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Noise evaluation of a digital neutron imaging device

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ABSTRACT

To assess the applicability of neutron radiography technology, it is important to compare the performance characteristics of different neutron detection systems and their implementations. Although widely used in X-ray imaging, performance evaluation measures, such as the noise power spectrum (NPS) and the detective quantum efficiency (DQE), have not been readily applied to neutron radiography. This paper introduces the concepts of NPS and DQE and presents an adopted procedure for the calculation of NPS and DQE, using an in-house developed digital neutron radiography device as an example. This low-cost radiography apparatus has remarkable features such as using an off-the-shelf digital camera modified by open-source code and a front surface aluminized mirror made of ^{6}Li-doped glass. The results show that a high spatial resolution does not necessarily translate to better detectability of faint details and noise evaluation has to be taken into account. In order to improve the poor DQE of the evaluated system, it is suggested to reduce the fast neutron content and increase the light collection efficiency. Such improvements would bring the output signal-to-noise ratio (SNR) much closer to the input quantum noise, which would consequently increase DQE.

1. Introduction

The earliest neutron radiography work dates back to 1948 [1]. Extensive work was performed during the following decades to develop this technique [2] that continues to provide solutions to this day for hard-to-solve problems that encompass a wide variety of topics, such as imaging water flow in fuel cells [3], detecting drugs and explosives [4], and revealing illicitly smuggled special nuclear materials [5,6], to name a few. Such increased number of applications was made possible by the rapid advancement of detector technologies [7], especially the digital radiography instruments [8]. This transition has fostered the advancement of methodologies that allow characterization of image quality and provide metrics used to compare existing and emerging neutron detector technologies.

However, the performance evaluation criteria and methods for neutron radiography have fallen far behind what has been practiced in X-ray imaging, where the modulation transfer function (MTF) [9], noise power spectrum (NPS), and detective quantum efficiency (DQE) [10] have become widely accepted metrics. In short, MTF describes the detector or system's spatial resolution in terms of contrast, which is defined as the ratio of output modulation to an input sinusoidal modulation with varying spatial frequency. NPS measures noise amplitude observed in images obtained in a uniform field of radiation. It is argued that contrast alone (i.e., MTF only) is insufficient in describing image quality [11], since MTF ignores noise components. An example of such poor detectability is a high-contrast edge profile image embedded with high noise levels. Therefore, DQE, which quantifies the effects of noise level and contrast performance, better describes the ability to discern small details. A detailed discussion given in this paper shows that DQE, which involves the calculation of both MTF and NPS, reflects how a detector/imaging device produces an output SNR that is degraded from an input SNR in the spatial frequency domain.

In neutron radiography, MTF has won acceptance as the figure-of-merit for spatial resolution [12,13]. However, the debate over MTF and DQE present in X-ray imaging is far from being observed in neutron radiography. A rare discussion of DQE in digital neutron radiography detector can be found in Barmakov's work [14], but the discussion of DQE's frequency dependency and its measurement are not included. In X-ray radiology, an imaging system with 20% DQE will require double the amount of incoming photons to produce the same SNR as an imaging system with 40% DQE. Naturally, it is preferred to design an imaging system with a high DQE to reduce patient dose exposure. Even though a patient's health is not a concern with regard to neutron radiography, it is still desirable to reduce the exposure time, and hence, the ambient radiation and the activation in both the sample and the working environment. More importantly, it is necessary to compare the performance characteristics of different neutron detectors or system implementations to support various applications of neutron radiography technology. The concepts of NPS and DQE are discussed in this paper, with emphasis given to neutron radiography, and the calculation protocol has been partially revised and applied to an in-house developed digital neutron radiography system.

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2. Theory and concepts

2.1. Noise and SNR

An image with good contrast marred by a high noise level points the discussion to the original concept of SNR ratio. The Poisson distribution governing both X-ray photons and neutrons renders a simple relationship between SNR and incident quanta at the input stage, which is given by

$$(SNR)_{input} = \frac{N}{\sigma_N} = \frac{N}{\sqrt{N}} = \sqrt{N} \tag{1}$$

where N is the number of incident neutrons and σ, the standard deviation, is equal to the square root of N. While this parameter (known as photon noise or quantum noise) shows that the performance of an imaging system (radiation source included) can be improved by improving the radiation source strength or exposure time, it has little to do with the detector's performance.

Thus, the output SNR has to be accounted for, given by

$$(SNR)_{output} = \frac{\overline{P}}{\sigma_{\overline{P}}} \tag{2}$$

where $\overline{P}$ is the mean pixel value and $\sigma_{\overline{P}}$ is the standard deviation of the pixel value.

In an ideal detector, in which there are no other sources of noise and a one-to-one correspondence exists between an absorbed neutron and a registered pixel value, the output SNR is equal to the input SNR. However, in reality, there are signal loss and noise gain during the signal conversion stages inside the imaging detectors. This causes the output SNR to be smaller than the input SNR.

2.2. Noise equivalent quanta and DQE

When assuming that quantum noise is the dominating factor in the system noise, it is useful to determine how the other minor sources of noise decrease the ideal SNR. Intuitively, one can relate the measured output SNR to an imaginary incident neutron quantity that would be known if the imaging system served as an ideal neutron counter. This quantity is called the noise equivalent quanta (NEQ) [10] and is written as

$$NEQ = (SNR_{output})^2 \tag{3}$$

NEQ informs about the effective number of neutrons used by the detector or system (radiation source excluded) to produce the measured SNR. With this definition and (1), DQE [10], can be expressed as

$$DQE = \frac{(SNR_{output})^2}{(SNR_{input})^2} = \frac{NEQ}{N} \tag{4}$$

In this form, DQE becomes a metric that relates the imaging system's ability to receive incident quantum and produce an output of a desired quality. The best output SNR obtainable in an ideal system is equal to the input SNR. Such condition would suggest a one-to-one correspondence and an absence of measurement errors and other extraneous factors. Naturally, DQE will always fall in the range 0–1.

2.3. Noise power spectrum (NPS)

The second challenge presented by (1) and (2) is their weakness in addressing the spatial correlation of noise. It is known that the image formation chain normally consists of multiple signal transform processes. Some of the intermediate signals inside the detector may be spatially (or partially) correlated even though neutrons are spatially independent of each other. Thus, it is necessary to use second-order statistical measures that not only describe the power or intensity of the noise, but also describe the spatial correlations within it.

NPS, also recognized as the Wiener spectrum, is routinely applied in X-ray radiology, and should be used in neutron radiology to characterize the noise. For a stationary random process, NPS is the Fourier transform of the auto-covariance function. The computational equation is given as [15]

$$NPS(u_n, v_k) = \lim_{M, N_x, N_y \to \infty} \frac{\Delta x \Delta y}{M \cdot N_x N_y} \sum_{M=1}^{M} \left| \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} [I(x_i, y_j) - S(x_i, y_j)] \times \exp(-2\pi i (u_n x_i + v_k y_j)) \right|^2 \tag{5}$$

According to (5), a gray scale radiographic output consists of M regions of interests (ROI), where each ROI is a matrix of N_x by N_y elements, or pixels. Each pixel position within a ROI is identified by Cartesian coordinates (x_i, y_j) and its gray scale intensity is denoted as $I(x_i, y_j)$. In addition, for each ROI, a two-dimensional polynomial S is fitted to determine the mean of the region. The two-dimensional Fourier transform is applied to each ROI corrected for the mean trend, $I(x_i, y_j) - S(x_i, y_j)$, and then squared. The resulting sum of squared Fourier transform amplitudes must be divided by M to achieve a representative result for an average ROI. Furthermore, the results of the average ROI must be multiplied by the pixel size (where Δx and Δy are pixel width and height in the i and j directions, respectively) and then normalized by the number of pixels in the ROI (N_x and N_y that correspond to number of pixels in the i and j directions).

A complete derivation of a one-dimensional case can be found in the book written by Blackman [16], and the extension to a two-dimensional case is obvious. Eq. (5) implies that NPS can be understood as the variance of image intensity described in a spatial frequency domain. Not surprisingly, the internal mechanism of the detector/imaging device has a tendency to blur both the input signal and noise alike, which usually translates to a decrease in power of these noise sources with increasing spatial frequency [17].

2.4. The DQE in frequency domain

Many authors [18] express NEQ as function of spatial frequency. In particular, Dobbins [19] gives NEQ as the ratio of MTF to NPS at a given frequency f, shown in

$$NEQ(f) = (SNR_{output})^2 = \frac{MTF^2(f)}{NPS(f)/(\overline{P})^2} \tag{6}$$

here $NPS(f)$ is normalized by the square of the mean pixel value of the image, $\overline{P}$. Since all the terms are ready to be measured, (6) is inserted into (4) to determine DQE as a function of frequency

$$DQE(f) = \frac{(\overline{P})^2 \cdot MTF^2(f)}{NPS(f) \cdot N} \tag{7}$$

Eq. (7) is used to calculate DQE of a low-cost neutron radiography system developed originally at the National Institute of Standards and Technology (NIST) by the author and further modified at The Ohio State University for this study.

3. The in-house made digital neutron radiography system and its MTF

The low-cost digital neutron radiography system, for which the performance is evaluated as an example, was first developed at NIST 20 MW research reactor to "see" the focal spot of a neutron lens in real-time [20]. The remarkable components of this