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Factors affecting Probability of Detection with Computed Radiography

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Abstract

Computed Radiography (CR) can be a viable alternative for conventional film-based industrial radiography. This new technology uses flexible and re-usable storage phosphor plates that can be used in a fashion similar to film. To ensure that CR provides Probability of Detection (POD) performance for flaw indications that is equivalent to that of film radiography, international standards have been developed (ASTM E2445/E2446 and CEN 14784-1/2) to govern the assessment of the image quality. These standards classify CR systems using the concept of normalized SNR (nSNR), which is based on the hypothesis that the SNR is inversely proportional to the basic spatial resolution (SR) of the system. Because of concerns that CR plates can have a lower spatial resolution than some industrial films, the above-mentioned standards specify the maximum SR depending on the penetrated thickness.

However, in practice POD is primarily determined by the minimum subject contrast threshold that can be observed. The contrast threshold depends on many parameters including primary-to-scatter ratio, attenuation coefficient of the material, flaw geometry (globular, needle etc.), SNR, and the effective contrast modulation. Of these, the effective contrast modulation is the only parameter that depends on the system resolution.

We present a model that estimates the relative importance of the different factors affecting the success of a radiographic technique. Only for very small globular flaws and materials with very high X-ray attenuation is the system resolution expected to be the limiting factor. We also present experimental evaluations comparing the classification according to the standards with the observed wire IQIs sensitivity on Fe and Al from a modern CR system.

Keywords: NDT, Computed Radiography, Image Quality Standards

1. Introduction

Computed Radiography (CR) is rapidly becoming a viable alternative for conventional film-based industrial radiography. This new technology uses flexible and re-usable storage phosphor plates that can be used in a fashion similar to film, and which can provide significant reduction in inspection costs. To ensure that CR provides Probability of Detection (POD) performance for flaw indications that is equivalent to that of film radiography, international standards have been developed (ASTM E2445/E2446 and CEN 14784-1/2) to govern the assessment of the image quality. These standards classify CR systems using the concept of normalized SNR (nSNR), which is based on the hypothesis that the SNR is inversely proportional to the basic spatial resolution (SR) of the system. Because of concerns that CR plates can have a lower spatial resolution than some industrial films, the above-mentioned standards specify the maximum SR depending on the penetrated thickness, particularly EN14784-2 for weld inspection.

Other authors [1-4] have investigated the impact of resolution and signal-to-noise ratio (SNR) on the detectablility of fine defect indications in amorphous silicon DR detectors and in other CR systems. We performed similar investigations on another combination of CR plate and scanner.

2. Test Results

Using image quality assessment techniques specified in EN462 for film radiography and in EN1435 for welding applications, we evaluated visibility of wire-type IQIs on common steel and aluminum for a variety of material thicknesses. The CR images were acquired with a GE CRxTower and GE type-IPS CR plates at a 50-micron pixel pitch setting. Table 1 shows that Class A requirements were demonstrated for all thicknesses of steel and aluminum tested, and that Class B requirements were demonstrated with the techniques used for all but the thinnest sections of steel that were tested.

EN 462	Single wall technique					
(EN1435)	CRx Tower					
					IPS	
Material	X-Ray (kV)	Wall thickness w (mm)	Class A Minimum	Class B Minimum	Class A Score	Class B Score
Fe	320	52.00	8	9	11	11
Fe	320	32.00	10	11	11	11
Fe	255	22.00	11	12	13	13
Fe	220	22.00	11	12	12	12
Fe	145	14.00	12	13	14	14
Fe	155	8.05	13	14	14	14
Fe	140	8.05	13	14	14	14
Fe	155	2.05	16	18	17	17
Fe	110	2.05	16	18	17	17
Al	177	100.00	6	8	9	9
Al	149	67.00	7	8	10	10
Al	255	60.00	7	9	11	11
Al	255	40.00	9	10	12	12
Al	155	10.00	12	14	15	15
Al	64	10.00	12	14	15	15
Al	49	5.00	14	16	17	17
Al	60	2.05	16	18	18	18

Table 1. The visibility of wire penetrameters according to EN462 demonstrates practical image quality sufficient to meet Class A requirements for all thicknesses tested, and even Class B requirements were demonstrated for all but the thinnest sections of steel.

EN14784-2 sets forth additional requirements on system resolution when using CR in place of film to inspect welds. The same equipment was analyzed for these additional resolution requirements according to the techniques of EN14784-1, as shown in Table 2.

EN 14784-2_2005: Table 4		Class IPA			Class IPB		
Radiation source	**Wall thickness *w* (mm)**	**Max. pixel size µm**	**Double wire IQI number**	**IPS 50µ**	**Max. pixel size µm**	**Double wire IQI number**	**IPS 50µ**
X-ray Up ≤ 50 kV	w < 4	40	> 13	X	30	>> 13	X
	4 ≤ w	60	13	10	40	> 13	X
X-ray 50 kV < Up ≤ 150 kV	w < 4	60	13	10	30	>> 13	X
	4 ≤ w < 12	70	12	10	40	> 13	X
	w ≤ 12	85	11	10	60	11	10
X-ray 150 kV < Up ≤ 250 kV	w < 4	60	13	10	30	>> 13	X
	4 ≤ w < 12	70	12	10	40	> 13	X
	w ≥ 12	85	11	10	60	13	10
X-ray 250 < Up ≤ 350 kV	12 ≤ w < 50	110	10	**10**	70	12	10
	w ≥ 50	125	9	**10**	110	10	**10**
X-ray 350 < Up < 450 kV	w < 50	125	9	**10**	85	11	10
	w ≥ 50	160	8	**10**	110	10	**10**
Se 75, Ir 192	w < 40	160	8	**10**	110	10	**10**
	w ≥ 40	200	7	**10**	125	9	**10**
Co 60		250	6	**10**	200	7	**10**
X-ray Up ≥ 450 kV		250	6	**10**	200	7	**10**

Table 2. Although wire IQI sensitivity was demonstrated in actual CR test images, the additional resolution requirements imposed by EN14784-2 for weld inspections with CR may not be met in all cases. Even without focal spot blurring, for the cases marked by dark gray either the specified duplex wire pair on an EN462-5 gauge might not be reliably resolved, or the pixel pitch setting would be larger than specified (denoted by an "X" mark).

3. Assessment of Image Quality

The assessment of image quality may be performed from different perspectives using visual (subjective) or quantitative (objective) methods.

Overall image quality is composed of different aspects, including signal gain, noise, and spatial resolution. Each of these quantities can be characterized by an objective metric that is derived from the physics of the imaging process using a mathematical framework. This framework describes how object properties are translated into image properties. The mathematics is greatly simplified when one works in Fourier space instead of in real space. This means that the metrics will not be based on the feature projections onto the spatial x and y axis (units mm) of the object plane, but instead on spatial frequencies u and v (units line-pairs/mm). In this way the spatial resolution is characterized by the modulation transfer function $MTF(u,v)$. This function describes how the magnitude of a spatial sine-wave signal with spatial frequencies u is decreased by the imaging system. The imaging system typically adds noise as well, which is typically characterized by the noise power spectrum function $NPS(u,v)$, describing the noise magnitude in function of the spatial frequency.

The validity of the metrics is limited by the boundary conditions of the mathematical framework, requiring a signal response that is stationary, shift invariant, and linear. The linear system response is then fully characterized by the slope and offset of the linear relationship between input signal (dose, exposure, absorbed energy) and the output signal.

It is now generally accepted [5] to combine the various image quality metrics into a single metric $DQE(u,v)$ given by equation (1).

$$DQE(X,u,v) = \frac{S_0(X)^2 \cdot MTF^2(u,v)}{NPS(X,u,v)} \qquad (1)$$

In equation (1), S_0 is the signal at zero spatial frequency. This signal depends on the input exposure or dose (X). The NPS is also dependent on the input dose, while the MTF is generally regarded to be independent of dose. As a result the overall DQE also depends on dose.

In medical imaging, the measurement and computation of DQE are fixed by a standard (IEC 62220-1). DQE has become the most popular metric for image quality because it describes the degradation of the SNR by the imaging process as shown in equation (2).

$$DQE(X,u,v) = \frac{SNR_{out}{}^2(X,u,v)}{SNR_{IN}{}^2(X,u,v)} \qquad (2)$$

From a practical point of view, the user is mainly interested in the ability of a radiographic inspection to detect defect indications. Since there are many different inspection application areas, and for each application the diagnostic task is different, an application-based assessment methodology is straightforward but not easily extended from one application to others. To simplify classification and ranking of various imaging systems, standard test pieces are designed that incorporate features of different size and contrast. These objects are called Image Quality Indicators (IQIs). Images of the IQIs are visually evaluated by indicating the smallest and least-contrast feature that is discerned clearly. This subjective metric depends on the ability of the individual observer to extract image features from the image background. The scoring can vary by individual observer, and also with differing viewing conditions, limiting the utility of subjective image quality performance.

Improved evaluation of diagnostic performance can be achieved through a statistical study of a specific diagnostic task, involving multiple observers and multiple imaging trials. Nevertheless, it remains challenging to correlate objective image quality metrics and subjective diagnostic performance. Although numerous papers have been devoted to this subject [6-8], the link between objective image quality metrics and contrast-detail performance is not yet fully understood. Correlating both objective and subjective image quality performance metrics with diagnostic performance, is even more complicated, and therefore remains open to discussion.

In the literature a wide range of observer models have been discussed. These models focus on summarizing the observer performance by a figure of merit, here called SNR for a specific diagnostic task. The observer SNR is expressed as a function of the objective image quality parameters of the detector: $MTF(u,v)$, $NPS(u,v)$, the system gain G, and the Fourier transform of the object signal that needs to be detected $\Delta S_i(u,v)$.

For the ideal observer [6] (i.e., the observer that reaches the maximum SNR), the correlation is expressed by equation (3).

$$SNR_{ideal}{}^2 \equiv \int\int du \cdot dv \cdot \frac{G^2 \cdot \Delta S_i{}^2(u,v) \cdot MTF^2(u,v)}{NPS(u,v)} \quad (3)$$

For this case, both object and background are known exactly, and further the observer has a-priori knowledge that allows him to correct for any correlations in the image noise. In this way a maximum of information may be extracted from the image.

However, actual human observers are not able to correct for correlations in the image noise. This is called the Non Pre-Whitening Matched Filter (NPWMF) case. We have to account also for the fact that background and object signal are not known exactly. The variability of the object is described by $W_f(u,v)$: the Fourier Transform of the object auto-covariance. The correlation between diagnostic performance and the objective image quality parameters is then described [6] by equation (4).

$$SNR_{NPWMF}{}^2 \equiv \frac{\left[\int\int du \cdot dv \cdot G^2 \cdot \Delta S_i{}^2(u,v) \cdot MTF^2(u,v)\right]^2}{\int\int du \cdot dv \cdot \Delta S_i{}^2(u,v) \cdot MTF^2(u,v) \cdot \left[W_f(u,v) \cdot MTF^2(u,v) + NPS(u,v)\right]} \quad (4)$$

Intuitively it is clear that the detector resolution $MTF(u,v)$, is less important for the NPWMF case than for the ideal observer case, because the presence of $MTF(u,v)$ in both numerator and denominator of equation (4) will result in a partial cancellation of its effect. The NPWMF case is generally regarded as a closer description of the real observer. For the NPWMF case, system resolution is less important than for the ideal observer

The observer performance is further limited by the human visual system, the display and ambient light conditions. To account for these factors an observer modulation transfer function $H(u,v)$ and the internal observer noise power $NPS_{observer}$ can be added, yielding equation (5) for the modeled observer performance.

$$\begin{aligned} SNR_{\text{mod}}{}^2 \equiv & \left[\int\int du \cdot dv \cdot G^2 \cdot \Delta S_i{}^2(u,v) \cdot MTF^2(u,v) \cdot H^2(u,v)\right]^2 \times \\ & \{\int\int du \cdot dv \cdot \Delta S_i{}^2(u,v) \cdot MTF^4(u,v) \cdot H^4(u,v) \cdot W_f(u,v) + \\ & \int\int du \cdot dv \cdot \Delta S_i{}^2(u,v) \cdot MTF^2(u,v) \cdot H^2(u,v) \cdot \left[NPS(u,v) + NPS_{observer}\right]\}^{-1} \end{aligned} \quad (5)$$

The fact that the effective MTF is cascaded, i.e. that the detector MTF is on its turn modulated by the observer MTF, further reduces the importance of the detector MTF. This may partially explain why the CR system studied showed good detection performance despite limited spatial resolution.

4. Model

We have developed a model for the DQE of a computed radiography system using a cascaded linear systems analysis previously proposed in literature [9, 10]. It differs with respect to the model described in [9] by the fact that it also accounts for the Lubberts effect [11].

Two hypothetical CR systems are modeled, a high-resolution system and a medium-resolution system. The exposure and read-out parameters are summarized in Table 3. Similar light collection efficiencies are assumed for both systems.

The hypothetical high-resolution system would require the use of specialized image plates to achieve its ultimate spatial resolution capability. Even when manufactured with the same coating tolerances (ΔT), such image plates would exhibit a higher fixed pattern noise because a smaller phosphor coating thickness (T) is needed to prevent lateral blurring from intra-coating optical scatter. And since the fixed pattern noise is approximately proportional to the relative thickness variations $\Delta T/T$, a smaller coating thickness results in higher fixed pattern noise.

The thinner phosphor layer also reduces the x-ray absorption efficiency, slowing the response of these plates. Blue dye also has been added to limit the scatter of the stimulated light, but it reduces the penetration of the laser light within the phosphor layer. As a consequence the effective thickness (i.e., the thickness of the phosphor layer contributing to the image) is even further reduced.

	Medium-Resolution	**High-Resolution**
Tube Voltage (kV)	120	120
Source Filter Cu thickness (mm)	1.50	1.50
SDD (mm)	1840	1840
Laser spot size (Ø 1/e2 in µm)	50	17
Scan speed (µm/µs)	25	25
Pixel pitch (µm)	50	25

Table 3. Model parameters for two hypothetical CR imaging systems.

The MTFs of the two systems modeled are shown in Figure 1. As expected, the resolution of the high-resolution system is better, but the resolution anisotropy (the difference in resolution between the horizontal and vertical image directions) is also more pronounced.

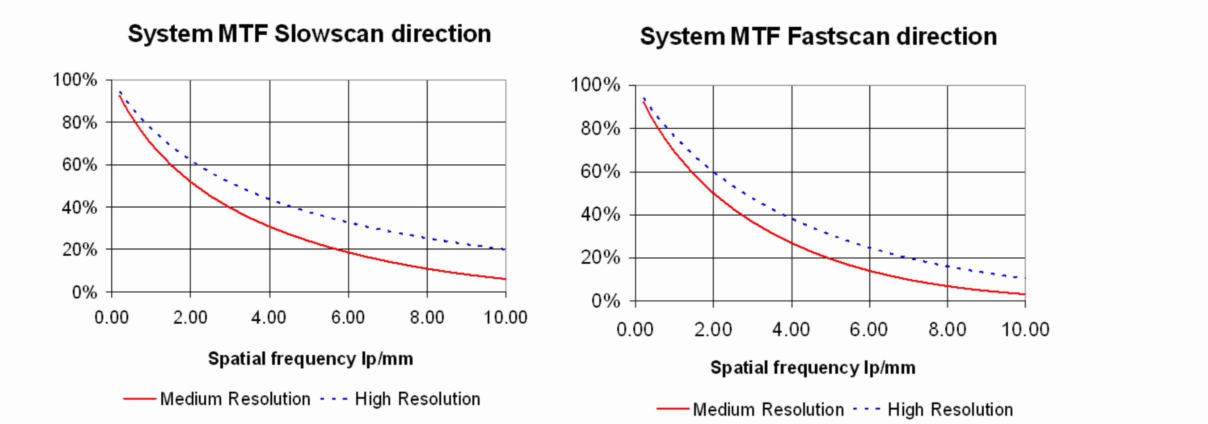

Fig. 1. Modeled MTF of two hypothetical CR systems.

SNR and normalized SNR (nSNR, calculated according to EN14784-1) are plotted as function of dose in Figure 2. The ultimate SNR at high dose is reduced for the high-resolution system, leading to a reduction in effective detection from equation (4). At the saturation limit, both systems exhibit similar normalized SNR values. In the low dose regime, the medium resolution system requires only approximately 50% of the exposure time of the HR system to reach the same normalized SNR value.

If we assume that there is a correlation between nSNR and POD, we would expect both systems to have similar ultimate diagnostic efficiencies (POD) at high dose. But for dose levels below the SNR saturation limit, the medium resolution system would demonstrate a better POD in many applications.

As a next step, we plan to integrate the DQE model results with the NPWMF observer model for a typical contrast-detail detection task (e.g. wire IQI sensitivity on Fe).

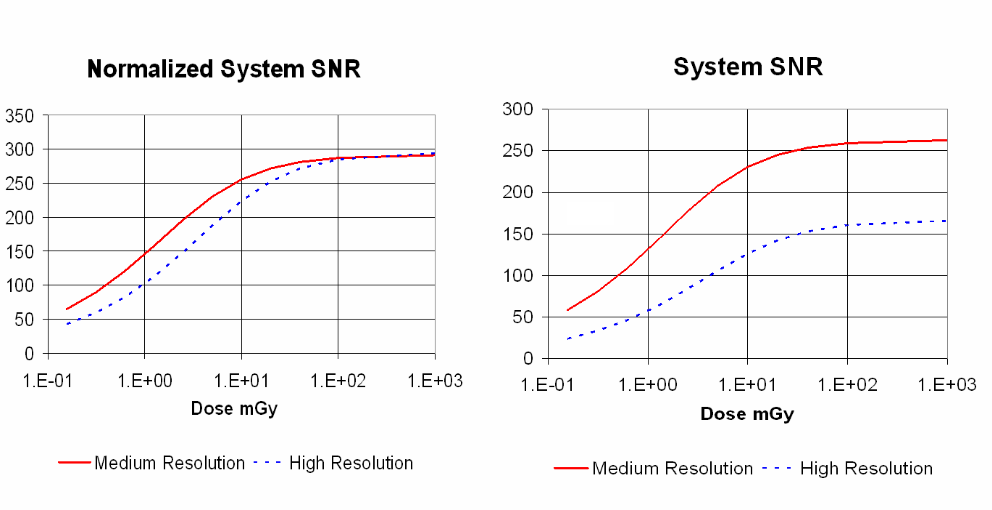

Fig. 2. Modeled nSNR and SNR of two hypothetical CR systems.

5. Conclusions

A visual assessment of CR image quality using standard wire-type IQIs was conducted for a variety of thicknesses with common steel and aluminum materials. These data are very favorable in terms of meeting commonly accepted radiographic standards for inspection of welds. The same CR system was also evaluated for the additional resolution requirements set specifically for CR devices in weld inspection by EN14784-2.

These data are consistent with a human observer detection model that suggests spatial resolution may sometimes be given too much relative importance in evaluations of imaging system performance. Analysis of a cascaded system performance model shows that emphasizing resolution over efficiency in a CR system can have undesirable performance consequences in some applications.

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