QUANTITATIVE ANALYSIS OF REAL-TIME RADIOGRAPHIC SYSTEMS

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INTRODUCTION

Radiographic inspection is an essential tool in the nondestructive evaluation of devices such as solid rocket motors which must work properly when fired. The advent of real-time radiographic (RTR) inspection systems has dramatically improved the throughput and coverage of these inspections over film-based techniques. The RTR inspection, however, is only as sensitive as the system used. Qualitative measures of image quality which were originally developed for film-based inspection have been applied to these real-time systems. While these qualitative measures are useful, there is a clear need to develop quantitative measures which are more appropriate for the RTR inspection systems which do not rely on a subjective judgement and which can be used to indicate the cause of problems in the system.

A program to develop quantitative image quality indicators (IQI) was initiated in response to problems occurring over time in a group of 16 MeV solid rocket motor inspection systems originally put into service in 1976. The goal of the program was to develop a system of IQI's which would be analyzed digitally to indicate the quality of the radiographic images being obtained and which would be utilized to indicate which component of the RTR system was not working correctly. The components of these systems are shown schematically in Fig. 1. The parameters of these systems which require regular monitoring are (1) the size of the x-ray focal spot of the Linatron accelerator, (2) degradation in the imaging chain which consists of the x-ray to light conversion screen, mirror, lens, camera and electronics, and digital image processor, and (3) degradation in the CRT monitor used as the main image display device. The progress made to date on this project is reported in this paper.

QUANTITATIVE IMAGE QUALITY INDICATORS

One of the problems with the ASTM E-142 qualitative plaque and wire penetrameters [1] is that typically both the contrast and spatial resolution limits of the system are being measured at the same time. Figure 2 illustrates the detectability of an object depending on the object contrast and size. For film-based inspection systems where the spatial resolution is significantly better than that required to resolve the holes or wires in the penetrameter, the detectability as measured with the penetrameters is close to the contrast asymptote in Fig. 2. However, for RTR systems, the penetrameters are typically probing the response of the system in the region indicated by the circle in Fig. 2. Thus the spatial resolution and contrast sensitivity are intermixed in the reading of the penetrameter sensitivity. It is often important to separate the effects of system resolution and sensitivity, especially when troubleshooting the system.

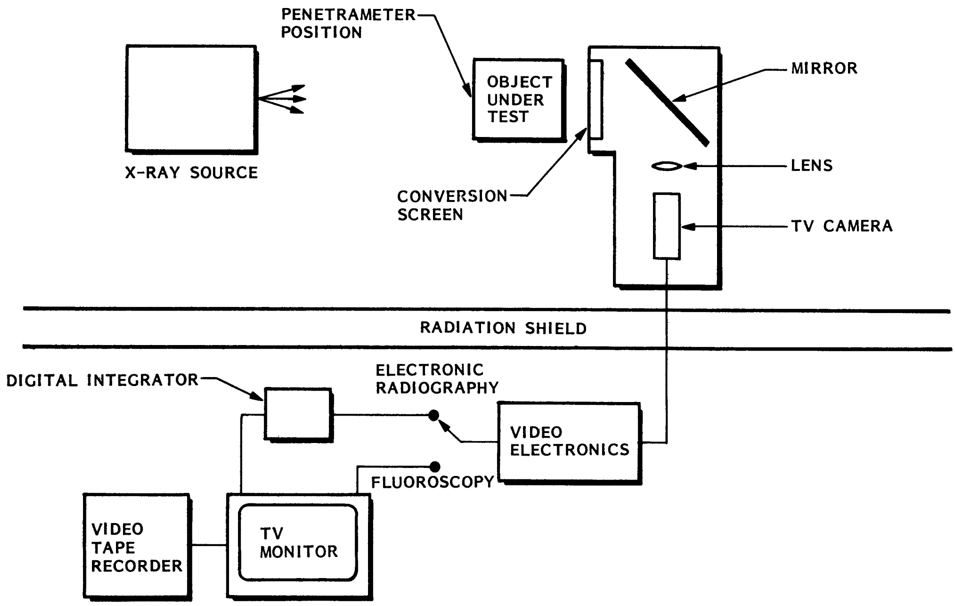

Fig. 1 Schematic of the high energy radiography inspection system

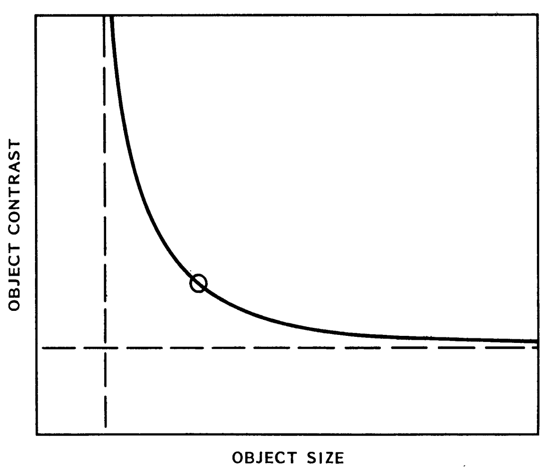

Fig. 2 Illustration of the inter-relationship of contrast sensitivity and spatial resolution in object detectability. Qualitative penetrameters typically probe the response of the system in the region indicated by the circle.

A new system for image evaluation has been developed which independently measures the contrast sensitivity by utilizing large low contrast objects, i.e., a step tablet with shims, and the spatial resolution by using small high contrast objects, i.e., a bar pattern. The system utilizes the digital information in the images to obtain quantitative information. This evaluation system involves using optical IQI's to measure the camera performance and x-ray IQI's to analyze the x-ray system performance. The x-ray source focal spot size is monitored by using geometric magnification of the bar pattern, while the intrinsic resolution of the x-ray detection system is monitored with the bar pattern at a magnification of one. In addition, a simple method has been developed to measure the sensitivity of the CRT monitors used to display the radiographic images.

To facilitate testing the efficacy of the x-ray IQI's, all experiments were performed at low energy (around 100 kV). The materials and thicknesses used for the final IQI's will be appropriate for the 16 MV Linatron energy needed for the solid rocket inspection systems. The concept and computations required are independent of the x-ray energy range actually used.

One serious problem to overcome in evaluating the digital information in the images is the image shading. With a camera based system, a uniform input does not yield a uniform image after passing through the optics and camera imaging chain; there is typically a bright center with the signal level falling off toward the edges. In addition, electronic shading correction is included in the camera control unit to flatten the signal prior to digitization of the image. This electronic shading has linear (ramp) and quadratic (parabola) components. In evaluating images, the changes in signal level due to shading must be distinguished from changes in signal level due to changes in the input. Thus, the image must be corrected for the shading. This can be done in one of two ways. One is to subtract an image acquired with a uniform input from the image acquired with the actual object. This method removes the image shading, but requires the acquisition of two images where the object is changed between the two images. In addition, subtraction adds to the image noise. In the 16 MeV solid rocket motor inspection systems, it is too time consuming to obtain subtracted images of this type. An alternative is to correct the shading mathematically. A region with known uniform input can be fitted using a two-dimensional quadratic Taylor's series expansion. The true signal is then the difference between this fit and the measured signal value.

In order to perform the quadratic fit to the image, the system must provide: (1) digital signal values; (2) access to the signal value at any given pixel; (3) computer processing of the digital information, and (4) a region of interest cursor display (not required, but helpful). To make use of the quadratic fit, particular IQI's were designed. First the contrast sensitivity IQI will be discussed, then the spatial resolution IQI will be described.

Contrast Sensitivity Measurement

The contrast sensitivity was measured using a step tablet with shims placed in the center of each step as shown in Fig. 3a. The contour of the image for a given step, including the effects of shading, is illustrated in Fig. 3b. The thickness of the steps should be chosen to measure the sensitivity at two different x-ray intensity levels so that the sensitivity over the dynamic range of the system can be determined. The shims should be a small fraction of the step thickness, in the range of 0.5% to 8%.

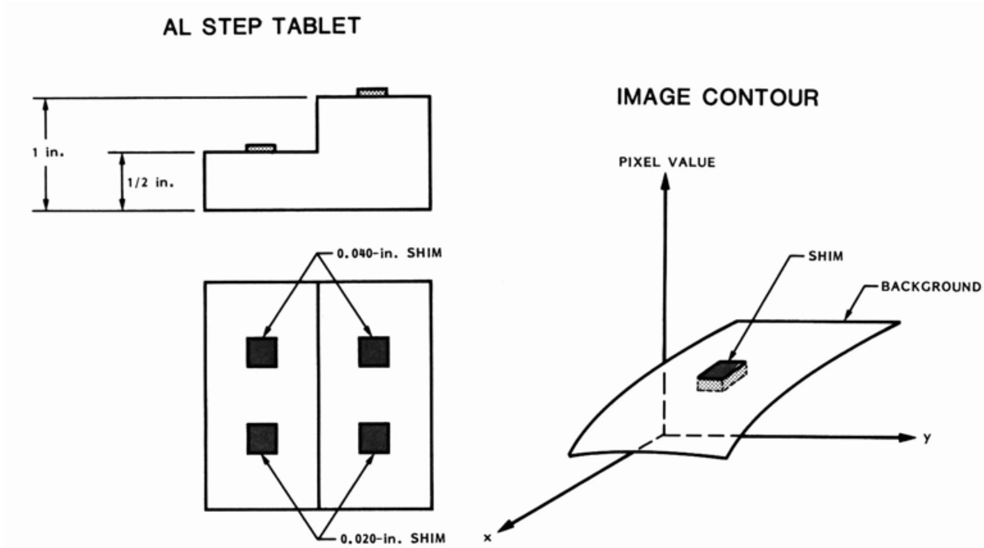

Fig. 3. (a) Aluminum step tablet used to measure system resolution, Steps of 0.5" and 1.0" Al were used with 0.02" and 0.04" thick shims. (b) Contour of the digitized image in the region surrounding a shim. This contour indicates the presence of image shading.

For the low energy tests of this method, an aluminum object with 1/2" and 1" step thicknesses was used with shim thicknesses of 2% and 4% for the 1" step, and 4% and 8% for the 1/2" step. The regions outside and inside of each shim were simultaneously fit with the two-dimension quadratic Taylor's series expansion

$$p_o = a + b\,x + c\,y + d\,x^2 + \quad x\,y + f\,y^2. \qquad (x,y) \text{ outside shim region,}$$

$$p_i = p_o + S_1 \qquad (x,y) \text{ inside shim region.}$$

The difference between the inner and outer regions, S_1 is then the image signal change due to the presence of the shim with the effects of image shading removed.

The image noise, σ, is estimated from the reduced chi-squared, χ^2/NDF, of the fit as

$$\sigma = (\chi^2/\mathrm{NDF})^{\frac{1}{2}}$$

$$\chi^2 = \sum_{ij} (p_{ij} - p\,(x_i y_j))$$

where p_{ij} are the actual values and $p\,(x_i\ y_j)$ the Taylor expression evaluated at pixel location x_i, y_j and NDF is the number of degrees of freedom, i.e., the number of pixels included in the fit minus the number of fitting parameters. The contrast sensitivity is then defined to be

$$CS = S\ /\ [(\%T)\sigma]$$

where S and σ are the shim signal and image noise as defined above and %T is the thickness of the shim expressed as a percentage of the step thickness. Note that, just as with the qualitative plaque penetrameters, the CS value will be different for different step thicknesses and material types. The larger the numerical value of CS, the better the image sensitivity.

Table 1. Typical contrast sensitivity, CS, measurement compared to ASTM E-142 penetrameter, PENE, observations.

kV	mA	CS	PENE	CS	PENE
80	1	0.9	2-4T	0.6	2-4T
80	2	1.3	2-4T	0.8	2-4T
80	4	1.7	2-4T	1.1	2-4T
110	4	1.9	2-2T	1.6	2-2T

Table 1 gives the results of several measurements taken using this new quantitative contrast sensitivity method. Images of ASTM E-142 plaque penetrameters were taken with the same camera settings for each x-ray kV and mA setting, and the plaque sensitivity, noted in Table 1, was measured by a trained observer. X-ray images of both the new and plaque IQI's are given in Fig. 4a and b. Subtracted images have been shown to improve the visibility for reproduction. Several trends are worth noting from these data. As the mA is increased, the CS value also increases and shows discrimination between the mA settings which is not available from the qualitative penetrameter results. When the kV is increased, the CS value increases by a larger amount for the thicker step and once again shows more discrimination than is available with the plaque penetrameters.

Repeated tests of this method have demonstrated good consistency between repeated measurements, between measurements taken with shims of different thicknesses, and between measurements taken with and without subtraction. The method is easily automated and takes only a few seconds of computer time to obtain quantitative results. Work is continuing on correlating the quantitative methods to penetrameter observations and on establishing ranges of CS which indicate acceptable image quality.

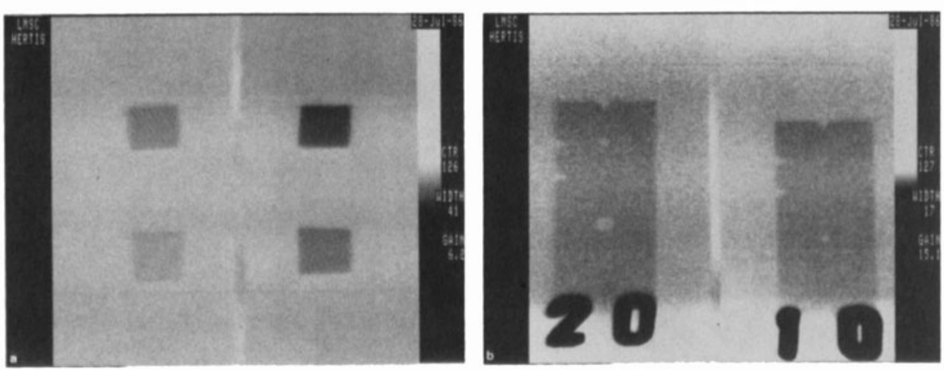

Fig. 4. (a) X-ray image obtained with the contrast sensitivity phantom at 110 kV, 4 mA. The 1" step is on the left with the 0.5" step on the right half of the image. (b) X-ray image obtained using the aluminum step tablet and 2% aluminum penetrameters. For both (a) and (b) a sugtracted image is shown to improve visibility for reproduction.

Spatial Resolution Measurement

The spatial resolution was measured using a bar pattern. A two-dimensional quadratic Taylor's series expansion was fitted to the data in a region containing an integral number of line pairs following the concepts of Ref. 2. The fit is able to follow the image shading, but has no component which can fit the bar modulations so long as two or more line pairs are included in the region. Thus, the amplitude of the bar pattern modulation, A, contributes to the reduced chi-squared of the fit as

$$\chi^2/NDF = A^2 + \sigma^2 = (A')^2$$

The square root of the reduced chi-squared, A', is a measure of the modulation amplitude in the image. This measure is plotted against the line pairs per mm (lp/mm) of the bar pattern, as shown in Fig. 5. The value of A' increases until it is dominated by the image noise and then becomes flat. A straight line fit, on log-log paper, is constructed of the decreasing A'. The limiting resolution of the system has been defined as the point where the constructed line intersects the image noise. The values obtained by this method are very close to those which were selected by trained observers looking at the x-ray image. Figure 5 shows the modulation for a geometric magnification of 1.75 taken with 1.5 mm and 0.4 mm nominal focal spot sizes.

These data can be used to separate the effects of x-ray focal spot size and limiting resolution of the detection system. To make this separation, a uniform detector response and uniform focal spot intensity were assumed. This results in a system modulation transfer function (MTF) composed of sinc functions:

$$MTF(f) = \mathrm{sinc}\,(\pi fa/m)\ \mathrm{sinc}\,(\pi fs(m-1)/m)$$

where f is the spatial frequency in cycles per mm, a is the effective system

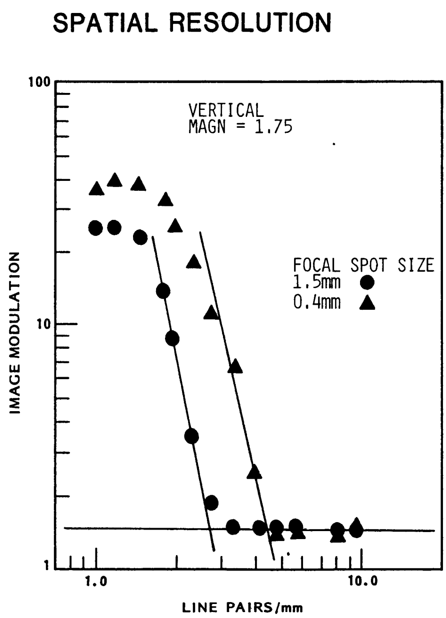

Fig. 5. The square root of the chi-squared or A', labelled Image Modulation, is shown plotted against the line pairs per mm of the object.

resolution element in mm, s is the effective focal spot size in mm, and m is the geometric magnification of the image. While this approximation oversimplifies the actual MTF, it gives a useful estimate of the relative resolution and focal spot size which will indicate when changes have occurred in the system.

The limiting resolution, f_o, as measured with the bar pattern, is equated to the spatial frequency at which the MTF equals zero. For a magnification near unity, the zero crossing due to the focal spot size can be neglected, thus

$$a = m / f_o, \text{ for } m = 1.$$

To measure the focal spot size, the zero crossing due to the system resolution must occur at a higher spatial frequency than that due to the focal spot size. Thus,

$$s = m / ((m-1) f_o), \quad \text{if } a f_o / m < 1.$$

This typically holds true for magnifications of 1.5 or greater, but must be checked for the particular system under investigation.

Using these expressions, the effective system resolution element and the effective focal spot size were estimated in the horizontal and vertical directions for a Siefert 160/10 x-ray tube with dual focal spots of 0.4 mm and 1.5 mm nominal size. These results are given in Table 2. This method of measuring system resolution is easily automated and gives numerical estimates of the system resolution and focal spot size which will be quite useful to detect changes in the system performance.

Table 2. Resolution and focal spot measurements taken with two different spot sizes using the new quantitative method. Part (a) gives the effective resolution elements, a, of the system measured with a magnification of 1. Part (b) gives the focal spot size, s, measured with a geometric magnification of 1.75. All measurements are in mm.

		Nominal Spot Size (mm) 0.4	1.5
Part (a)	Horizontal	0.33	0.33
	Vertical	0.31	0.31
Part (b)	Horizontal	0.71	1.3
	Vertical	0.51	0.83

CRT Evaluation

The light output of a CRT screen is a monotonic function of the voltage applied to the control electrode of the CRT. For large voltages, the output saturates at a maximum value; for very low control voltages, the output bottoms out at a small, but non-zero background level. In the middle range of control voltages, the output is approximately a linear function of the control voltage. As the tube ages, the maximum brightness decreases, the background level increases, and the slope of the function in the middle range decreases. The middle range slope is a measure of the brightness responsivity of the CRT.

The contrast control on a CRT monitor adjusts the gain of the amplifier that drives the CRT control electrode. The brightness control adjusts the offset of the input-output function in the middle range by changing the bias voltage on another electrode of the CRT. To evaluate the CRT fairly, these controls must be set to some standard condition.

In our evaluation procedure, the CRT monitor is driven with a staircase function, while the screen brightness is measured with a portable light meter held in direct contact with the CRT screen. The staircase function drive produces a vertical bar step pattern on the screen. To set a standard condition of the contrast knob, the drive signal on the control electrode is adjusted with an oscilloscope to 7 volt steps. To set the brightness control, the measured brightness of the brightest bar is adjusted to 50 ft-L. This value was chosen because it is the minimum specified brightness of new CRTs. The brightness of the other bars in the pattern is then measured and recorded. Data for a new CRT monitor and for a very old one are shown in Fig. 6. The brightness responsivity (slope) of the old tube is clearly less than that of the new tube. Also, the maximum brightness of this old tube had degraded so much that 50 ft-L could not be obtained. Data will be acquired on tubes of intermediate age. These data will be used to select a slope value at which the tube should be retired from service.

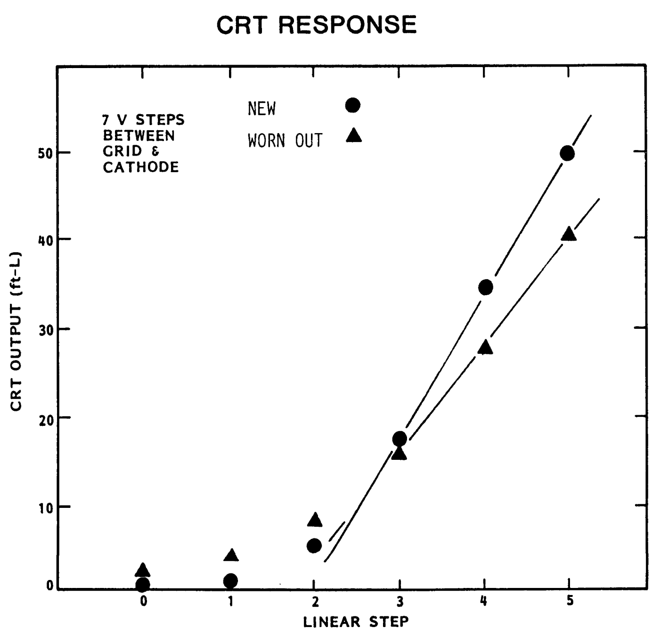

Fig. 6 Output brightness as a function of a staircase driving voltage for both a new and a very old CRT.

SUMMARY

A new method has been developed to quantitatively extract information on the spatial resolution, contrast sensitivity, image noise, and focal spot size from real-time radiography images on a routine basis. The method requires simple image quality indicators and computer calculations. It is used for x-ray and optical images to allow for trouble shooting to determine which component of the system is not operating to the required standard. The method is easily automated and provides greater discrimination than ASTM E-142 qualitative penetrameters without need for subjective evaluation of images. In addition, a method has been developed to monitor the performance of CRT display systems using a simple procedure and a hand-held light meter.

This method has been tested for low energy x-rays, and will soon be employed at high energy to monitor the performance of 16 MeV solid rocket motor inspection systems. The method shows great promise for future quantitative evaluation of a wide variety of radiographic inspection systems.

REFERENCES

1. Annual Book of ASTM Standards, Part 11: Metallography; Nondestructive Testing, ASTM, Philadelphia (1982)

2. R. T. Droege and M. S. Rzeszotarski, Med. Phys. 12, 721 (1986).