Detective quantum efficiency of a phosphor-coupled photodiode array detector for use in digital X-ray tomosynthesis systems

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1. Introduction

A laboratory-scale planar cone-beam computed tomography (CBCT) system is being developed for printed-circuit board (PCB) inspection [1]. Conventional CT scan motions could be impractical for thin, slab-like PCBs [2]. Instead, we use the “digital tomosynthesis” technique which can produce cross-sectional images parallel to the axis of rotation with projections obtained for a limited angular range [3,4].

The image quality of CT is mostly dominated by the number of signal quanta per voxel relative to the noise quanta [5–7]. Therefore, the image quality improves with increasing number of projections used for image reconstruction. However, this can affect the CT evaluation time, in contrast to the digital tomosynthesis technique, which can provide tomographic images in a relatively short time with few projections. Another way to improve image quality is increasing the X-ray photon “fluence” used to obtain a single projection from an X-ray imaging detector. However, this influences the radiation effects of objects and imaging detectors [8].

Industrial imaging may be less restricted in terms of X-ray exposure than medical imaging, in which the exposure levels should be minimized to limit the patient dose. However, radiation can still damage electronic components on PCBs [9–11]. Moreover, the heat load on X-ray tube (the product of the applied peak kilo-voltage, beam current, and operation time, or kVp × mAs) is a great concern for the reliable operation of industrial X-ray inspection systems, particularly when they are used for quality control in mass production. Therefore, a detector with an efficient signal-to-noise ratio (SNR) transfer capability from the incident X-ray fluence to the output image is crucial for the successful development of industrial CT systems.

The detective quantum efficiency (DQE) is the most comprehensive measure of detector performance for producing high-SNR images while using the lowest possible X-ray exposure [12]. The spatial correlations of the pixel signal and noise in an imaging detector are usually inevitable, which makes it essential to assess DQE in the frequency domain. Hence, optimal image quality can only be achieved by maximizing DQE at all important spatial frequencies [12]. In medical imaging, the concept of DQE has been successfully and widely used for the selection and development of detectors for specific applications [13–17] and to optimize imaging techniques [18–22]. In contrast, there has been insufficient investigation of the application of DQE to industrial applications of nondestructive testing and evaluation (NDT&E).

This article briefly reviews the concept of DQE. The DQE of a
phosphor-coupled photodiode array detector was measured for 40-kVp and 50-kVp tungsten (W)-target X-ray spectra for use in a digital tomosynthesis system for PCB inspection. The modulation-transfer function (MTF) and Wiener noise-power spectrum (NPS) were also measured to describe the contrast- and noise-transfer performance.

2. Theoretical background

X-ray images are generally scaled by an arbitrary factor for display, and hence absolute image signal values have little meaning [18]. To overcome this problem, the concept of noise-equivalent number of quanta (NEQ) was introduced to express the image SNR in terms of the number of Poisson-distributed input photons per unit area $\eta$ (mm$^{-2}$) at each spatial frequency [23]. The NEQ describing an absolute scale of SNR of a linear and shift invariant (LSI) detector can be defined as follows [18,24]:

$$\text{NEQ}(\eta; u, v) = \frac{[\pi T(u, v)]^2}{\text{NPS}(u, v)}$$

where $u$ and $v$ denote the Fourier conjugates of spatial variables $x$ and $y$ in Cartesian coordinates, respectively. $T(u,v)$ is the detector's characteristic function describing the signal transfer from the input to the output. Its magnitude is equal to $G \times \text{MTF}(u,v)$, in which $G$ (DN mm$^{-2}$) is the detector gain relating the X-ray photon fluence $\eta$ to the pixel output $I$ (in units of digital numbers, DN). Therefore, the numerator of Eq. (1) describes the squared output signal, and the denominator describes the corresponding output noise power. Hence, Eq. (1) implies the squared SNR at the detector output, $\text{SNR}_2^2$.

The DQE is defined as the ratio of NEQ to $\eta$ (SNR$_2^2$) [12,25]:

$$\text{DQE}(u,v) = \frac{\text{NEQ}(\eta; u, v)}{\eta}$$

$$= \frac{[\pi G^2 \text{MTF}^2(u, v)]}{\text{NPS}(u, v)}$$

$$= \frac{\text{MTF}^2(u, v)}{K\pi \text{NPS}(u, v)}$$

(2)

which is independent of $\eta$ when additive electronic noise in the detector is negligible [18]. Therefore, the DQE is a measure of the detector's performance in capturing the fundamental image SNR of the incident $\eta$. Hence, it can also be used as a surrogate for the detector's dose efficiency.

NPS$(u,v)$/$\eta^2$ in the last expression of Eq. (2) implies the normalized NPS (NNPS). $K$ ($\mu$Gy) is the X-ray air kerma measured at the top surface of the detector, and $\eta_0$ is the X-ray photon fluence per unit air kerma (mm$^{-2}$ $\mu$Gy$^{-1}$).

The third expression in Eq. (2) is only applicable if the intercept of the detector characteristic response measured in the coordinates $\eta$ or $(K, \eta)$ is zero. The Fourier-based performance metrics (MTF, NPS, and DQE) are only measurable for imaging systems with an LSI response and wide-sense stationary noise sources [24].

When the detector operates in a “quantum noise-limited” region, where the quantum noise dominates over the electronic noise, the DQE at the zero-spatial frequency is simply [26]:

$$\text{DQE}(0) = a \lambda,$$

(3)

where $a$ is the quantum absorption efficiency of a phosphor and $I$ is the Swank noise factor [27]. $I$ describes the X-ray conversion noise, including variations in optical photon transmits within a phosphor, and it is not readily estimated by a simple analytic approach [28–31]. The value of $a$ for a phosphor can be estimated by a simple analytic method [32]:

$$a = \frac{\int_0^\infty q(E)\lambda(E) \, dE}{\int_0^\infty q(E) \, dE},$$

(4)

where

$$\lambda(E) = 1 - e^{-\mu_{\text{tot}}(E)/\mu_{\text{tot}}(E)}.$$ 

(5)

In Eq. (5), $\mu_{\text{tot}}$ and $\mu_{\text{tot}}$ denote the total and photoelectric linear attenuation coefficients, respectively, and $t$ is the thickness of the phosphor.

3. Methods and materials

3.1. CMOS digital detector array

The detector considered in this study (Shad-o-Box 1548 HS, Teledyne Radicon Imaging Corp., Sunnyvale, CA) consists of a single complementary metal-oxide-semiconductor (CMOS) photodiode pixel array that contains multiple output taps to enable high frame rates, as well as Gd$_2$O$_2$:S:Tb phosphor (DRZ-Std™, Mitsubishi Chemical, Japan). These two main components are coupled through a fiber-optic faceplate (FOP). The phosphor converts X-ray photons into visible light, which is sensed by the CMOS photodiodes. The FOP is used to prevent the CMOS photodiodes from directly absorbing X-ray photons, which reduces the direct X-ray absorption noise [33,34] and the radiation damage to the CMOS electronics [8]. The CMOS photodiode array has a 1032 × 1548 pixel format in the x × y directions with a pixel pitch of 0.099 mm. The x and y directions correspond to the pixel address and data readout directions, respectively. The output analog signal is digitized using 14 bits. The maximum image readout frame rate is 30 frames per second (fps), but the detector is operated at 5 fps for all the measurements, which corresponds to a readout time of 0.2 s.

3.2. Imaging conditions

The X-ray source (Series 5000 XTF5011, Oxford Instruments, USA) uses a W target to produce X-ray spectra with energies of up to 50 kVp at 50 Watts. To mimic the X-ray beam transmitted through PCBs, an aluminum (Al) sheet with a thickness of 3 mm was placed near the beam exit of the X-ray tube. The nominal focal spot size is 0.035 mm. The X-ray source irradiates the detector at a fixed distance of 550 mm during all the measurements. The air kerma $K$ at the entrance surface of the detector is measured with a calibrated ion chamber (Pirahna R&F/M 605, RTI Electronics AB, Sweden). Table 1 summarizes the X-ray beam setups and their qualities. The beam qualities were assessed by half-value layer (HVL) measurements. For each spectrum, $\eta_0$ was estimated using the energy-dependent X-ray fluence per unit air kerma and the W spectral model [35].

3.3. Performance evaluation

The detailed measurement procedure is available from Ref. [36], including the mathematical descriptions of the MTF, NPS, and DQE evaluations. Standard reports on the measurements are also available from the International Electrotechnical Commission [37]. We provide only a brief description of the evaluation procedure.

Table 1

<table>
<thead>
<tr>
<th>Added Al filtration (mm)</th>
<th>3</th>
<th>3</th>
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</thead>
<tbody>
<tr>
<td>HVL (mm Al equivalent)</td>
<td>1.73</td>
<td>2.26</td>
</tr>
<tr>
<td>Irradiated beam current range (mA)</td>
<td>0.2–1.0</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Measured air-kerma range ($\mu$Gy)</td>
<td>0.78–6.22</td>
<td>1.53–7.23</td>
</tr>
<tr>
<td>Estimated $\eta_0$ (mm$^{-2}$ $\mu$Gy$^{-1}$)</td>
<td>$1.20 \times 10^3$</td>
<td>$1.52 \times 10^4$</td>
</tr>
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</table>
For the given X-ray beam setups, the detector output signal was analyzed as a function of air kerma in a central region of 256 × 256 pixels for 20 flood-field images at each air-kerma level. The detector response characteristic was then assessed by least-squares regression analysis using a first-order polynomial. The typical gain-offset correction procedure [38] was applied to all images before analysis (i.e., detector response, MTF, and NPS).

We used the slanted-edge technique to obtain the aliasing-free MTF [39]. We measured the edge-phantom images at high air-kerma levels (7.30–8.26 μGy) to reduce noise in the measurements under the assumption that the MTF is independent of the air kerma [12]. From the edge-phantom images, we extracted 180 oversampled edge-spread functions (9 regions of interest or ROIs times 20 images). Each of them was differentiated to produce a line-spread function (LSF). To obtain MTFs, we applied the 1D fast Fourier transformation to the LSFs. We then took the average of 180 MTFs to minimize uncertainty in the measurements. The MTF was obtained in the orthogonal x and y directions of the CMOS photodiode array.

The NPS was determined by 2D Fourier analysis of 180 zero-mean noise images (9 ROIs times 20 images) with a size of 256 × 256 pixels for each air-kerma level. The zero-mean noise images were obtained by subtracting the mean pixel value from each pixel value in the images and then dividing the result by the mean pixel value. The 1D NNPS was extracted from the 2D NNPS in the two orthogonal directions averaging the directional frequency bands (10 bands) in the 2D NNPS while excluding the selected axis to avoid on-axis artifacts [40]. The DQE was calculated using the last formula of Eq. (2) with the measured MTF and NNPS and with the estimated $\bar{q} = \kappa_0 q_0$.

4. Results and discussion

4.1. Detector response

Fig. 1 presents the measured output signal of the detector as a function of air kerma for the 40-kVp and 50-kVp spectra. Least-squares regression analysis was performed on the measured output signal using a linear model, which described the measured data well. The coefficients of determination (R²) were 0.9996 and 0.9999 for the 40-kVp and 50-kVp datasets, respectively. The slope of the linear model represents the detector sensitivity (in units of DN/μGy). We obtained detector sensitivities of 1.104 × 10³ and 1.249 × 10³ DN/μGy for the 40-kVp and 50-kVp spectra, respectively. The 50-kVp spectrum showed ~13% higher detector sensitivity than the 40-kVp spectrum.

4.2. MTF

Fig. 2 presents the detector MTF curves in two orthogonal directions measured for the 40-kVp and 50-kVp spectra. The MTF curves for the two orthogonal directions were almost the same, which implies that the pixel geometry of the CMOS photodiode array was symmetric. We also observed no difference between the MTF characteristics for the 40-kVp and 50-kVp spectra. The Nyquist spatial frequency is 5.05 mm⁻¹. For comparison, the “sinc” function is also plotted in Fig. 2. This function describes the geometric pixel aperture response in the Fourier domain and is the best MTF that could be achieved. To calculate the sinc function, we used a pixel fill factor of 0.86 from the manufacturer. There was a large discrepancy between the theoretical and measured MTFs. This can be explained by the optical photon scattering within the phosphor layer, through the air gap between the phosphor and FOP layers, and through the optical glue between the FOP and CMOS photodiode layers, including the optical photon scattering within the FOP layer itself [25].

4.3. NPS

Fig. 3(a) shows the NPS curves in two orthogonal directions measured for the dark images (without X-ray irradiation). We observed sharp peaks at spatial frequencies less than 0.5 mm⁻¹ for the u and v directions. The low-frequency peaks in NPS imply large-scale non-uniformity in the dark
The peak along the \( u \) direction may come from gain and offset variations both in column-to-column data lines and across each amplifier chip located at the end of data lines in parallel to the pixel address lines. The peak along the \( v \) direction may come from variations in the row-to-row pixel address lines. This line noise usually originates from parasitic capacitances and resistances.

Fluctuations in addressing and amplifier voltages can couple change into the signal being addressed through the parasitic capacitances and produce line noise. If these non-uniformities are fixed in space, they could be removed by subtracting two dark images from each other. Thus, we measured NPS for the difference between two dark images. Each difference image was corrected by dividing by \( \sqrt{2} \) because the two images have independent noise samples with equal variance. As shown in Fig. 3(a), the NPS obtained for the difference images removed the low-frequency peak and reduced the overall noise-power spectral densities over the entire spatial frequencies. Thus, a frequency-independent white spectrum was obtained.

The noise can be quantified by a single-valued metric such as the variance or the standard deviation of pixel values in images. The relationship between the variance and the NPS is [36]:

\[
\sigma^2 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \text{NPS}(u, v) \, du \, dv.
\]  

We confirmed that the difference between the two different approaches is negligible. The dark noise can be described in terms of the random shot noise and the readout fixed-pattern noise: \( \sigma_{\text{dark}}^2 = \sigma_{\text{RN}}^2 + \sigma_{\text{FP}}^2 \). From the NPS obtained for dark images and their difference images, we obtained \( \sigma_{\text{RN}} = 4.7 \) DN and \( \sigma_{\text{FP}} = 2.4 \) DN.

Normalized NPS results for the 40-kVp and 50-kVp spectra are shown in Fig. 3(b) and (c), respectively. The directional MTF characteristics of the detector were well reflected in the NNPS results, and the same NNPS performance was achieved between the two orthogonal directions. The NNPS performance of the detector followed the general trend of a phosphor-based imaging detector [26]. The noise-power spectral density rolled off with increasing frequency because the number of secondary quanta (e.g. optical photons or electrons) decreased with increasing frequency. The MTF plays the role of a “spatial filter (low-pass filter)” for the signal and quantum noise [41].

The overall magnitude of the spectral densities decreased with increasing air kerma because the increase in the signal became larger than the increase in noise [42]. The shapes of NNPS over the spatial frequency measured at each air kerma were almost the same. This implies that the FOP layer effectively stopped the unattenuated X-ray photons through the phosphor, and the quantum noise mostly dominated the additive electronic noise over the entire frequency region, even at lower air-kerma levels. If the additive electronic noise and the direct X-ray absorption noise were not negligible compared to the quantum noise at lower air-kerma levels, the roll-off of spectral densities at higher frequencies would become small or be flattened because of the frequency-independent characteristic of electronic noise power densities [43,44].

The effect of air-kerma levels on the noise performance is shown in Fig. 3(d). The variance relative to the squared pixel signal, \( \sigma^2/\bar{I}^2 \), can be calculated by using pixel values in the images directly or using Eq. (6) with NNPS(\( u, v \)) instead of NPS(\( u, v \)). As expected from Fig. 3(b) and (c), the relative variance decreased with increasing air kerma. Assuming that the pixel signal is proportional to the air-kerma level and the quantum noise follows the Poisson statistics, \( \sigma^2/\bar{I}^2 \) will be reciprocally dependent on the air-kerma level, as shown by the dotted curve (\( c/K \) with \( c = 1.73 \times 10^{-3} \)) in Fig. 3(d). \( R^2 \) of the trend curve was 0.999 for the 40-kVp and 50-kVp datasets.

### 4.4. DQE

The DQE results are summarized in Fig. 4. The DQEs extracted along the two orthogonal directions were very similar to each other, as expected from the directional properties of MTF and NPS (not shown for...
The quantum-noise-limited air-kerma level of the detector was less than 0.78 μGy and the zero-frequency DQE value was greater than 30%.

While the DQE has been widely used for describing detector performance in medical imaging, it might be less popular in NDT applications. Instead, the “normalized SNR” or “normalized contrast-to-noise ratio (CNR)” is known as the corresponding metric in the NDT field [45]. For the development of planar CBCT system, therefore, the assessment of detector performance in terms of normalized SNR and CNR will be our future study. In addition, we will take the detector design with a thinner phosphor or a structured scintillator (e.g. columnar CsI:Tl) into account for better spatial-resolution performance while minimizing detector gain loss.

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References


