Evaluation of high grid strip densities based on the moiré artifact analysis for quality assurance: Simulation and experiment


Department of Radiation Convergence Engineering, ITOMO Group, Yonsei University, Wonju 26493, Republic of Korea

ARTICLE INFO

Keywords:
Grid strip density
Nyquist sampling rate
Moiré artifact
Quality assurance

ABSTRACT

We have recently developed precise x-ray grids having strip densities in the range of 100 – 250 lines/inch by adopting the precision sawing process and carbon interspace material for the demands of specific x-ray imaging techniques. However, quality assurance in the grid manufacturing has not yet satisfactorily conducted because grid strips of a high strip density are often invisible through an x-ray nondestructive testing with a flat-panel detector of an ordinary pixel resolution (>100 µm). In this work, we propose a useful method to evaluate actual grid strip densities over the Nyquist sampling rate based on the moiré artifact analysis. We performed a systematic simulation and experiment with several sample grids and a detector having a 143-µm pixel resolution to verify the proposed quality assurance method. According to our results, the relative differences between the nominal and the evaluated grid strip densities were within 0.2% and 1.8% in the simulation and experiment, respectively, which demonstrates that the proposed method is viable with an ordinary detector having a moderate pixel resolution for quality assurance in grid manufacturing.

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1. Introduction

X-ray grids have widely been used in diagnostic X-ray imaging for reducing the amount of scattering radiation and thus improving image contrast. Common grids consist of an aluminum interspace and lead strips. However, aluminum as an interspace material is relatively inferior to organic materials for image contrast, keeping dose as low as possible, due to the considerable absorption of primary radiation penetrating the aluminum interspace [1]. In addition, the uniformity of lead strips is typically coarse due to the conventional fabrication process of grids, which may cause grid line artifacts, known as moiré. Moiré is easily observed as a wavy shadow of the lead strips in X-ray images and may be the most critical problem to be solved for the successful use of grids in digital X-ray imaging [2–4]. To overcome these difficulties, we have recently improved the manufacturing standard by adopting the precision sawing process and carbon interspace material, and produced precise grids having strip densities in the range of 100–250 lines/in for the demands of specific X-ray imaging techniques. However, quality assurance in the grid manufacturing has not yet satisfactorily conducted because grid strips of a high strip density are often invisible through an X-ray nondestructive testing with a flat-panel detector of an ordinary pixel resolution (>100 µm).

In this work, we propose a useful method to evaluate actual grid strip densities over the Nyquist sampling rate by positively using the moiré phenomenon for quality assurance in grid manufacturing. We performed a systematic simulation and experiment with several sample grids and a detector having a 143-µm pixel resolution to verify the proposed quality assurance method.

2. Material and methods

2.1. Analysis of the moiré artifact

Fig. 1 shows the threshold pixel resolution, \( a_{th} \), determined by the Nyquist criterion as a function of the grid strip density. The threshold is defined as the maximal detector pixel size required to discern given grid strips separately in the X-ray image:

\[
 a_{th} = \frac{1}{2 \mu_g} = \frac{P}{2},
\]

where \( \mu_g \) is the grid strip density, sometimes called grid frequency, and \( P \) is the grid period. For example, the threshold pixel resolution is calculated about 63.5 µm for \( \mu_g = 200 \) lines/in. The most important
A real system MTF, \( \mathcal{M}_T \), is the modulation transfer function (MTF), which is a useful index in the theoretical description of the spatial resolution of an X-ray image system. Here \( \mathcal{M}_T \) is the angle between the detector and the grid is associated with a moiré interference pattern in the grid image. Here \( \theta \) is the angle between the detector and the grid, and \( \phi \) and \( d_g \) are the angle and the period of the moiré artifact, respectively. In digital radiography, moiré artifact is typically caused in the use of a stationary grid with a digital X-ray detector due to the inadequate sampling of the grid shadows by the detector pixels.

Comprehensive theory for the formation of the moiré artifact is described in great detail by Gauntt et al. [5]. The moiré frequency (\( u_m \)) and angle (\( \phi \)) are theoretically given as follows [6,7]:

\[
\begin{align*}
&u_m = \sqrt{(u_g \cdot \sin \theta - m \cdot u_s)^2 + (u_g \cdot \cos \theta - n \cdot u_s)^2}, \\
&\phi = \tan^{-1}\left[\frac{u_g \cdot \cos \theta - n \cdot u_s}{u_g \cdot \sin \theta - m \cdot u_s}\right],
\end{align*}
\]

where \( u_g \) is the sampling frequency, and \( m \) and \( n \) are integers satisfying following conditions:

\[
\begin{align*}
&\frac{1}{2} \leq u_g \cdot \sin \theta - m \cdot u_s < \frac{1}{2}, \\
&\frac{1}{2} \leq u_g \cdot \cos \theta - n \cdot u_s < \frac{1}{2}.
\end{align*}
\]

From Eqs. (3) and (4), theoretical relationship between the moiré frequency and the grid frequency for \( \theta = 0^\circ \) is derived as follows:

\[
\begin{align*}
&u_g = \left\langle k/2 \right\rangle \cdot u_s + (-1)^k \cdot u_m, \\
&k \equiv \left[ u_g/u_s \right],
\end{align*}
\]

where the mathematical symbols \( \langle x \rangle \) and \( \lceil x \rceil \) mean rounding \( x \) toward positive infinity and negative infinity, respectively. Thus, actual grid strip density can be evaluated from the measured moiré frequency, \( u_m \), measured, as follows:

\[
\begin{align*}
&u_g = \left\langle k'/2 \right\rangle \cdot u_s + (-1)^{k'} \cdot u_m, \\
&k' \equiv \left[ u_g/\langle u_s \rangle \right],
\end{align*}
\]

where \( u_g \), measured and \( u_g, \) original are the evaluated and the original (or nominal) grid strip densities, respectively. Fig. 3 shows the theoretical relationship between the moiré frequency and the grid frequency for \( \theta = 0^\circ \). Note that, as indicated by a dotted line in Fig. 3, if \( u_s \) satisfies the Nyquist sampling theorem (i.e., \( u_s \geq 2u_g; k = 0 \)), the pattern in
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