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Detective Quantum Efficiency of a Dynamic Flat-Panel Detector across Frame Progression under Low-Energy X-ray Conditions

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1. Introduction

In high-precision industrial non-destructive testing (NDT) fields such as secondary battery stack structure inspection and semiconductor defect analysis, there is a growing demand for real-time X-ray inspection technology in the low-energy range (30–40 keV), which can effectively represent contrast differences between fine internal structures. In particular, high-speed in-line inspection systems that must continuously examine products moving along a conveyor belt cannot keep pace with process speeds using static image acquisition methods, making dynamic Flat-Panel Detectors (FPD) capable of acquiring tens of frames per second in real time indispensable.

However, in low-energy X-ray environments, the number of effective photons reaching the detector is inherently limited, causing quantum noise—arising from photon counting statistics—to become the dominant noise source. This is compounded by the system's intrinsic readout noise, collectively degrading the signal-to-noise ratio (SNR) and significantly constraining the detection sensitivity for fine defects. Pixel binning mode is commonly employed to mitigate these noise-related issues; however, binning introduces a trade-off between spatial resolution and noise characteristics, necessitating careful selection of optimal operating conditions depending on the inspection objective [1].

In dynamic image acquisition, additional degradation phenomena distinct from static conditions also arise [2]. Afterglow from the scintillator and temporal lag caused by charge trapping within the thin-film transistor (TFT) panel result in signal carry-over from previous frames into the current frame [3]. This induces a significant discrepancy between detection efficiency measured under static conditions and that observed under actual dynamic operating conditions. As frame rate (FPS) increases, the cumulative effect of temporal lag on image quality becomes increasingly complex, underscoring the need for its quantitative characterization.

This study experimentally simulates a low-energy industrial inspection environment and aims to quantitatively analyze the effects of varying binning modes and frame rates on the key image quality metrics of the detector—modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE)—as a function of time.

2. Methods and Materials

2.1 Modulation Transfer Function (MTF)

The MTF is a metric that quantifies, in the spatial frequency domain, how faithfully an imaging system reproduces the spatial detail of a subject. A value closer to 1 indicates that the corresponding frequency component is transmitted without distortion. The MTF is defined as the absolute value of the Fourier transform of the Line Spread Function (LSF), and is expressed as

$$MTF(f) = |F\{LSF(x)\}|. \tag{1}$$

Experimentally, the Edge Spread Function (ESF) is measured from an edge phantom, differentiated to obtain the Line Spread Function (LSF), and then subjected to Fourier transformation. In this study, the MTF was individually calculated for each frame in a continuous frame sequence, enabling the temporal tracking of spatial resolution changes as frames accumulate during dynamic detector operation.

2.2 Noise Power Spectrum (NPS)

The NPS is a metric that characterizes not only the total amount of noise in an image but also its distribution across spatial frequencies. Even with identical noise variance, the visual image quality and detection performance can differ depending on the frequency composition, and the NPS captures this by describing noise in the frequency domain. The NPS is computed through the two-dimensional Fourier transform of the noise component extracted from uniformly exposed flat-field images. In this study, the NPS was individually calculated for each frame from the corresponding flat-field image, enabling the temporal tracking of noise characteristics as frames accumulate during dynamic detector operation.

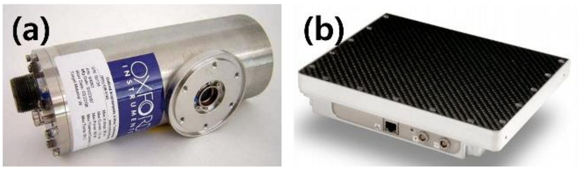

Fig.1. Photographs of the experimental components: (a) X-ray Source (XTF5011, Oxford Instuments) and (b) dynamic flat-panel detector (Xineos1515, Teledyne Dalsa)

2.3 Detective Quantum Efficiency (DQE)

The DQE is a comprehensive performance metric that represents how well the signal-to-noise ratio (SNR) of X-ray quanta incident on the detector is preserved in the output image. It is defined by combining the MTF and NNPS as

$$DQE(f) = \frac{MTF^2(f)}{q_0 \times NNPS(f)}, \qquad (2)$$

where, q_0 represents the incident photon fluence per unit area. Since DQE simultaneously reflects both the resolution and noise characteristics of the system, it is used to evaluate the overall detection performance that cannot be fully captured by either metric alone. In this study, the DQE was sequentially calculated for each frame using the frame-wise MTF and NPS derived above, with the primary objective of quantitatively tracking the temporal variation in detection performance as frames accumulate during dynamic detector operation.

2.4 Experimental Setup and Conditions

The experiment was conducted using a real-time imaging system consisting of an X-ray source (XTF5011, Oxford Instruments) and a dynamic FPD (Xineos1515^{TM}, Teledyne Dalsa) with a CsI scintillator. To achieve the target low-energy beam quality in the 30–40 kVp tube voltage range, an additional aluminum filter was applied beyond the inherent filtration of the X-ray source. [4]

Three independent variables were defined for this experiment. (1) Binning mode: 1×1 binning and 2×2 binning. (2) Frame rate: 5, 10, 20, and 24 FPS. (3) Tube voltage and current: tube voltage at 25, 30, 35, 40, and 45 kVp, and tube current at 0.1, 0.3, 0.5, 0.7, and 0.9 mA. For each condition, a continuous sequence of 100 frames was acquired to track the evolution of image quality metrics over time and with increasing frame accumulation.

3. Preliminary Results

Fig. 2(a), (b), and (c) show the MTF, NNPS, and DQE of the 1st, 3rd, 5th, 10th, 50th, and 100th frames, respectively, acquired under X-ray irradiation conditions of 40 kVp and 900 mA with detector settings of 1×1 binning and 10 fps. The MTF showed similar results across frames regardless of frame progression. The NNPS tended to decrease as frames progressed. The DQE, however, exhibited severe fluctuations across spatial frequencies, making it difficult to identify a clear trend with frame progression.

4. Conclusion

In this study, an edge phantom was imaged in the low-energy X-ray range using a dynamic X-ray detector, and the temporal evolution of key image quality metrics (MTF, NPS, and DQE) as frames progress was investigated. The preliminary results indicate that MTF was relatively unaffected by frame progression, while NNPS showed a decreasing trend with increasing frame number.

In contrast, the DQE exhibited severe fluctuations for individual frame images, which is attributed to the dominance of quantum noise resulting from the short X-ray exposure time per frame. To address this issue, videos will be acquired 20 times under identical

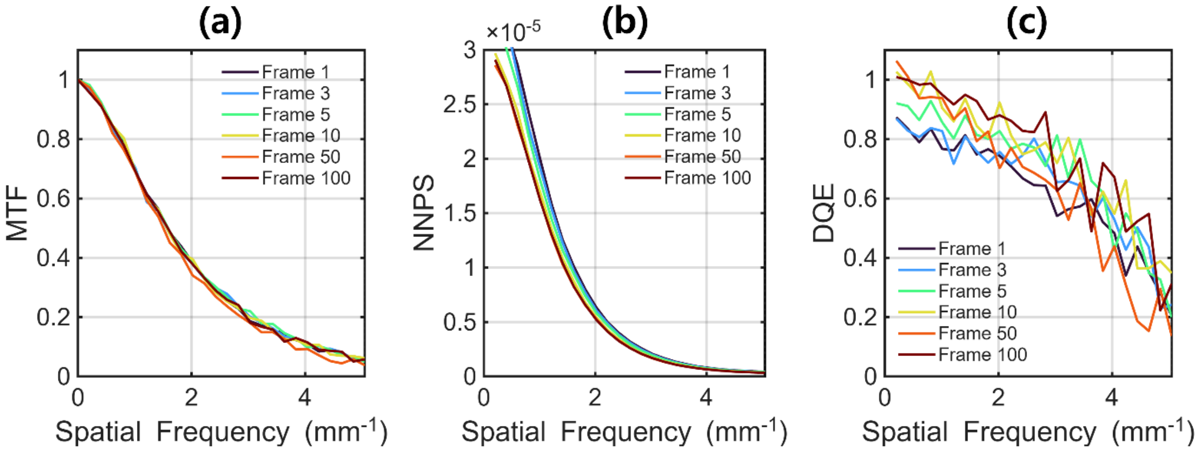

Fig. 2. Temporal evolution of spatial frequency-dependent (a) MTF, (b) NNPS, and (c) DQE curves as a function of accumulated frames during dynamic detector operation.

conditions, and ensemble averaging will be applied across frames of the same index to suppress white noise and improve the reliability of DQE estimation.

This study is significant in that it directly and quantitatively tracks the temporal evolution of detector performance from the onset of dynamic operation. The results obtained are expected to serve as a quantitative basis for future research aimed at stabilizing image quality and optimizing operating conditions in high-speed in-line inspection systems utilizing dynamic FPDs. In addition, analysis across the full range of source and detector operating conditions is planned.

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REFERENCES

[1] Y. Srinvas, D. Wilson, "Quantitative image quality evaluation of pixel-binning in a flat-panel detector for x-ray fluoroscopy," Journal of Medical Physics, Vol. 31, No. 1, pp. 131-141 (2004)

[2] H. Kawashima, R. Tanaka, K. Ichikawa, K. Matsubara, H. Iida, S. Sanada, "Investigation of image lag and modulation transfer function in fluoroscopy images obtained with a dynamic flat-panel detector," Journal of Radiological Physics and Technology, Vol. 6, No. 2, pp. 367-374 (2013)

[3] J. Starman, J. Star-Lack, G. Virshup, E. Shaprio, R. Fahrig, "A nonlinear lag correction algorithm for a-Si flat-panel x-ray detectors," Journal of Medical Physics, Vol. 39, No. 10, pp. 6035-6047 (2012)

[4] S. Yun, S. Kim, D. Kim, H. kim, "Detective quantum efficiency of a phosphor-coupled photodiode array detector for use in digital X-ray tomosynthesis systems," Journal of NDT & E International, Vol. 92, pp. 130-135 (2017)