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Theoretical optical performance of phosphors for megavoltage X-ray imaging

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1. Introduction

In modern industrial settings, flexible films have been predominantly used for non-destructive testing of large structures like pipes using X-rays, particularly to accommodate curved surfaces. However, this method is time-consuming for imaging and development, and less efficient in high-energy environments. To address these issues, the use of flat-panel detectors (FPDs) is increasing, with ongoing development of flexible FPDs to mimic the flexibility of films [1].

Flexible FPDs primarily adopt indirect conversion detectors using phosphors and photosensors due to their structural flexibility. In this approach, the phosphor screen plays a crucial role as the first stage of X-ray interaction, determining the upper limit of detector performance. Therefore, developing a framework for optimal phosphor screen design is of utmost importance.

Monte Carlo methods are commonly used for simulating phosphor screen performance, typically modeling X-ray energy absorption efficiency within the phosphor. However, the final screen performance is determined by the behavior of light after X-ray conversion, making optical performance simulation essential.

This study conducts optical simulations for granular and columnar structures, which are representative phosphor configurations. Based on the results, screen performance is evaluated using light collection efficiency, line-spread function (LSF), and modulation transfer function (MTF). By fitting the obtained data, we aim to provide a method for easily predicting the optical performance of phosphors with various thicknesses and screen backing reflectivity.

2. Methods and Materials

2.1 Monte Carlo simulation

For the optical simulation of phosphor screens, we utilized the DETECT code [2]. This code allows for the configuration of various parameters that influence light photon behavior, including: screen geometry, refractive index of materials, reflection coefficient (RC) of surface, absorption and scattering distance (AD and SD) of light photon [3]. Additionally, DETECT enables the specification of points where X-rays interact to generate light. By adjusting these parameters, we can model light photon behavior in detail and predict phosphor screen performance under various conditions.

2.2 Evaluation

2.2.1 Light collection efficiency

Light collection efficiency (η) is defined as the ratio of photons reaching the detection plane, which mimics the photodiode array, to those generated, with only those photons that reach the photodiode array being converted into electrical signals for imaging. Thus, η serves as a measure of the phosphor screen efficiency. In this study, we derive light collection efficiency for two parameters: light generation depth (z) and RC of screen backing. We fit the results to a low-order polynomial as shown in equation (1). To obtain the overall light collection efficiency for a screen model, we perform a weighted sum of the depth-dependent data, considering the probability of X-ray interaction at various depths within the screen [4, 5].

$$\eta(\mathrm{z}) = c_0 + c_1 z + c_2 z^2 \quad (1)$$

2.2.2 MTF

The MTF quantitatively assesses the spatial resolution of imaging systems and is obtained by Fourier transformation of the LSF, as shown in equation (2). The LSF is derived by sampling the coordinates of photons reaching the detection plane after simulation. We aim to fit the obtained LSF using a linear combination of equations (3) and (4). Furthermore, we intend to combine depth-dependent LSF and MTF with X-ray interaction probabilities to determine the resolution for a single screen model [4, 5].

$$\mathrm{MTF}(u) = \left|\mathrm{FT}\left\{\frac{\mathrm{LSF}(x)}{\int \mathrm{LSF}(x)dx}\right\}\right| \quad (2)$$

$$\mathrm{LSF}(x;z) = e^{-|x|/\sigma_1} \quad (3)$$

$$\mathrm{LSF}(x;z) = \frac{1}{\sigma_2\sqrt{2\pi}} e^{-x^2/2\sigma_2} \quad (4)$$

3. Preliminary Results

Analysis of light collection efficiency (η) with respect to screen thickness and RC of screen backing, as shown in Fig. 1, revealed significant trends. Thicker screens exhibited decreased η, while higher reflectivity led to increase η Notably, the enhancement in η due to increased reflectivity was more pronounced in thinner

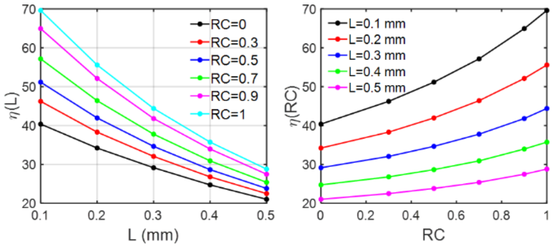

Fig. 1 Light collection efficiency as a function of thickness and reflectivity of reflectors in a screen model with a granular structure

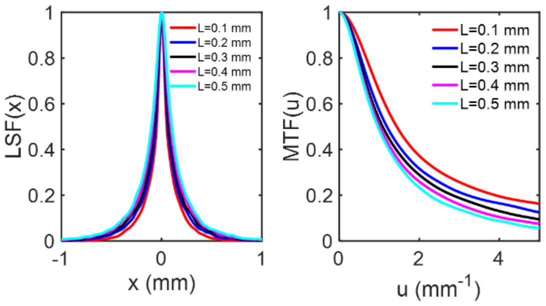

Fig. 2 LSF and MTF shown for screen thickness only when the reflector has zero reflectance on a screen with a granular structure

phosphor screens.

Fig. 2 illustrates our investigation of LSF and MTF across different screen thicknesses. Thicker screens produced more spread-out LSFs, consequently resulting in decreased MTF values. This observation indicates a greater spread of collected light in screens of increased thickness.

Further examination of LSF and MTF with respect to reflector reflectivity for various screen thicknesses, presented in Fig. 3, yielded interesting insights. Across all screen thicknesses, higher reflectivity consistently led to more spread in LSF and lower MTF values. However, it was observed that the rate of change in these parameters with respect to reflectivity diminished as screen thickness increased.

4. Conclusion

Based on our preliminary results, we observed that light collection efficiency is maximized for thinner screens with higher RC of screen backing. Conversely, light spread is minimized in thinner screens with lower RC. However, as screen thickness increases, the influence of reflectivity on both light collection efficiency and light spreading diminishes, indicating that reflector-induced performance variations become less significant for thicker screens.

Using the data obtained, we aim to perform graph fitting to propose mathematical performance models for both granular and columnar phosphor screens. Ultimately, we intend to determine the optimal thickness for granular and columnar screen models and design detectors that account for megavoltage interactions.

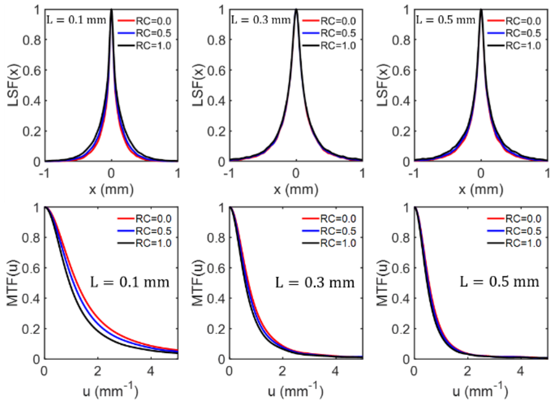

Fig. 3 LSF and MTF for reflector reflectance for each thickness on a screen with granular structure

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