitor and analyze the time dependent response of the sample surface temperature to the thermal impulse. In areas of the sample surface directly above a buried defect, the transient flow of heat from the surface into the sample bulk is partially obstructed by the flaw, thus causing a transient, local temperature increase. For a semi-infinite, defect free sample, the time-dependent surface temperature response to an instantaneous heat pulse is given by

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

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). Plotting the natural logarithm of both sides of Eq. 1 reveals a

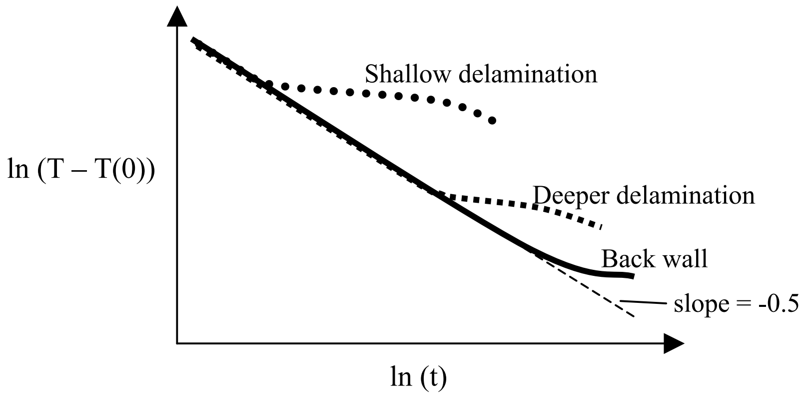

Figure 1: Logarithmic time evolution of the surface temperature. Temperature decay is linear with slope –0.5 until heat flow is obstructed by a subsurface defect or a boundary such as a wall.

characteristic linear profile with slope –0.5 (Fig. 1). As the heat applied to the surface propagates into the sample and encounters a subsurface defect, a pronounced deviation from linearity occurs. The time required for this deviation from ideal behaviour to occur is a function of the depth of the flaw, 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.

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. The Thermographic Signal Reconstruction (TSR) method was developed specifically to take advantage of the physics of heat diffusion, in order to remove noise and extraneous non-thermal signal components from the raw signal, and to accentuate signals that deviate from typical cooling behavior (4-6). The TSR process generates an equation based 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. The overall result of the TSR process is a significant increase in sensitivity to low aspect ratio features, as well as an order of magnitude reduction in RAM and storage space requirements.

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 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 zero crossings and inflection points, compared to conventional parsing of the raw data.

Results: 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

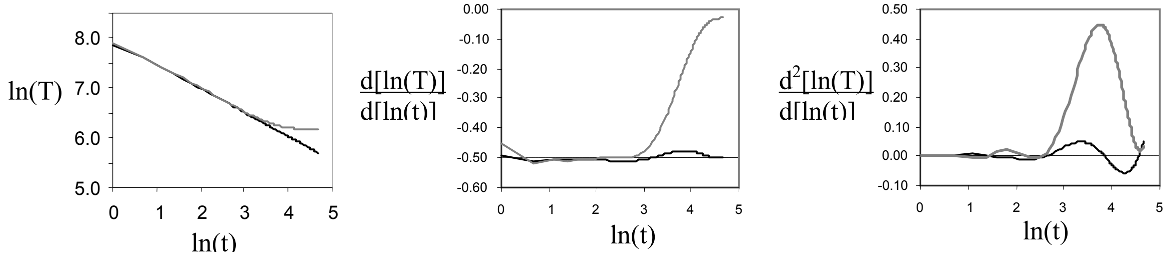

Figure 2: Comparison of logarithmic temperature-time plot of surface temperature of defect and intact points (left) with reconstructed 1st and 2nd derivatives. Contrast between defect and intact points increases with each derivative.

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), 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.

Conversion of a 300 frame (5 second) data set to a TSR data set requires approximately 10 seconds on a 1 GHz PC. Once the data has been converted, creation of a TSR image, or a reconstructed time derivative image, requires only a few milliseconds. The original data set of the image sequence is typically quite large. For example, a 300 frame (5 second) sequence from a 320 x 256 pixel camera operating at a 60 Hz frame rate occupies approximately 49 MB of storage space or RAM. However, the TSR data structure created from this same data set occupies less than 5 MB. As a result of this data reduction provided by TSR, it is possible to operate on several data structures simultaneously (the arrays of equation coefficients from each image sequence are combined into a single large array and processed in a single operation). This capability is extremely useful when large structures, which require multiple shots for complete

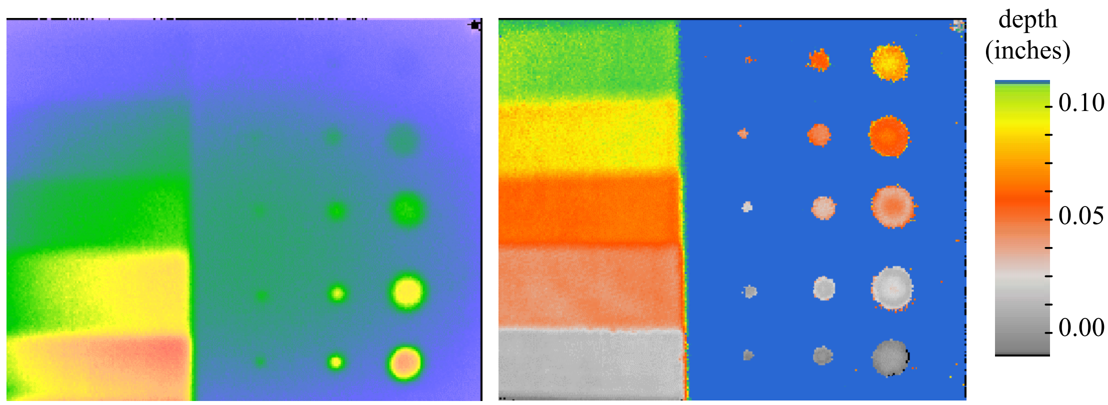

Figure 3. Thermographic images of a composite panel with Rohacell inserts between each ply layers. The inserts in each row are 0.25", 0.5" and 1" in diameter. (left) Raw IR image of the panel 1.6 seconds after flash heating. (right) Depth map created from reconstructed data.

coverage, are to be inspected, as the individual shots are automatically combined into a single shot, and processed and analyzed simultaneously using a dedicated software program. In practice, the inspector acquires the data views the final, combined shot, and then zooms in to view areas of particular interest.

Discussion: Several methods have been proposed and developed for nondestructive inspection using active thermography. These methods often involve creating an infrared image, or an image sequence, of a sample after it has been thermally excited, and comparing the resulting image or sequence with that of a previously characterized reference sample. However, practical comparison of either images or sequences is complicated by the need for precise placement of the samples in order to achieve pixel-to-pixel registration with the reference, and the variation of excitation energy, camera calibration, and ambient temperature etc. for each individual acquisition sequence.

The TSR method allows us to acquire instantaneous derivatives of the logarithmic temperature-time history of each pixel. The resulting derivative can be calculated quickly and is extremely accurate as it is based on the noise-reduced TSR signal. We can use these features to exploit the highly deterministic nature of the logarithmic temperature-time behaviour, and quantitatively and efficiently characterize and compare entire thermographic data sequences, rather than single images. Our approach is immune to the limitations described above, and does not require a human operator to compare or evaluate results.

From the solution to the 1-dimensional diffusion equation (Eq. 1), we know that the slope (with respect to ln(t)) of the logarithmic temperature-time sequence is –0.5. This fact is independent of the material composition of the sample or the camera used to acquire the data, and remains true until a subsurface boundary (i.e. a defect or a wall) is encountered. Thus, we could create a histogram (number of pixels vs. ln (t)) for the time derivative of every frame in the sequence (Fig. 4). For a defect free sample, the histogram will be sharply peaked about –0.5. If we consider the top down view of the entire set of these histograms, we will see a sharp straight line that flows –0.5. However, if a subsurface defect impedes the flow of heat into the sample, a branch off the main line will emerge at a time that is proportional to the depth of that defect. The net result is that we have reduced the behavior of the entire data sequence to a single image, or even a single curve if we just consider the primary and secondary peaks of the histogram (7). As subsequent acquisitions occur, they can be compared to a master image of the histogram sequence projection (e.g. the master can be subtracted from subsequent results with the expectation that the result

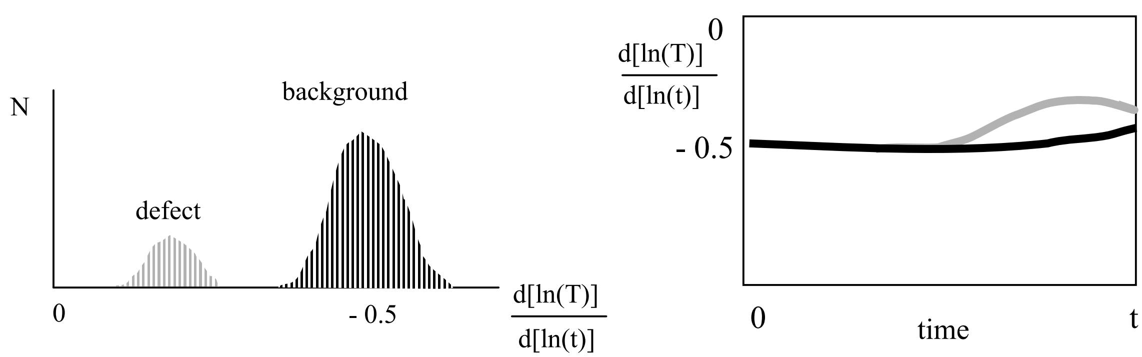

Figure 4: (left) Histogram of logarithmic slope values for a sample with discreet subsurface defect. Background pixels are clustered around a peak value of -0.5. (right) Time evolution of principal peak values of the logarithmic slope histogram. The secondary (gray) line indicates the emergence of a subsurface defect peak.

should be a nearly null image for a defect free sample). It is important to note that this approach does not depend on precise pixel-to-pixel registration between samples, or exact replication of excitation energy levels or ambient conditions, as it utilizes the logarithmic slope behavior, which is highly deterministic.

The results of this type of "thermographic fingerprint" analysis are shown in Figure 5, using the time sequence of the composite panel shown in Figure 3. The sample consists of a composite laminate with inserts and steps at successive ply layers. However, much of the sample area comprises a defect free background. Each image in Figure 5 is a reduction of the 300 frame data entire sequence to a single image. The image at the top left shows the fingerprint image for the entire sample. The subsequent images show the fingerprints associated with specific features in the sample. A sample of similar composition that was entirely defect free would yield a fingerprint that is essentially identical to the background fingerprint shown in Fig. 5 (lower right). The shape of the fingerprint curve does not depend on the orientation of the sample, or its position in the field of view, thus facilitating automated sequence comparison by statistical correlation of the fingerprint images.

Conclusions: Pulsed thermography has evolved to a point where for many applications it is a viable alternative to conventional inspection technologies. It is particularly well suited to situations where single side access is required, or where contact with the sample surface is not allowed. It is adaptable to inspection of flat or curved surfaces, and can be used in to inspect large surface area relatively quickly (a 5-10 ply graphite-epoxy laminate can be inspected at a rate of approximately 20 seconds per square foot). The Thermographic Signal Reconstruction method provides a significant increase in the sensitivity of thermography to low aspect ratio features, while minimizing blurring through the use of time derivatives. It also allows automated comparison of samples using the "fingerprint" provided by the logarithmic slope histogram sequence.

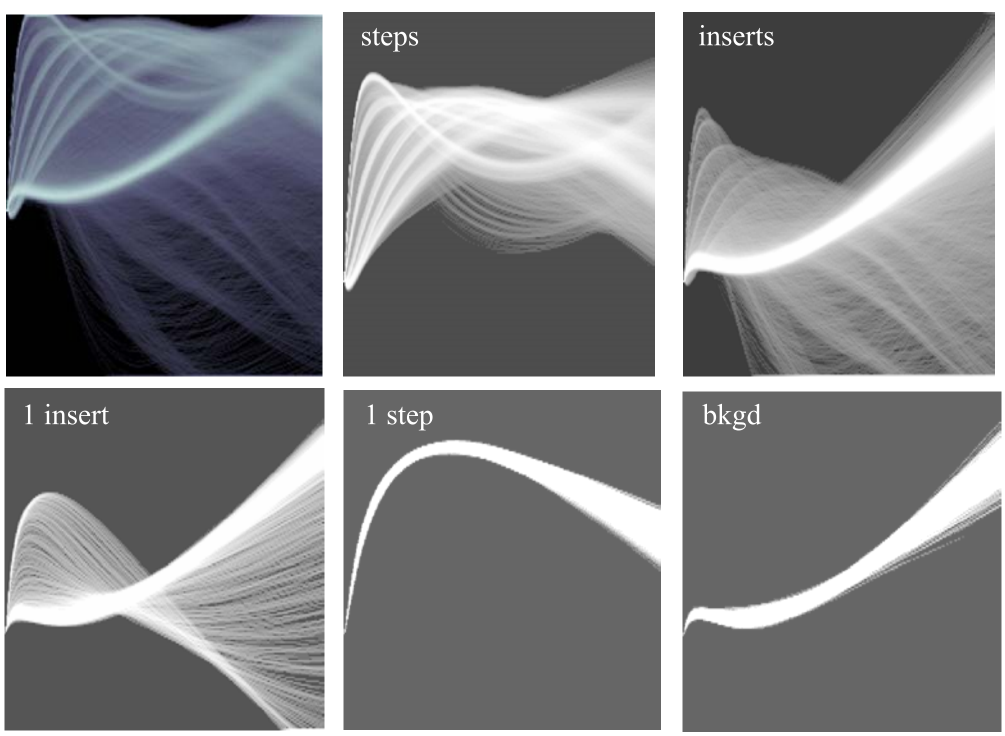

Figure 5: Logarithmic slope histogram fingerprints of the composite sample shown in Figure 3.

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7. Patent pending.