CHARACTERIZATION OF DEFECTS IN AEROSPACE COMPONENTS USING INFRARED PULSE THERMOGRAPHY

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ABSTRACT

Infrared Pulse Thermography inspection is gaining wider acceptance particularly in Aerospace industry due to its speed of inspection, sensitivity, repeatability and wider area coverage. Silica Phenolic shell and high strength steel casing bonded inside with rubber layer were characterized using Pulse Thermography for delaminations and debonds respectively. Thermal Signal Reconstruction (TSR) is used where the material response (cooling curve) is fitted to a polynomial in the logarithmic domain derived from one dimensional heat conduction equation under pulsed conditions. Time–Temperature (t-T) curve plotted for intact portions and delaminations in the Silica Phenolic shell and t-T curve plotted for intact portions and debond in the steel casing with rubber layer revealed that intact portion has slope equal to -0.5, whereas deeper defects deviated with large slope and shallow defects deviated with least slope. Thermography results are compared with the data of X-ray Radiography and Ultrasonic testing and found good agreement. Finally, Pulse Thermography is emerged as a non contact, faster, reliable and effective NDE method for characterization of defects in Aerospace components.

Keywords: Pulse Thermography, Thermal Signature Reconstruction, Silica Phenolic Shell, High Strength Steel Casing bonded inside with Rubber layer, Delamination, Debond

INTRODUCTION

Infrared Pulse Thermography inspection is gaining wider acceptance particularly in Aerospace, Automotive and Power generation industries due to its speed of inspection, sensitivity, repeatability and wider area coverage. Further, Infrared Pulse Thermography is a fast growing technique especially for the characterization of Composite structures due to its merits compared to conventional Non Destructive Evaluation (NDE) methods. Active Thermography involves an external stimulus to generate heat in the test object, whereas in Passive Thermography the test object has its own internal source of heat. In Pulse Thermography, a short and high intensity flash is used to heat up the sample. The decay of the sample surface temperature is detected and acquired by an Infrared camera. Each image in the acquired sequence corresponds to the surface temperature distribution at a particular time. Any anomaly in the subsurface will give rise to a localized temperature change resulting in thermal contrast.

In the present work, Infrared Pulse Thermography has been employed for identification and marking of delaminations and debonds from intact portions in Silica Phenolic shell and high strength steel casing bonded inside with rubber layer. Thermography data is also compared with X-ray Radiography and Ultrasonic data on the samples in terms of faster inspection, wide area coverage, etc.

The surface temperature of the sample is altered by the presence of anomalies (i.e., defects) in the sample after heat energy is impinged. These changes are transient and in many cases, too small or subtle to be observed directly in the Infrared image. The material response (cooling curve) is then recorded using a thermal camera to compare the Temperature versus time history to know the defect-free behavior. This comparison has been done using Thermal Signal Reconstruction (TSR), where the cooling curve is fitted to a polynomial in the logarithmic domain derived from the one-dimensional heat conduction equation under pulsed conditions. TSR technique produces three types of images, i.e., synthetic, first derivative and second derivative images. These images facilitate detection of smaller and/or deeper defects, which are undetectable on the raw data sequence. The principle of TSR technique is discussed [1]. S Quek et al [1] used TSR technique on Aluminum, CFRP & GFRP composites and mild Steel samples and studied the detection limits on these samples.
Principle of Thermal Signal Reconstruction (TSR) Technique

TSR technique [1] utilizes the phenomenon of heat conduction in a thick solid sample (semi-infinite), which is described by the 1D heat diffusion equation:

\[
\frac{\partial^2 T}{\partial z^2} - \alpha \frac{\partial T}{\partial t} = 0
\]  

(1)

Where \( \alpha \) is thermal diffusivity. For the case of instantaneous pulsed heating, equation 1 can be solved to give the surface temperature \( T \) as:

\[
T = \frac{Q}{e^{\alpha t}}
\]  

(2)

By considering equation (2) in the logarithmic domain, this gives:

\[
\ln(T) = \ln\left(\frac{Q}{e}\right) - \frac{1}{2} \ln(\pi t)
\]  

(3)

Which implies that, for an ideal defect-free sample, the relationship of its surface temperature to cooling time is a linear function with a slope of \(-1/2\) (Figure 1). In practice, logarithmic data will deviate from this ideal relationship for a variety of reasons such as non-linear camera response and background radiation. In this case, equation 3 is extended to give:

\[
\ln(T) = \sum_{n=0}^{\infty} a_n \ln(t)^n = a_0 + a_1 \ln + \ldots + a_{n} \ln(t)^{n} \]  

(4)

In addition, the temperature time dependences at the surface over defects deviate significantly from the linear function, so the additional terms in equation 4 are needed to fit the curves. In the TSR process, equation 4 is fitted to the logarithmic time history of each individual pixel in the raw data. Subsequently, the first derivative is calculated using equation 2 and 3:

\[
\frac{d \ln T}{d \ln t} = \sum_{n=1}^{\infty} n a_n \ln(t)^{n-1} = a_0 + 2a_2 \ln t + \ldots + n a_n \ln(t)^{n-1} \]  

(5)

With this approach, large data sequence can now be stored in the form of polynomial coefficients, which greatly reduces the storage space and also enhances image quality since the high frequency noise in the raw data is suppressed.

EXPERIMENTAL DETAILS

Pulse Thermography was carried out on 3 mm thick Silica Phenolic shell and 2 mm thick high strength steel casing bonded inside with 0.5 mm thick rubber layer, by impinging heat energy from outside using two linear xenon flashtubes (each with 4.8 kJ power) for 5 ms flash duration. Pulse Thermography was done using a Thermographic NDT system, EchoTherm from Thermal Wave Imaging, Inc. The system is equipped with an Infrared camera with 320×240 pixels operating in the 8-9 µm spectral range. Continuous 14-bit data was acquired at a 50 Hz frame rate for 10 seconds after flash heating. Logarithmic Time-Temperature (t-T) curve is plotted for defect and intact portions in the above samples for first derivative images and the data is analyzed.

RESULTS AND DISCUSSION

Fig. 2(a) to 2(n) show First Derivative images of Silica Phenolic shell using TSR technique. The First derivative images of Figs. 2(a) to 2(n) clearly reveal the temperature variations between delaminated and intact regions.

Fig. 3 shows logarithmic Time-Temperature (t-T) curve plotted for delaminated and intact portions of Silica Phenolic shell. It is seen from fig. 3 that the intact portion (Red line) has slope of -0.5 on the t-T plot, where as the shallow delamination (Green line) deviated from intact portion with least slope and the delamination at deeper depth (Blue line) deviated from intact portion with large slope. This is how intact portion and the delaminations at different depths are identified.

Fig. 4(a) to 4(l) show First Derivative images of High strength steel casing bonded inside with rubber using TSR technique. The First derivative images of fig. 4(a) to 4(l) clearly reveal the temperature variations between debonded and intact regions.

Fig. 5 shows logarithmic Time-Temperature (t-T) curve plotted for intact portions and debond of High strength steel casing bonded inside with rubber. It is seen from fig. 5 that the intact portion (Red line) has slope of -0.5 on the t-T plot, where as debond between steel casing and Rubber (Green line) deviated from intact portion with least slope. This is how intact portion and debond are identified.

X-ray Radiography Testing (RT) and Dryscan Ultrasonic Testing (UT) were also carried out on Silica Phenolic liner at intact and delaminated portions for identification and marking delaminated area. Tangential Radiography revealed delamination as a black line in the radiograph (refer fig. 6), correspondingly higher dB was found at delaminated portion (i.e., 70 dB) compared to intact portion (50 dB) in Through-Transmission data of UT. However, several tangential shots are required at closed intervals for getting the delaminated area in Radiography, subsequently UT is to be
Fig. 2: (a) to (n). First Derivative images of Silica Phenolic shell using TSR technique.
Fig. 3: Log time-log temperature curve of Silica Phenolic shell showing intact portion has slope of -0.5 (Red line), delamination at shallow depth (Green line) and delamination at deeper depth (Blue line).

Fig. 4: (a) to (l). First Derivative images of High strength steel casing bonded inside with rubber using TSR technique
Fig. 5: Log time-log temperature curve of High strength steel casing bonded inside with rubber showing intact portion has slope of -0.5 (Red line), debond (Green line) between steel casing and Rubber

Fig. 6: Radiograph revealing delamination in Silica Phenolic shell carried out at closer grid points for marking the delaminated area. RT & UT methods take longer time for marking the delaminated area compared to that of Pulse Thermography (6 sec). It is clear from the above results that Thermography can be used as a stand alone method, which has taken considerably less time compared to UT & RT for identification of delaminations at shallow & deep depths and marking the delaminated area. The same is true in the case of High strength steel casing bonded inside with rubber layer.

CONCLUSION

The t-T plots using Infrared Pulse Thermography revealed the differences between intact portions, delaminated & debonded portions in Phenolic shell and high strength steel casing bonded inside with rubber layer. Pulse Thermography is able to use as a stand alone method for identification and marking the area of delaminations & debonds more clearly at lesser time than conventional UT & RT methods. Finally, it is concluded that Infrared Pulse Thermography is a non-contact, faster, reliable and effective NDE method for detection and characterization of delaminations and debonds in Aerospace components.

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REFERENCES