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This paper was prepared for submittal to the
SPIE Optical Science, Engineering, and Instrumentation Conference
San Diego, CA
July 9-14, 1995

June 27, 1995

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Stimulated dual-band infrared computed tomography: a tool to inspect the aging infrastructure

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ABSTRACT

We have developed stimulated dual-band infrared (IR) computed tomography as a tool to inspect the aging infrastructure. Our system has the potential to locate and quantify structural damage within airframes and bridge decks. Typically, dual-band IR detection methods improve the signal-to-noise ratio by a factor of ten, compared to single-band IR detection methods. We conducted a demonstration at Boeing using a uniform pulsed-heat source to stimulate IR images of hidden defects in the 727 fuselage. Our dual-band IR camera and image processing system produced temperature, thermal inertia, and cooling-rate maps. In combination, these maps characterized the defect site, size, depth, thickness and type. We quantified the percent metal loss from corrosion above a threshold of 5%, with overall uncertainties of 3%. Also, we conducted a feasibility study of dual-band IR thermal imaging for bridge deck inspections. We determined the sites and relative concrete displacement of 2-in. and 4-in. deep delaminations from thin styrofoam implants in asphalt-covered concrete slabs. We demonstrated the value of dual-band IR computed tomography to quantify structural damage within flash-heated airframes and naturally-heated bridge decks.

Keywords: dual-band infrared imaging, infrared computed tomography, thermal nondestructive evaluation

1.0 INTRODUCTION

1.1 Conventional thermography

Recent applications of thermography include nondestructive inspection and evaluation (NDI and NDE) of airframes, composites, and aerospace structures. Infrared imaging and detection has the potential of rapidly inspecting large areas at video frame rates (30 frames per second) to provide an early warning of subsurface defects, e.g., corrosion thinning, sites with poor adhesive bonding (unbonds), voids, inserts, and delaminations. Using single-band infrared (SBIR) imaging methods, scientists have successfully depicted the sites of subsurface defects in manmade structures.¹⁻⁵

Conventional SBIR imaging methods have not been able to classify defect types. They have not successfully distinguished between major defects that affect the mechanical integrity of large structures, e.g., more than 10% corrosion thickness reduction, and minor defects that do not warrant costly repairs, e.g., ripples, sealant globs, uneven paint, stains, tape markers, scratches, dents, and insulation wads attached to the interior of the aircraft fuselage. A recent round-robin investigation of commercial NDI equipment used to detect hidden corrosion on U.S. Air Force aircraft indicated that false detection of corrosion results in unnecessary and destructive exploratory maintenance.⁶

1.2 Thermography needed to image anomalous structural heat flows

Lawrence Livermore National Laboratory (LLNL) has pioneered an emissivity-corrected, dual-band infrared (DBIR) method, which images anomalous heat flows from buried objects and structural defects.⁷ The DBIR method quantifies corrosion (percent metal-thickness reduction) damage within flash-heated metal and naturally-heated concrete structures.⁸⁻¹⁷ Typically, the DBIR method provides from five-to-ten-times improved defect signal-to-noise ratios, and better interpretability, compared to SBIR methods. Improved temperature contrast, clutter removal, and quantification of material losses are features of the DBIR method that clarify interpretation of defect sites by classifying defect types and eliminating false-defect calls.

1.3 Rationale for precise, emissivity-corrected, thermal imaging

We discuss an adaptation of the DBIR thermal imaging method for aircraft and concrete bridge deck inspections.⁷ To this end, we image two simultaneously-recorded infrared (IR) wavelength intervals at 3-5 μm and 8-12 μm . We make use of a property of Planck's Radiation law, that near 288 K (15 °C), the DBIR (radiant emittance) signal intensities vary as the emissivity times absolute temperature (T) to the power ($50/\lambda$) where λ is the wavelength in microns.¹⁸

This expression is based on a power-series expansion of Planck's radiation law which provides a convenient approximation (at wavelength intervals centered near 5 μm and 10 μm). The signals near 5 μm vary as the tenth power of temperature, T , whereas the signals near 10 μm vary as the fifth power of temperature, T . By taking the appropriate DBIR image ratios, we produce images of high-contrast temperature (T^5) maps and surface emissivity-noise (E) maps, where:

$$(T/T_{av})^5 = (S/S_{av}) / (L/L_{av}) \quad (1)$$

$$E = (L/L_{av})^2 / (S/S_{av}). \quad (2)$$

In Eqs (1) and (2), S is the short-wavelength intensity signal, S_{av} is the average value of the pixels in S , L is the long wavelength intensity signal, and L_{av} is the average value of the pixels in L .

We use DBIR image ratios, from DBIR cameras which scan targets at infrared wavelengths of 3-5 μm and 8-12 μm , to enhance surface temperature contrast and remove the mask of surface emissivity noise. This clarifies interpretation of subtle heat flow anomalies associated with hidden structural defects in multi-layered metal and concrete structures.

1.4 Pulsed thermal imaging

During 1994, we developed a field-portable DBIR prototype system for non-destructive inspection (NDI) of flash-heated aircraft structures for the Federal Aviation Administration Technical Center. The DBIR prototype system has a unique combination of spatial (0.5 mm), thermal (0.1 $^{\circ}\text{C}$), spectral (3-5 μm and 8-12 μm), and temporal (0.5 ms per line) resolution. Spatial, thermal, temporal and spectral resolution are exploited to clarify interpretation of hidden structural defects in pulsed-thermal NDE.

1.5 Thermal inertia maps

Thermal inertia is a measure of the bulk thermal properties for the target material. We developed thermal inertia (or effusivity) maps to characterize structural defects depicted by pulsed thermal imaging. Thermal inertia maps have been used previously for other applications.^{19,20} We solve the heat transfer equation for a thick target with an instantaneous surface heat flux:²¹

$$T(x,t) = \frac{q}{\sqrt{4\pi k\rho c t}} \exp\left(-\frac{x^2}{4\alpha t}\right) \quad (3)$$

where T is temperature, x is the distance from the surface, k is thermal conductivity, ρ is density, c is heat capacity, α is thermal diffusivity, t is time and q is the surface heat flux. For a semi-infinite solid approximation, the surface temperature is proportional to the inverse square root of time. In practice, we map the fuselage composite thermal inertia, $(k\rho c)^{1/2}$, based on the (inverse) slope of the surface temperature versus the inverse square root of time.

1.6 Timegram cooling-rate maps

The timegram records the dynamics of flash-heated linescan profiles across the target. The timegram has time increasing downward, along the vertical axis, the target profile positioned along the horizontal axis, and the target cooling-rate signature measured by color-coded temperature differences. Algorithms generate co-registered thermal, timegram cooling-rate, and thermal inertia maps which clarify interpretation of structural defects and eliminate false (corrosion-loss) defects. Using pulsed-thermal imaging, we characterize structural defects by their location, depth and the degree to which their cooling-rate signatures differ from ambient for the host-material.

1.7 Detecting defect sites, sizes and depths in three dimensional space

Using VIEW image processing macros, we developed algorithms for infrared computed tomography (IRCT). We produced co-registered images of emissivity-corrected temperature, thermal inertia and timegram cooling-rate maps. Using these maps, we inferred the defect type, site, size, material-loss and depth. The heat flow anomalies generated by a 4.2 ms heat flash have thermal signatures which characterize the target physical properties, such as temperature, cooling rate, and thermal inertia. These thermal signatures differ at sites where the multi-layered structures are defective.

1.8 Interpretability of structural defects

We addressed the important issue of interpretability. False (corrosion-loss) defects are generated quite frequently from sealant thickness variations and production ripples. Corrections made with dual-band IRCT methods clarify interpretation of material-loss defects from corrosion. Based on the Tinker AFB studies, conventional thermal imaging methods locate about as many

false as true corrosion-loss defects. For military aircraft, the IRCT method potentially halves the exploratory maintenance repair costs.

We developed algorithms to remove factors which obscure proper identification of airframe corrosion-loss defects. Firstly, typical flashlamp sources produce uneven heat patterns. We correct for this with filters generated by IRCT algorithms which remove the uneven heat source effects for a uniform thickness reference standard. Secondly, emissivity noise from surface clutter (tape marks, dirt, uneven paint, stains, roughness variations) obscures identification of defect sites. Both clutter and defect sites appear on uncorrected thermal maps, while only defect sites appear on corrected thermal maps.

Thirdly, interpreting airframe bulges as "pillowing" from expansion of corrosion by-products is subjective. Visible indicators of surface bulges vary only slightly for different types of material defects (e.g., corrosion by-products, sealant globs, and production ripples). To gain improved precision, definition and interpretability, we measure the dynamic pulsed-thermal timegram and thermal inertia responses.

2.0 IRCT DEMONSTRATION TO INSPECT THE BOEING 727

We describe temperature, timegram and thermal inertia maps which clarify interpretation of defects and quantify the percent metal losses from corrosion within the 727 airframe. See Figures 1 and 2.

2.1 Description of temperature maps

The temperature maps refer to skin measurements at 0.43 seconds after the flash. They show the various surface temperatures for skin thicknesses of .063, .070 and .107 inches, measured with ultrasonic thickness gauges, near S27r at body station 1066. Using the six reference standards, we determined that a typical 1 °C temperature rise at 0.43 seconds after the flash corresponded to a 12.5 % metal loss for laps and skins ranging in total thickness from .030 to 0.125 inches. The color-coded temperature scale uses a separate color hue to represent a 1 °C change, and intensity differences to represent 0.1 °C changes.

2.2 Description of timegram cooling-rate maps

The timegram cooling-rate maps show the cooling-rate signatures at 0 to 0.16 seconds after the flash for linescan profiles along S26r and S27r. Metal thinning, from chemical milling, corrosion, or other causes, has a characteristic cooling-rate signature on the timegram map. Thinner skins reach higher peak temperatures, and take longer to cool to the ambient temperature.

2.3 Description of thermal inertia maps

The thermal inertia maps show how the near surface structures, when compared to the deeper structures, have varying physical properties. Thermal inertia is the square root of the target conductivity, density, and heat capacity. It is a measure of the resistance to temperature change for bulk materials within the target.

Corrosion by-products have a very different thermal inertia than metal skins. At early times, from 0.1 to 0.4 seconds, the thermal inertia maps depict thermal property differences for near-surface materials, objects, and structures, such as uneven paint, sealant globs, rivets, and skin-corrosion by-products. At later times, the thermal inertia maps characterize corrosion defects, fabrication flaws, substances which impede corrosion within deeper structures, and substances on the inside surface.

2.4 Thermal NDE results for the Boeing 727 airframe

The results for the 727 airframe which we inspected at Boeing are shown in Figures 1, and 2. Figure 1 shows the stringer S26r lap splice and the stringer S27r skin temperature maps and timegrams. The temperature map is a composite of eight images, each of which overlapped the adjacent images.

Typical above-ambient temperature variations along the .115-in. thick lap profile at S26r, from body stations 1035 to 1070, averaged 0.3 ± 0.2 °C. This is equivalent to the effect of 4 ± 2 percent, or .004-in. $\pm$.002-in., corrosion thinning. Clearly, the lap may have had fabrication thickness variations of this order. Apart from the effect of rivets, the lap timegram cooling-rate signatures were uncharacteristic of corrosion.

Also shown in Figure 1 are typical above-ambient temperature variations along the .063-in. skin profile at S27r, from body stations 1035 to 1070, where above-ambient temperatures averaged 0.8 ± 0.2 °C. This is equivalent to the effect of 10 ± 2.5

percent, or .006-in. $\pm$.0015-in., corrosion thinning. The single-skin timegram cooling-rate signatures for S27r were more characteristic of corrosion, especially near body stations 1053 and 1063 where there were, in addition, visible indications of pillowing. Doublers and triplers at S27r body stations 1070 to 1085 produce regions cooler than their surroundings by several degrees Celsius. These regions had cooling-rate signatures unlike the regions without doublers or triplers.

The 727 temperature maps in Figure 2 show .107 in. skins as green, .070 in. skins as yellow and .063 in. skins as red. The thinner skins were chemically milled. Co-positioned doublers, triplers and stiffeners which had a total thickness of about 0.50 in., appeared as blue at 0.43 s after the flash. The stringer S27r skin thicknesses were measured using an ultrasonic thickness gauge.

Figure 2 also shows the 727 thermal inertia maps for stringer S27r. Thermal inertia is a measure of the target material resistance to temperature change. At early times, from 0.1 to 0.4 s, thermal inertia maps show shallow riveted skins. At late times, from .4 to .7 s, the thermal inertia maps show the deeper structures such as those used as stiffeners to strengthen Stringer 27r. The S27r skin at body station 1066 was riveted to a deeper structure. By clarifying interpretation, thermal inertia maps eliminate false-defect calls which could lead to costly destructive exploratory maintenance.

3.0 RESULTS OF FEASIBILITY STUDY FOR BRIDGE DECK INSPECTIONS

We describe the rationale and image-processing analysis for NDI of known synthetic delaminations, such as thin styrofoam implants, in concrete and asphalt-covered concrete slabs. See Figures 3 and 4.

3.1 Distinguishing structural defect sites from emissivity noise in concrete structures

To successfully demonstrate the feasibility of concrete bridge deck inspections, we used emissivity-corrected thermal NDE to clarify the sites of synthetic delaminations within a concrete slab. Our tower-mounted DBIR system simulated the bridge-deck optics. Figure 3 shows the sites of five known 2-inch deep synthetic delaminations in a concrete slab, which were left and right of center. Figure 4 shows the sites of known 2-inch deep, at top left, and 4-inch deep, at top right, synthetic delaminations in an asphalt-covered concrete slab.

3.2 Enhancing temperature contrast and eliminating emissivity noise

Using DBIR image ratios, e.g., from DBIR cameras which scan at infrared wavelengths of 3-5 mm and 8-12 mm, we enhanced temperature contrast and removed the mask from surface-emissivity noise. We studied the effects of surface contamination and compositional variations. We placed various objects along the perimeter of the slabs, such as sand, gravel, grease stains, oil spots, metal objects, and lane markers. We developed algorithms to distinguish surface object sites from hidden defect sites.

The use of enhanced temperature-contrast and emissivity-noise maps clarified interpretation of the concrete slab implant sites in Figure 3. The concrete composition, near the slab center and upper left corner, produced a surface which did not behave like an ideal blackbody surface. Consequently there was a non-thermal pattern on the enhanced temperature map. Since this pattern was also on the emissivity-noise map, we knew it was not related to a heat flow anomaly generated by the thin styrofoam implants. The concrete composition at this site had a molecular-stretch resonance at the 8-12 mm wavelength interval.

3.3 Processing to remove top-layer temperature gradient

To clarify interpretation of subtle heat flow anomalies associated with deep delaminations sites, we removed the heat flow anomalies from the asphalt surface layer shown in Figure 4. Density variations over the upper 2-inch layer of pavement, e.g., for unevenly-compacted asphalt, produced a 2 °C temperature-gradient mask. Using the LLNL/VIEW code, we removed this mask with image processing to depict the deeper (and weaker) 0.6 °C temperature gradients from the site of the synthetic delamination at a 4 inch depth, top right corner, and at the asphalt-concrete interface, at a 2 inch depth, top left corner.

3.4 Follow-on bridge deck inspections from a moving vehicle

Having achieved all the goals of the feasibility study, we are adapting the emissivity-corrected thermal NDE system, with VIEW image processing, to inspect a concrete bridge deck from a moving vehicle. We will select a bridge deck which is designated for repair so that we can inspect it before and after the repairs have been made. The potential near-term benefits of the emissivity-corrected thermal imaging system are in-service monitoring from a moving vehicle to inspect the structural integrity of the bridge deck.

4.0 SUMMARY AND CONCLUSION

We demonstrated a fast, wide-area, NDI method to quantify aircraft corrosion damage, such as percent metal loss, above a threshold of 5 %, with 3 % calibration uncertainties. It has been used successfully to characterize defect types, and their respective depths, in multi-layered composite materials used for wing patches and doublers. The dual-band infrared, computed tomography method has potential to provide assurance of structural integrity for airframes, doublers and pipelines.

Affordable asphalt-covered bridge deck rehabilitation requires an NDI method to accurately estimate the amount of deteriorated concrete from delaminations, which result from corrosion of the steel reinforcing bars, placed two inches beneath the surface of the concrete. We plan to conduct bridge deck demonstrations from a moving vehicle, for Phase 2 of the feasibility study. This is a logical extension of the investigation we successfully completed for Phase 1, e.g., by mapping the synthetic delaminations under asphalt-covered concrete slabs. These demonstrations are expected to estimate the amount of deteriorated concrete impairing the deck integrity. Potential longterm benefits are affordable, and reliable, rehabilitation for bridge decks.

5.0 ACKNOWLEDGMENTS

This work was performed by LLNL under the auspices of DOE contract number W-7405-ENG-48. We acknowledge support from the FAA Aging Aircraft Non-Destructive Inspection R&D Program, Interagency Agreement DTFA03-92-A-00007 and Federal Highway Administration (FHWA Order Number DTFH61-93-Y-00145. We are grateful for the loan of the Bales Scientific Inc. uniform flashlamp heating source, the Rockwell 0.040-inch and 0.125-inch graded-thickness reference standards developed by Steve James, the F-15 corroded wing box which we used as a reference standard from Owen Manning at Northrop, and the reference panels from Jeff Thompson at Boeing. We acknowledge the helpful technical discussions, ultrasonic thickness-gauge measurements and support of the Boeing Commercial Airplane Group.

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Figure 1. The Boeing 727 fuselage temperature map and timegrams. Note surface temperature rises of 0.8°C along S27r skin profile which correspond to a 10% metal loss.

Figure 2. Temperature maps highlight outer skin thicknesses of .063 to .107 inches. Thermal inertia maps show shallow riveted skins at early times and deeper structures at late times.

Concrete slab defect maps derived from dual-band infrared images

Figure 3. Dual-band (two color) IR temperature and emissivity-noise maps are used to locate sites with 2-inch deep defects in concrete slabs and remove sites with surface emissivity-noise.

Asphalt-concrete slab defect maps with corrections for uneven asphalt compaction

* Corrections made to remove asphalt-layer thermal noise.
 ** Filter used to enhance surface objects.

Figure 4. Dual-band (two color) IR temperature and emissivity-noise maps are used to locate sites with 4-inch deep defects in asphalt-concrete slabs and remove sites with surface objects.