Forced-Diffusion Thermography Technique and Projector Design

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Abstract

A thermal projector design is discussed as implemented to perform Forced Diffusion Thermography. The system projects a continuos dynamic pattern of heat in order to drive thermal conduction across flaws. The simple projector utilizes a conventional 625 watt incandescent source and a servo-controlled mirror system to create a simple moving line pattern of heat. Although the system is capable of detecting a variety of flaws, it is most suited for crack detection. Projector design and results are presented.

Keywords: Thermography, Thermal Projector, Forced Diffusion Thermography, FDT, Cracks, Flaw Detection

1. Introduction

Thermal methods have shown great promise as powerful NDE tools. Thermal methods are applicable to a wide variety of situations. Almost every institution or facility has at least one application which in itself would justify the expense of a thermal camera. As the complexity and cost of cameras decrease, the popularity of passive thermal methods increases. Infrared cameras can be found inspecting anything from space shuttles to home insulation. However, where there are certainly applications that highlight active thermal methods, they have yet to appear in every lab and on every inspection line. This paper describes a thermal projector specifically designed for Forced Diffusion Thermography (FDT). It is designed to be simple yet effective. The design is only slightly more complex than an overhead projector and is even more robust. Coupled with the power of a differential thermographic camera this FDT projector may prove to help take thermal methods out of the lab and into the field.

2. Forced-Diffusion Thermography (FDT)

Thermographic NDE techniques correlate structural integrity with thermal diffusivity. Most often flash lamps are used to uniformly heat the surface of the structure with kilojoule magnitude pulses[1]. To find flaws, these techniques rely on structural asymmetry to drive in plane heat flow. Several thermographers have found it advantageous to maintain more control over the heat flow. Cramer of NASA Langley Research Center et al.[2] and Maclachlan Spicer et al.[3] have both used line flux sources. These techniques inspect a linear region for cracks parallel and adjacent to the hot line.

FDT extends the concept of spatially varied heat flux to full-field[4]. It projects a continuously-emitted, full-field, dynamic heat pattern onto the surface of the structure (Fig. 1).

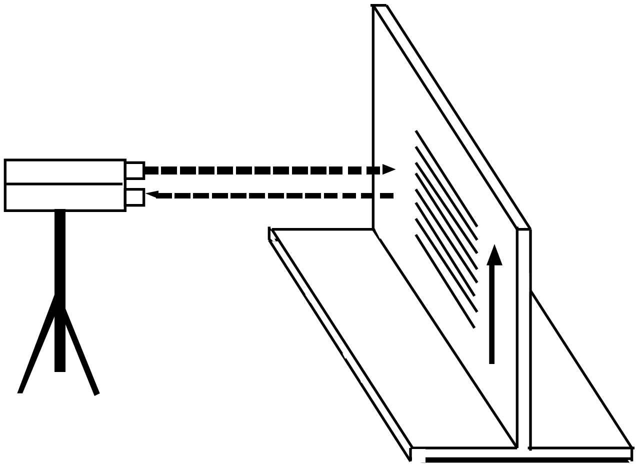
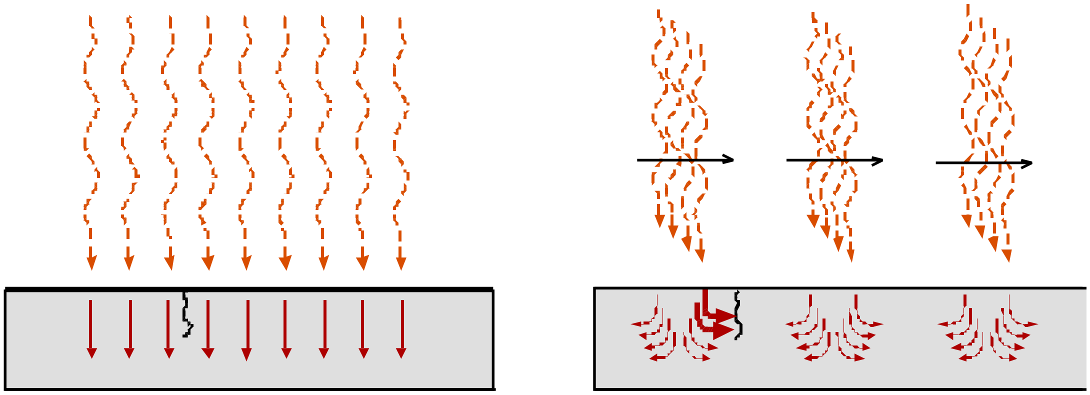


Fig. 1 Forced Diffusion Thermography

In its simplest form, a pattern of moving hot lines, FDT resembles the single scanned line approach except that the moving lines comb the object; therefore, the thermal event is continually repeated. While the first hot line continues on to heat an area farther down field, a new hot line repeats the process. The patterned heat can induce both through-depth penetration as well as in-plane heat flow (Fig. 2) . The extent of through-depth or in-plane conduction depends on the spatial and temporal frequencies of the pattern.



a) Uniform heating

b) Patterned radiation

Fig. 2 Heat flow patterns

Every location in the projection area experiences the continual passing of hot lines which results in a quasi-static state of cyclic thermal oscillations that can be very accurately measured with a differential thermographic camera. A differential thermographic camera measures the relative phase and amplitude of the small oscillating temperatures with a resolution on the order of 1 mK. The phase is taken with respect to a reference signal sent by the projector which describes the motion of the hot lines. As the reference signal reaches a peak, a new line enters the projection area. An oscillating thermal signal of arbitrary amplitude and phase can be described by

$$S\cos(\omega t+\theta) = A\cos(\omega t) + B\sin(\omega t) \qquad (1)$$

Where S is the amplitude of the thermal oscillation, A and B are the magnitudes of the respective components, and θ is the relative phase angle. S, A, B and θ can be related by

$$S = \left(A^2 + B^2\right)^{1/2} \qquad \theta = \mathrm{Tan}^{-1}(B/A) \tag{2}$$

which in graphical electrical engineering terms is represented by a phasor diagram (Fig. 3).

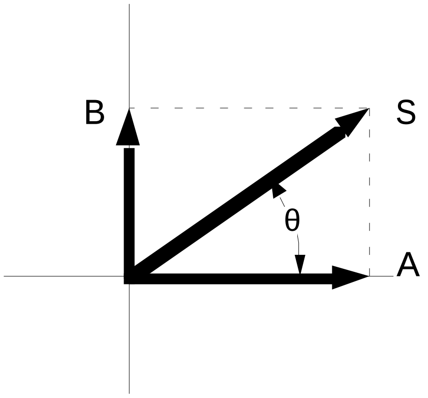


Fig. 3 Phasor representation of oscillating thermal signal

3. Differential Thermography System

The differential thermographic system used in conjunction with the FDT projector employs a 128 x 128 InSb focal plane array (FPA). The camera digitally processes 434 frames per second applying a correlation algorithm described by

$$A(x,y) = \frac{2}{N}\sum_{n=1}^{N} S_n(x,y)\sin\theta_n \qquad B(x,y) = \frac{2}{N}\sum_{n=1}^{N} S_n(x,y)\cos\theta_n \tag{3}$$

where A(x,y), B(x,y) are the measured components of the sampled signal, $S_n(x,y)$, N is the number of samples, and $\sin\theta_n$ is a reference provided by the projector. Note that these are functions of position (x,y) as the algorithms are being applied to entire full-field images, 128 x128 pixels in size. As described in Eq. 2 both amplitude and phase images can be calculated from the A and B images.

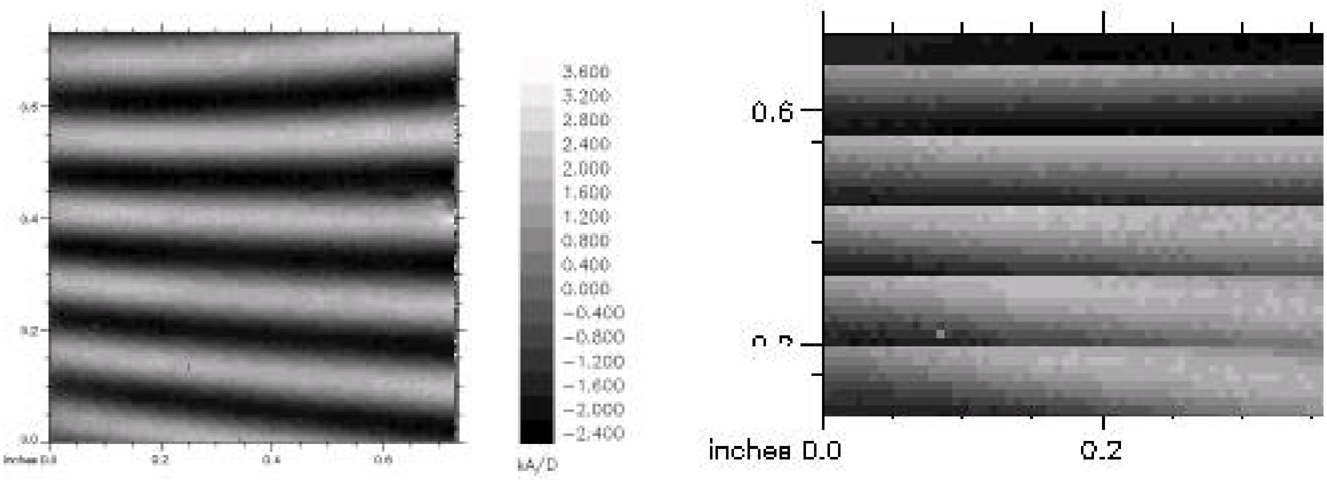
There are other ways to perceive the A and B images besides the electrical engineering analogy. One can imagine that the A and B images are like strobed snapshots of the temperature distribution. The B image is taken 1/4 period after the A image. From the amplitude and phase one could calculate the thermal snapshot for any instant in the excitation period.

4. Results

A set of parallel moving lines of flux can be described as

$$q(x,t) = \frac{C}{2}\left[1 + \cos(2\eta\pi x)\cos(\omega t) + \sin(2\eta\pi x)\sin(\omega t)\right] \tag{4}$$

where C is the amplitude of the flux. The resulting thermal image takes on a similar distribution which implies that the A and B images should look like parallel line patterns, or spatial sinusoids, with a 1/4 period shift (Fig. 4).



a) Component “A”

b) Component “B”

Fig. 4 Differential Thermographic images of response to dynamic pattern projection

A slight distortion resulting from a small angle of incidence is noticed in the images, as the stripes are wider on the right. This distortion does not effect the ability of the system to detect flaws. A vertical profile of either component image shows that thermal response indeed has the characteristics of a spatial sinusoid (Fig. 5). These images were taken using front side projection and imaging at a temporal frequency of approximately 8 HZ and a line spacing of ~1/8 in. All images are of a primarily closed 1/2 in. long fatigue crack in 1/16 in. thick steel.

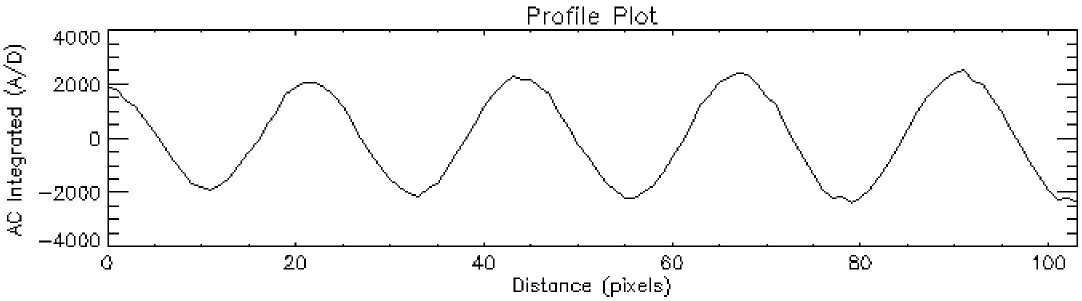
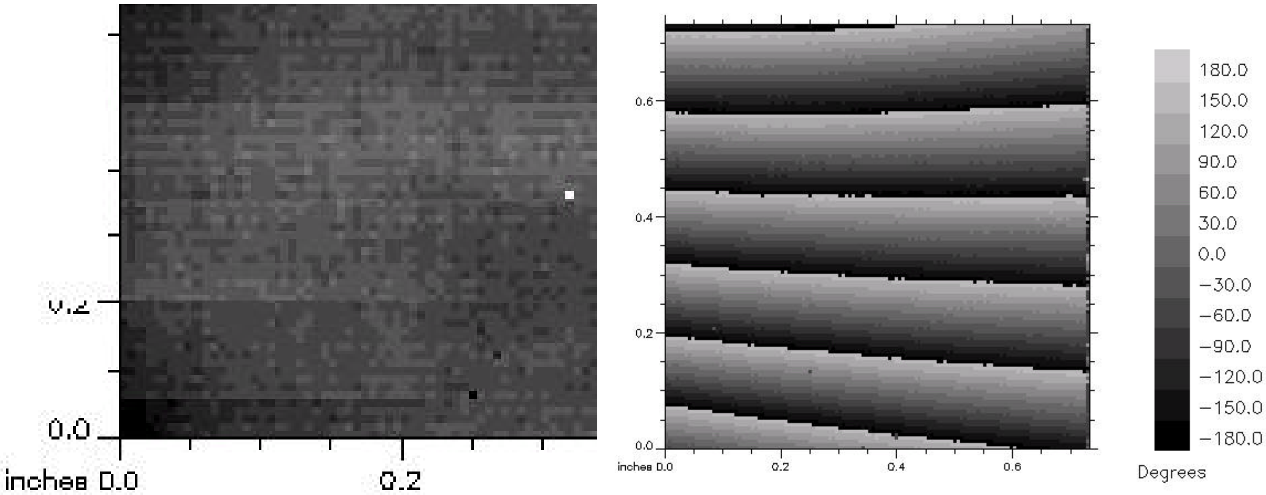


Fig. 5 Profile of the “A” image down right edge

The resulting heat conduction will be a function of the derivative of the thermal distribution. Because the slope of the thermal gradient is continuously changing sign, heat sloshes back and forth. The only thing that varies across the field is the phase at which this occurs (Fig. 6b). The amplitude of thermal oscillation should be constant, as is evident in the flaw free region of the amplitude image (Fig. 6a).

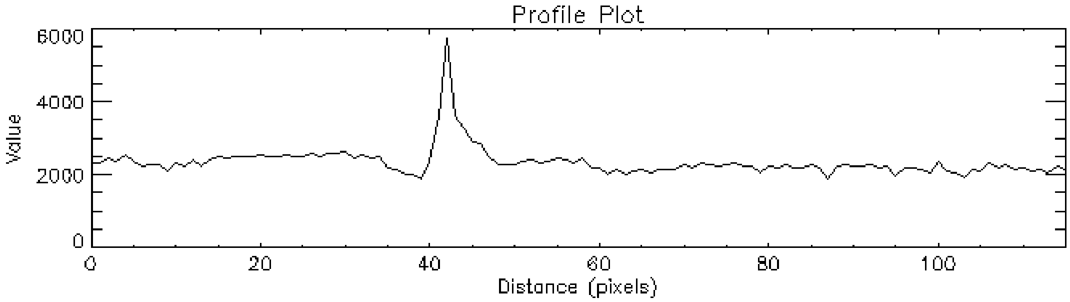


a) Amplitude image

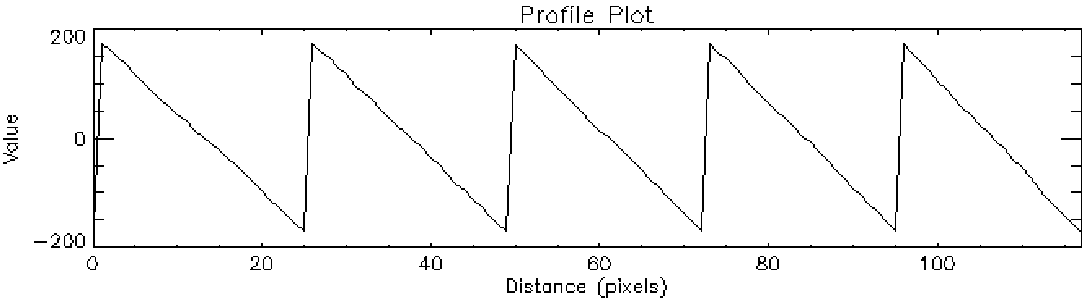
b) Phase image

Fig. 6 Calculated Differential Thermographic images

In the interior of the image heat is free to conduct from hot strip to "cool" strip resulting in a lower oscillating temperature. Near the crack, the heat can not conduct to adjacent material, so an elevated amplitude occurs at the boundary of the crack (Fig 7a). The phase ramps from 180 to -180 (Fig 7b) with some distortion at the crack. This phase information can be used to discern between types of flaws or paint anomalies.



a) Vertical profile of amplitude data through crack



b) Vertical profile of phase data down left edge

Fig. 7 Profiles of data

Simple filters can also be applied to make flaws more apparent. A Sobel edge enhancement filter has been performed on the raw data shown in Figure 6a above to highlight the crack (Fig. 8). These filters can be designed to use amplitude and phase data to discern between surface quality and actual flaws. They can also be used to identify different flaw types such as cracks, disbonds, or corrosion.

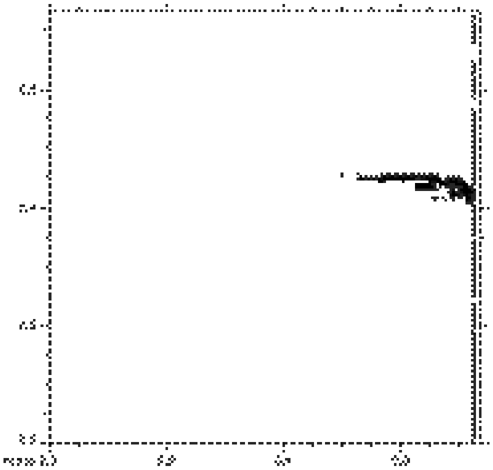


Fig. 8 Filtered FDT data highlighting crack

5. Projector design

In order for a thermal inspection technology to find wide ranging success, it must exhibit high probability of detection with low probability of false alarms. It must be operable by a moderately trained technician and most importantly it must be portable. Figure 9 shows the FDT projector with the IR camera fixed to the top mounting plate. The approximate weight of the prototype projector is 12 lb and has dimensions of 21 x 7.5 x 6.25 in. The projector currently has amplitude, frequency and light intensity controls. These controls are being moved to the lap-top computer, also used for data acquisition, for more precise control and repeatability.

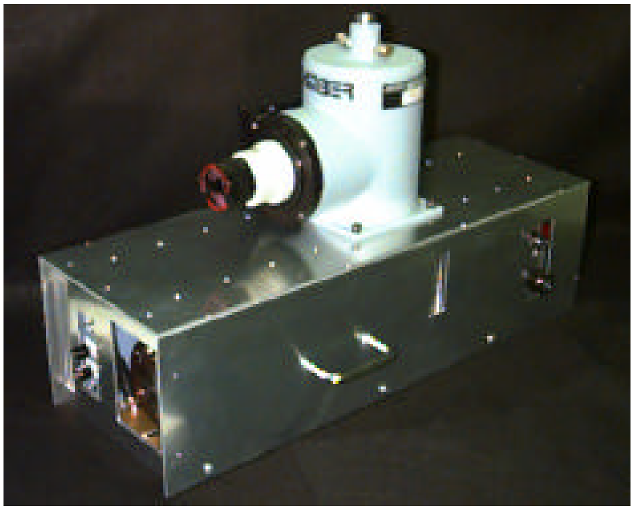
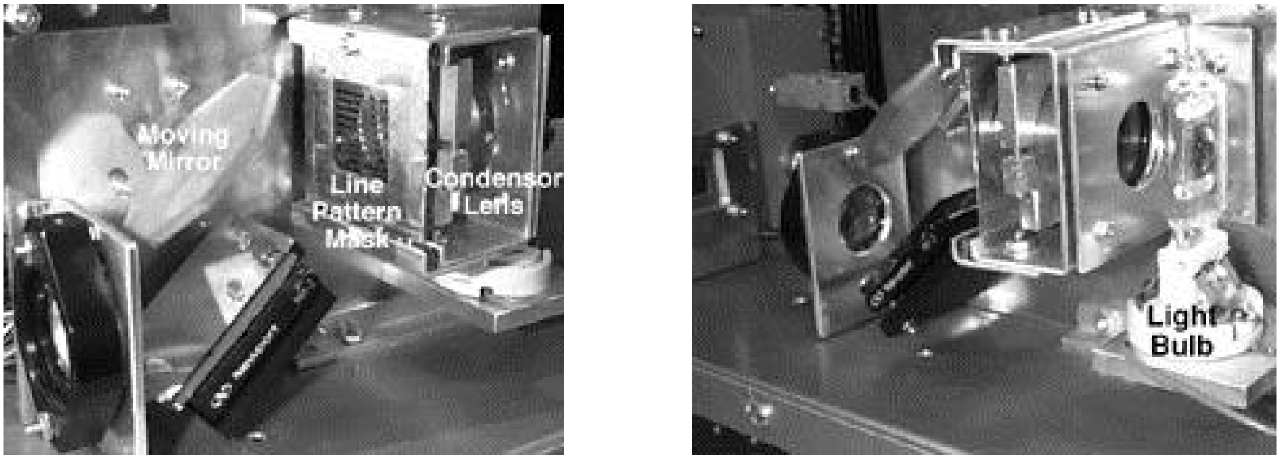


Fig. 9 Close up of prototype FDT projector

The prototype projector uses a 625 watt source and a moving mirror assembly to create a unidirectional moving line pattern (Fig. 10). An internal saw tooth function generator drives the servo-controlled mirror to translate the line pattern one or two line widths. It then jerks the mirror back to the original position, an action which is imperceptible to the eye or the quasi-static thermal state induced in the object. Masks of various line densities can be inserted into the pattern holder to change spatial properties of the projection.



a) Moving mirror and pattern assembly

b) Incandescent light source

Fig. 10 Projector details

Currently, the radiant energy output is less than 100 watts, but a few watts per square centimeter is sufficient to excite a structure to experience thermal oscillations well within the range of differential thermal cameras. Figure 11 shows the projector and camera operating at close range. The moving line pattern can be seen on the face of a small bridge model.

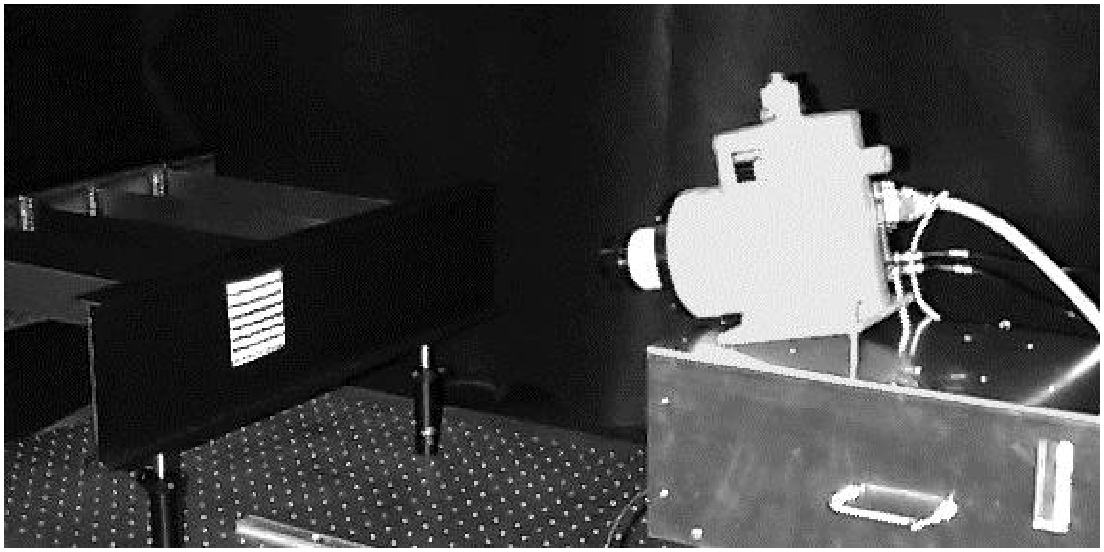


Fig. 11 FDT projector and camera imaging a small bridge model

6. Conclusions

Much was learned from this prototyping experience. Many improvements can still be made to this design including a prism element which allows rotation of the pattern orientation, utilization of antireflection coatings and more sophisticated projection lenses. Although more difficult to accomplish than it might seem, at least 100 watts of continuos radiation is desired. Not only will this projector be developed further, but new concepts will be explored as well to accomplish this goal. Two obvious options are the use of laser sources or arc lamps. The advantages in optical design of these choices must be weighed against the robustness and affordability of the simple incandescent projector. A long term objective of this program is to implement liquid crystal display type screens so that sophisticated patterns can be projected that will be optimized to the inspection at hand. All design options must be assessed on the basis of safety, portability and robustness. The advancement of this prototype projector will enable the power of FDT as an inspection technology to be demonstrated.

Acknowledgments

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