Theory and application of coating tolerant thermography

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ABSTRACT

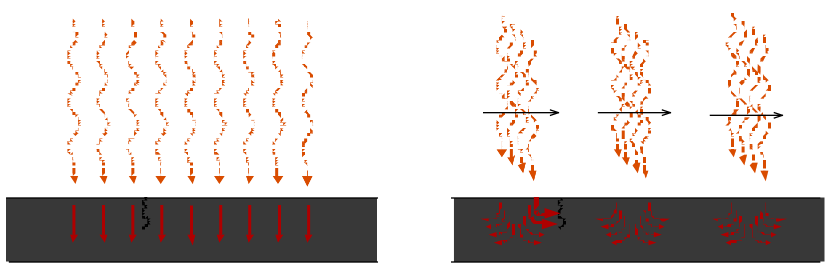
Thermal methods have been recognized above other NDI methods for rapid inspection of large structures. Thermal methods are safe, convenient and relatively inexpensive. Coating Tolerant Thermography is specifically designed to meet the demands of more challenging field conditions. The technique's ability to differentiate between chipped paint and structural flaws is essential to field performance. However, equally important is the packaging of the system. The system must be lightweight, safe and inexpensive to maintain. This technique utilizes thousands of Watts of radiant energy emanating from a hand held system. Inefficiencies in the projection optics can result in heating of the system itself, which then would necessitate significant cooling. This paper describes a unique projection system that can efficiently convert the energy emitted by an inexpensive incandescent line source into several projected stripes for Coating Tolerant Thermography.

Keywords: thermography, NDE, crack, bridge, coating tolerant, Forced Diffusion Thermography

1.0 INTRODUCTION

1.1 Technology review

Thermal methods correlate structural integrity with thermal diffusivity. If the molecular structure is altered, impairing transfer of forces, then the conduction of heat energy is impeded[1, 2]. Coating Tolerant Thermography projects a pattern of dynamic heat to force conduction across cracks (Fig. 1b) thereby, optimizing the measurable thermal gradient[3, 4, 5, 6].

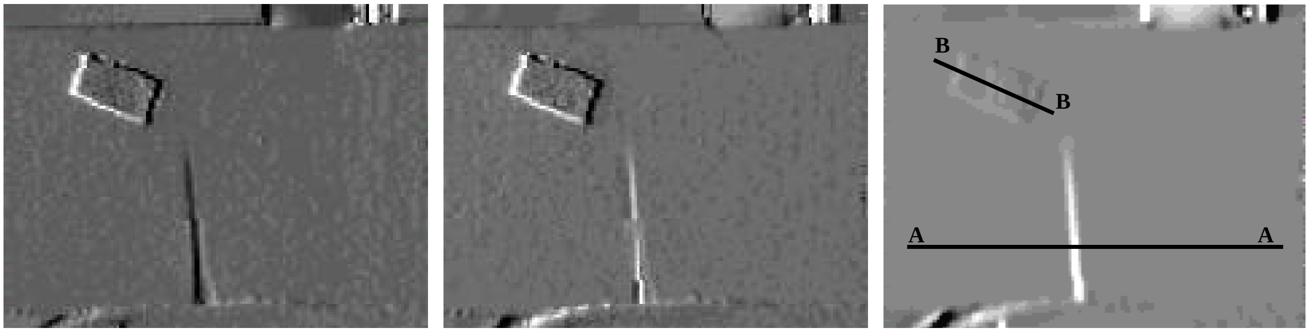


a) Uniform heating b) Forced diffusion heating

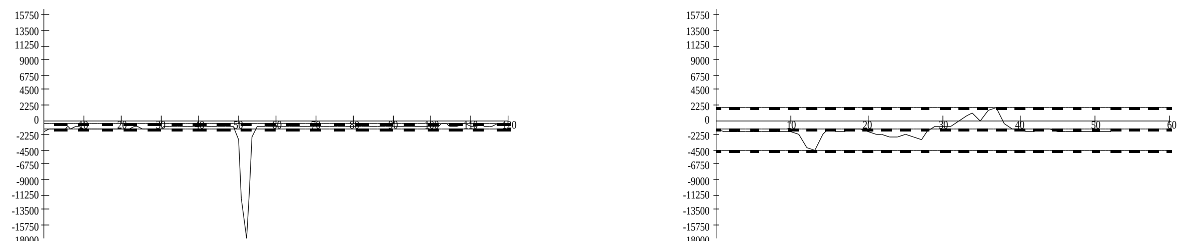
Fig. 1 Thermal methods

Heat travels from "hot" stripe to "cool" stripe as the stripes slowly comb the structure for cracks. The in-plane heat flow is impeded by a structural flaw, such as a crack, creating a gradient in the thermal image, which clearly defines the crack. The fundamental principle behind Coating Tolerant Thermography is that only the thermal spatial derivative of a true structural anomaly will change sign with opposing heat flow. When the heat is flowing from the left, the gradient is positive (as defined) because the heat builds up behind the crack on the left. When heat is flowing from the right, the gradient changes sign becoming negative because now heat builds up behind the crack on the right side. Only a true structural flaw has this characteristic.

A 12”x 2”x 1/4” steel specimen coated with a reflective white paint was prepared with a rusted paint chip near a fatigue crack. Notice the difference in shading of the crack between the first two images (Fig. 2a and Fig. 2b), and the lack of a change in the shading of the paint chip. The emissivity gradient caused by the paint chip is almost completely eliminated from the final data by performing the subtraction of the right and left images. The subtraction process accentuates the crack, because it impedes the flow of heat from both directions. The line plots (Fig 2d and 2e) show the relative signal remaining after subtraction for the chip and for the crack.



a) Heated from left   b) Heated from right   c) After subtraction



d) Line A-A Signal level from crack   e) Line B-B Signal level from paint chip

Fig. 2 Effects of paint anomalies minimized using the normalized subtraction process

A further understanding of Coating Tolerant Thermography can be gained by mathematical examination of thermal gradient images. Coating Tolerant Thermography measures the thermal distribution before and after heating thereby removing reflections and pre-existing conditions. The difference image, I(x,y), is only influenced by a change in the thermal state created by the thermal projection and the emissivity profile of the area,

$$I(x,y) = \varepsilon(x,y)\Delta\Phi(x,y) \tag{1}$$

where $\Delta\Phi(x,y)$ is the photon flux resulting from the added heat or heat lost since the capture of the initial image, and $\varepsilon(x,y)$ is the emissivity profile. By the product rule the apparent gradient image is described by

$$I_x(x,y) = \varepsilon(x,y)\Delta\Phi_x(x,y) + \varepsilon_x(x,y)\Delta\Phi(x,y) \tag{2}$$

From a single thermal gradient image it is difficult to discern between a structurally induced thermal gradient and an emissivity variance. By normalizing both sides of Eq. 2 by Eq. 1 a separation of variables is accomplished,

$$\frac{I_x(x,y)}{I(x,y)} = \frac{\Delta\Phi_x(x,y)}{\Delta\Phi(x,y)} + \frac{\varepsilon_x(x,y)}{\varepsilon(x,y)} \tag{3}$$

which creates a means of distinguishing structural flaws and emissivity gradients. If the direction of the heat conduction changes, then the $\Delta\Phi(x,y)$ (thermal) term changes sign, but the $\varepsilon(x,y)$ (emissivity) term does not. By taking the difference between two images where the direction of the heat conduction is opposite in sign, Coating Tolerant thermography can discern between real flaws and emissivity variances.

3.0 INSTRUMENTATION

3.1 Projector development

The key to designing any system is optimizing signal to noise ratios in a lightweight and compact form factor. For the design of this system a balance must be achieved between high resolution yet expensive infrared cameras and a high energy output projector. Although sufficient power can be made available at an inspection sight, the projector must be very energy efficient, because any energy not passing through the optics is absorbed by the projector and transferred to the operator. It was decided that readily available, inexpensive and safe incandescent light sources would be utilized. High wattage (1000W, 120V) line sources were chosen because hot-burning incandescent line sources emit most of their energy in the near IR below 3μm, and a number of simple cooling techniques for these sources were available. It is also convenient to project energy that does not significantly overlap with the sensitivity range of typical IR cameras (3-5μm and 8-12μm). A field worthy unit capable of projecting three 0.5" wide 12" tall stripes has been constructed. Eventually this unit can be made to provide a square foot of inspection coverage.

3.2 Final projector design

The projector uses unconventional yet simple optics to satisfy all of the above-mentioned criteria. All of these goals have been accomplished with the "heat squid" concept. At the heart of the projector is an elliptical light separator (Fig. 3). The separator creates three stripes of energy from a single line source. Two stripes are created by outside elliptical reflectors, and a cylindrical lens creates another stripe in the center, between the first two. On each side of the cylindrical lens (center) is a cylindrical reflector that reflects the light energy back to the line element and out the other side to be utilized by the opposing elliptical reflectors. Utilizing only cylindrical optics means that although the line source is imaged in three distinct locations, there is no spatial coherency in the vertical dimension between any point on the line source and the three line images. The light is funneled through the projector by parallel caps. These caps contain the light so that all the energy must pass through the line images. At this point the F-number in the plane of the ellipse has been changed from a single source emitting light in the round to three distinct line sources projecting at F/2. Out-of-plane, however, nothing has changed. The light radiates from the line images over a half hemisphere. All the reflective optics are gold-plated for maximum efficiency.

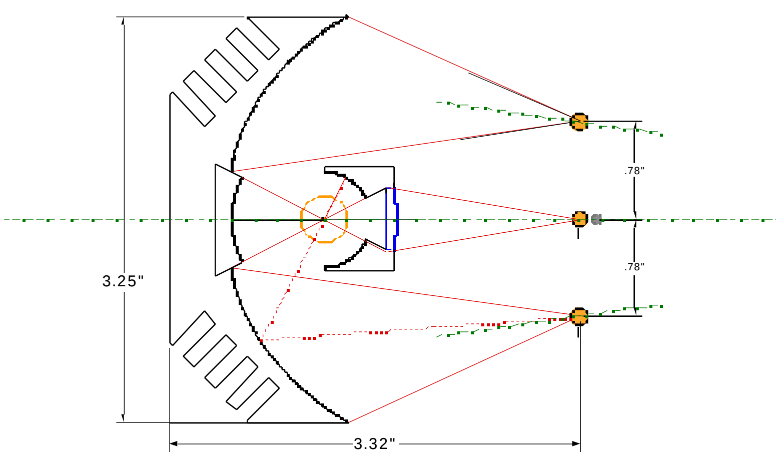


Fig. 3 Reflective ellipse light separator

In the plane of the ellipse the light is ready to be received by the projection optics, but in the vertical plane it is unconditioned. Therefore, before it is projected the light exits the capped ellipse area and enters the expansion light guides (Fig. 4). As the high angle of incidence rays of light strike the expansion guide, the slope of the ray is reduced. The end result is a taller more uniform pattern projection with a controlled radiant distribution. The thermal distribution is now conditioned in the vertical plane as well. Notice that the light entering is in no way spatially coherent with the light leaving the guide.

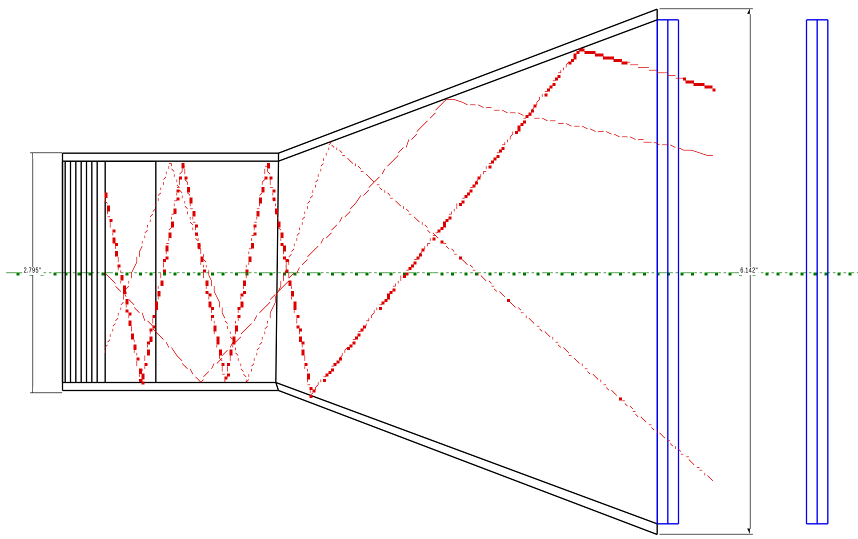


Fig. 4 Side view of projector layout (vertical light management)

The expansion guides also offer an opportunity to split the pattern into additional lines. If two guides are filled by a source image, and are then separated as they extend to the projection plane, the pattern line density is doubled. The final portion of the projector is the condenser/projector lens combination, which also gives some flexibility in the adjustment of standoff distance and coverage area (Fig. 5). The condenser lenses help direct the rays of light to the projection lens, which then projects the pattern onto the area of interest. A different focal length is needed in the vertical direction than in the plane of the ellipse. To accomplish this the condenser lens is actually formed by cutting a Fresnel lens into three vertical strips near the center. The strips are then fanned out so that the "lens" has less apparent power in the plane of the ellipse. Both the condenser and projection lenses are polycarbonate Fresnel lenses.

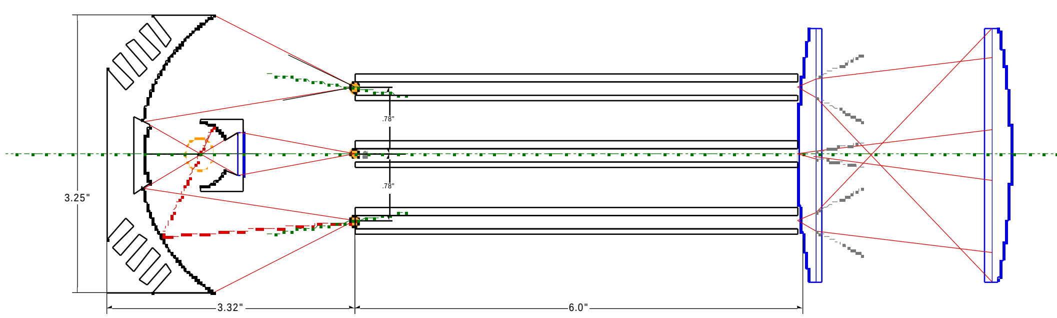


Fig. 5 Top view of projector layout (horizontal light management)

Movement of the stripes over the area of interest will be accomplished by rotating the cell or animating the projection lens. From element to projection lens, the system is about 15 inches long and is 3"w x 6"h. In the final system several of the 1000 Watt sources will be used in combination, permitting groups of three stripes to be divided, so that higher line densities can be achieved when necessary. The final configuration will be determined through lab and field testing of real bridge components.

3.2.1 Fresnel lenses

As mentioned, this system makes use of Fresnel lenses. Fresnel lenses are commonly employed as condenser lenses as they save space and weight; however, they are not commonly used as projection lenses in imaging systems. In our specific application, aberrations are minor relative to the spatial content of the projected pattern, so a Fresnel projection lens is acceptable. Figure 6 shows a plot of the transmittance of the Fresnel lens material used in this application, which should allow 95% of the total energy to pass through with the energy output of the bulb peaking at 0.8μm and tailing off to less than 10% at 3.5μm.

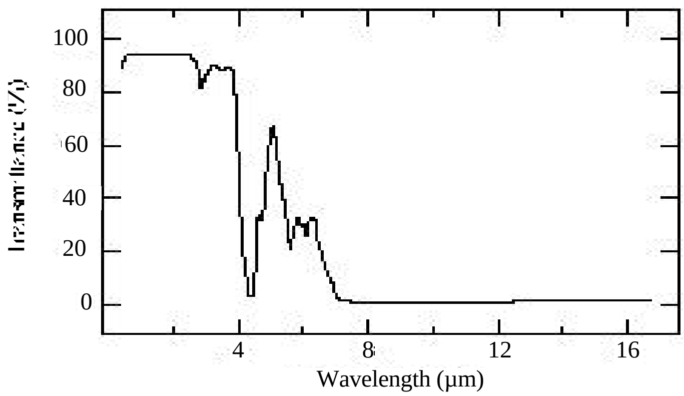


Fig. 6 Transmittance as a function of wavelength for POLY IR 5 material

3.2.2 Gold plated optics

All of the reflective optics within the system will be gold plated Al, which has superior reflective characteristics and is surprisingly affordable. Pure gold is generically 98% reflective through a broad range of wavelengths, but plating thickness and purity can vary, resulting in reflectance which may vary from as low as 87% to as high as 99.7% for a given wavelength. Figure 7 shows the assembled light guides with the elliptical and spherical reflectors in the foreground.

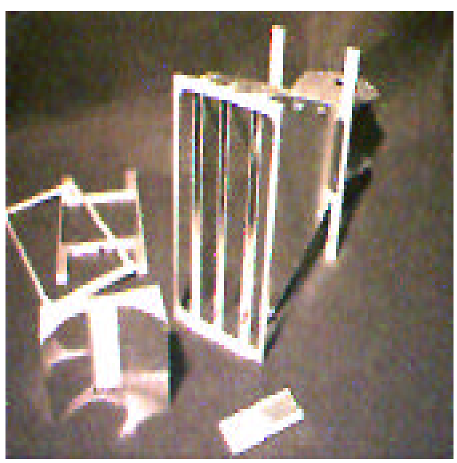


Fig. 7 Partially assembled Components of prototype projection unit

4.0 CONCLUSIONS

Coating Tolerant Thermography is specifically designed for inspection of large, steel structures that are heavily and nonuniformly coated with paints and perhaps debris. Emissivity variances caused by such non-uniformities are completely eliminated in the final result. There is a clear path to an inexpensive hand held system that will be portable, robust, rapid and widely distributable. Most importantly, the resulting images are easy to interpret, because the existence of a crack is as clear as black on white. Multiple projection channels can be used in parallel to create additional heating stripes.

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