

Optimization of High Energy X-ray Detector Based on SNR in Cargo Container Inspection System

Sung-Woo Kwak, Gyuseong Cho, and Jin Sung Kim
KAIST, 373-1 Kusong-dong, Yusong-gu, Daejon 305-701, KOREA

Abstract—Energetic x-ray is used for nonintrusive inspection of large cargo containers at seaport or airport, nondestructive inspection of machine engines or pipes in industry, and quantification of free water in radioactive waste drums in nuclear industry. Such inspection systems have employed a photodiode-based solid state detector consisting of a single crystal and a photo sensor. In x-ray inspection systems using low energy x-ray known well, there is no interrelation between the increase in the crystal thickness for improving signal amplitude and the expansion of an active area of a photodiode. On the other hands, due to different detector arrangement, the increase of detector depth for improving signal in imaging system using high energy x-ray gives rise to the increase of signal as well as noise. In addition, the noise in a large detector has a significant effect on detector SNR. However, no studies on how to design a high energy x-ray detector in consideration of electronic noise in detector system have reported in the literature. To address this problem, new generalized design model using SNR (Signal-to-Noise ratio) of x-ray detector is proposed in this paper. The design model of this paper is also applied to realize the actual x-ray detector for 0.45 MeV cargo container inspection system and the test results obtained by the inspection system are discussed.

I. INTRODUCTION

An x-ray imaging system has been used for the inspection of illegal drugs, agricultural products, and other contraband in customs applications, and for the inspection of weapons and explosives in security applications. Due to terrorist attack of Sept. 11 and the increase of the smuggling into our country from the neighboring countries, in recent years importance of an x-ray inspection system has been largely stressed. Some companies [1-4] have developed nonintrusive inspection systems using x-rays over the past several years. As shown in Table 1, in spite of equal x-ray energy, there is large difference in size of x-ray detector that commercial vendors use. Tracing the history of the study, we found that few detailed studies on detector design for high energy x-ray have been published.

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Sung-Woo, Kwak is with the KAIST 373-1 Kusong-dong, Yusong-gu, Daejon 305-701, Republic of Korea (telephone: 82-42-869-38884, e-mail: swkwak@kaist.ac.kr).
Gyuseong Cho with the KAIST 373-1 Kusong-dong, Yusong-gu, Daejon 305-701, Republic of Korea (telephone: 82-42-869-3821, e-mail: gseho@kaist.ac.kr).
Jin Sung Kim is with the KAIST 373-1 Kusong-dong, Yusong-gu, Daejon 305-701, Republic of Korea (telephone: 82-42-869-3861, e-mail: jinsung@kaist.ac.kr).

In x-ray imaging systems using low energy x-ray like mammography, dental radiography and computed tomography in medical applications, x-ray is incident on the side opposite to the scintillator (CWO) surface coupled to a photodiode. In this case, there is no interrelation between the increase in the crystal thickness for improving signal amplitude and the expansion of an active area of a photodiode. On the other hands, the detector for large and dense object examination is placed parallel to the x-ray incident direction due to its strong penetration ability. In this arrangement, increasing a detector depth (D) for improving signal gives rise to the increase of signal as well as noise.

Under this condition, advantage capable of being achieved by large detector depth has been reduced due to the increase of the noise. There should be careful trade-off between signal and noise in high energy x-ray detector design. However, as shown in Table 1, no studies on how to design a high energy x-ray detector in consideration of electronic noise have reported in the literature. To address this problem, new generalized design model using SNR of x-ray detector is proposed in this paper. The design model suggested is also applied to realize the actual x-ray detector for 0.45 MeV cargo container inspection system. The test results obtained with the inspection system will be discussed.

II. SNR MODELING IN HIGH ENERGY X-RAY DETECTOR

If an x-ray photon is incident on a scintillator (CWO), a part of the x-ray is absorbed by the scintillator and converted to light photons. The light photon from CWO reaches a photodiode through optical gap between the CWO and the photodiode and is converted to electric current by the photodiode. Finally, as shown in Fig.1, the photo-current obtained by bombarding tungsten target with beam current of \( I_e \) can be given as equation (1).

![Table I: Various X-ray Detector Sizes of Existing Vendors](image)

<table>
<thead>
<tr>
<th>Vendors</th>
<th>Maximal Energy (MeV)</th>
<th>Spatial Resolution (mm)</th>
<th>Detector size (W mm X D mm X H mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>9.0</td>
<td>2.5</td>
<td>5.0 x 50.0 x 6.0</td>
</tr>
<tr>
<td>R</td>
<td>9.0</td>
<td>2.4</td>
<td>4.6 x 30.0 x 15.0</td>
</tr>
<tr>
<td>H</td>
<td>2.5</td>
<td>2.6</td>
<td>5.0 x 20.0 x 6.0</td>
</tr>
<tr>
<td>P</td>
<td>2.5</td>
<td>2.0</td>
<td>4.0 x 10.0 x 10.0</td>
</tr>
<tr>
<td>R</td>
<td>0.45</td>
<td>2.6</td>
<td>5.0 x 8.0 x 9.5</td>
</tr>
<tr>
<td>P</td>
<td>0.45</td>
<td>0.5</td>
<td>2.0 x 5.0 x 25.0</td>
</tr>
</tbody>
</table>
where $I_{ph}$ : photo-current of a photodiode, $A$ (Coul/sec)
$I_e$ : beam current, $A$ (Coul/sec)
$A_s$ : active area of CWO, cm$^2$
$\phi$ (E) : spectral fluence of x-ray, x-ray/cm$^2$
$E$ : energy of x-ray
$\mu$ (E) : linear absorption coefficient, cm$^{-1}$
t(E) : linear attenuation coefficient, cm$^{-1}$
$L$ : detector distance from x-ray source (cm)
$Y_L$ : light yield of a scintillator (lights/MeV)
$C_i$ : light collection efficiency of a scintillator
$S_i(\lambda)$ : scintillator light emission spectra
$E_i(\lambda)$ : energy of light from a scintillator
$R(\lambda)$ : spectral response of a photodiode (A/W)

DAS (Data Acquisition System) in x-ray imaging system consists of a dual switched integrator, a programmable gain instrumentation amplifier, a MUX(multiplexer), a filter and a 16 bit ADC(Analog-to-Digital Converter). Main noise source in this system is due to parallel noise of a diode and series voltage noise of integrator. Fig.2 is an approximate circuit for electronic noise analysis. The noise introduced in process of switch on/off was modeled as series noise with 1.5k$\Omega$ resistance [5-6].

![Fig.2. Electronic Noise Analysis Circuit. Main noise source in this system is due to parallel noise of a diode and series voltage noise of integrator.](image)

In Fig.2, spectral noise current density due to parallel noise source and spectral noise voltage density of series noise can be expressed as follows :

$$I_{i\nu} = 1.6e^{-19} \cdot A_s \cdot I_e \cdot \int \phi(E) \cdot E \cdot \mu_s(E) \cdot e^{-\mu(E) \cdot L} \cdot Y_L \cdot C_i \cdot S_i(\lambda) \cdot E_i(\lambda) \cdot R(\lambda) \cdot d\nu$$

where

$$I_{i\nu} \equiv I_{i\nu}(E) : spectral fluence of x-ray, x-ray/cm^2$$

Fig.1. Signal propagation in a photodiode-based solid state detector.
In equation (7), the optimal height and depth correspond to geometry-related values (y and z) to give the maximal SNR in given x-ray spectra and characteristic parameters of x-ray detector. As shown in equation (7), the first step for analysis of signal propagation in x-ray detector is to characterize x-ray spectrum that is employed in the inspection system. This study has used MCNPX Monte Carlo code [8] to characterize x-ray spectra generated by six electron beams (0.3, 0.45, 1.0, 2.5, 6.0 and 9 MeV). Important parameters used in calculation were based on actual design data of commercial x-ray tube and linear accelerator and given in Table 2 [9-11].

### Table 2: Values of parameters used in x-ray spectra calculation

<table>
<thead>
<tr>
<th>X-ray generation</th>
<th>Spectral fluence(photons/cm²-electron)</th>
<th>Spectral fluence(photons/cm²-electron)</th>
<th>LRM/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy(MeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.300</td>
<td>0.500</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>0.450</td>
<td>2.500</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>1.000</td>
<td>3.000</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>2.500</td>
<td>3.000</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>6.000</td>
<td>3.000</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>9.000</td>
<td>3.000</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Thickness of target material</td>
<td>2.0mm</td>
<td>2.5mm</td>
<td>3.0mm</td>
</tr>
<tr>
<td>Focal spot (mm)</td>
<td>2</td>
<td>3</td>
<td>5.0</td>
</tr>
<tr>
<td>Radius of target material</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>External filter</td>
<td>0.3x10^-2</td>
<td>0.5x10^-2</td>
<td>0.8x10^-2</td>
</tr>
<tr>
<td>External filter</td>
<td>0.3x10^-2</td>
<td>0.5x10^-2</td>
<td>0.8x10^-2</td>
</tr>
</tbody>
</table>

Fig.3. X-ray spectra predicted by MCNPX(0.3, 0.45, 1.0, 2.5, 6.0 and 9.0MeV). 0.3 MVp x-ray is one of ISO beam series, ISO300. Other x-rays are spectra used actually in industrial field.

The amount of the deposited energy in CWO by x-ray was obtained with MCNPX and DETECT97 [12] was used for analysis of light behavior in CWO. Another parameter in equation (7), spectral response (Ampere/ Watt), which is related to the characteristics of a photodiode, was obtained by measuring light sensitivity of the PIN photodiode fabricated in our previous study [13]. For 0.3 and 0.45 MeV electron beams, detector width (W) was fixed at 2.0mm, while in case of other energies their detector width at 5.0 mm. Fig.4 shows the optimal detector geometry depending on the incident electron energy (or x-ray energy). Also, the effects of electronic noise on the optimal depth of a detector were analyzed and figured in Fig.4 (b). Fig.4 (b) reveals that the optimal depth decreases as noise performance becomes worse. On the other hands, there is no difference in optimal height because the change in detector height doesn't have an influence on the change in noise characteristics of a detector system. Compared with detectors of commercial vendors given in Table 1, the detector size obtained under noise conditions of 10 nA/cm² leakage current and 800 pF/cm² junction capacitance (5 mm X 20 mm X 5 mm for 2.5 MeV, 5 mm X 50 mm X 8 mm for 9.0 MeV) is similar to that of H's company detector.
Fig. 4. Optimal detector height and depth as function of incident electron energy. The optimal detector size is also dependent on electronic noise.

IV. APPLICATION

According to the design method suggested in previous section, 256 16-channel detector arrays with height of 3.0 mm and depth of 10.0 cm were fabricated to cover real container height of 4.0 m. A detector block is 1.7 mm (W) x 10 mm (D) x 3.0 mm (H). The detector pitch in the array is 2.0 mm and the gap of 0.3 mm is filled with Ta doped TiO$_2$ to prevent scattered x-rays and light between neighboring crystals. The x-ray tube used in the system produces a 120 Hz x-ray with maximum and average energies of 450 keV and about 167 keV. The tube voltage rises from zero to a peak of 450 kV during each pulse. FWHM and an electric current of one pulse are 30 second and 0.7 A, respectively. To test the detection performance of the system, the container including a variety of objects a small car, and a motorcycle was inspected with system developed in this study. The container moved with 8 cm/sec during inspection. Fig. 5 is also an image of a customized 20-feet ISO with a small car and a motorcycle and shows that even the detailed engine components of the car and motorcycle could be distinguished from background image. In addition to Fig. 5, inspection test of a variety of objects such as a plastic bottle, an iron ring, a liquor and wires with some diameters placed in the container were conducted. From the test results, it turned out that our inspection system gave about 0.29 lp/mm (0.15 mm resolution) at MTF of 10 % and was able to distinguish the object which has 4% density difference from background objects.

Fig. 5. Cargo container inspection test. Prototype inspection system gives about 0.29 lp/mm (0.15 mm resolution) at MTF of 10 % and is able to distinguish the object which has 4% density difference from background objects.
V. CONCLUSION AND DISCUSSION

New generalized design model for high energy x-ray detector has been proposed in this paper. Cargo container inspection system employing the x-ray detector fabricated in accordance with the results of this paper has had ability capable of distinguishing the object of 0.15 mm size and 4% density difference from background material. It is likely that approach of this paper can be used as an useful methodology for designing high energy x-ray detector in use for cargo container nonintrusive inspection in customs service applications and nondestructive inspection in industrial applications.

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VII. REFERENCES