Small-scale noise-like moiré pattern caused by detector sensitivity inhomogeneity in computed tomography

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Abstract: We report a new type of moiré pattern caused by inhomogeneous detector sensitivity in computed tomography. Defects in one or a few detector bins or miscalibrated detectors induce well-known ring artifacts. When detector sensitivity is not homogenous over all detector bins, these ring artifacts occur everywhere as distributed rings in reconstructed images and may cause a moiré pattern when combined with insufficient view sampling, which induces a noise-like pattern or a subtle texture in the reconstructed images. Complete correction of the inhomogeneity in detectors can remove the pattern and improve image quality. This paper describes several properties of moiré patterns caused by detector sensitivity inhomogeneity.

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1. Introduction

Computed tomography (CT) is one of the most important imaging techniques for examining the interior of objects noninvasively [1]. It is widely used in clinics to examine the interior of patient bodies and in industrial fields to examine the interiors of materials or products. For accurate examination of the interior of 3D objects, it is important to produce high-quality tomographic images from x-ray-based projection measurements in CT scanners. The quality of CT images depends on several factors, including primarily 1) scanner’s hardware specs, 2) scanning conditions, and 3) reconstruction algorithms. Even with state-of-the-art hardware specs, some limited scanning conditions, such as limited view projection (view undersampling), limited detector resolution (detector undersampling), or limited detector field-of-view (truncated projection), may degrade the overall quality of reconstructed tomographic images.

Typical degrading artifacts due to detector undersampling (undersampling within projection) are ray aliasing, in which artificial stripe patterns occur tangential to strong edges. Artifacts due to view undersampling (large angular interval between projections) are view aliasing, in which fine stripes appear to be radiating (at a certain distance) from the edge of a dense object or the center of an image [2]. When multiple aliasing artifacts are combined together, special two-dimensional artifactual patterns known as moiré patterns, similar to those in optics or digital displays, are often observed [3–7]. Because CT images are generally produced from limited projection data, which may cause the view aliasing or ray aliasing conditions, moiré patterns can be often observed in reconstructed tomographic images. There are several methods to reduce these aliasing artifacts, such as acquiring as large a number of projections as possible for view aliasing reduction and using quarter-detector shift or flying focal spot techniques for ray aliasing reduction [2]. In the reconstruction process, use of appropriate reconstruction kernels may reduce the aliasing artifacts at the expense of spatial resolution of reconstructed images [2, 8].

In this study, we examine another type of moiré pattern that is often mistaken as noise in reconstructed images. This noise-like moiré pattern is caused by inhomogeneous detector sensitivity combined with insufficient view sampling, especially in the outer areas rather than central areas of images. This type of moiré pattern should be properly addressed to produce high-quality tomographic images, especially for high-resolution micro-CT or high-resolution flat-panel detector-based CT scanners.
2. Concepts and phenomena

2.1. Artifacts due to inhomogeneous detector sensitivity

Perfect homogeneity of detector sensitivity is virtually impossible to manufacture. Detector elements cannot be equally cut in size and their surface roughness or photodiode response cannot be the same, resulting in different gains for each detector element. This problem can be more serious for more advanced photon-counting detectors [9]. There are several methods to reduce inhomogeneity in detector sensitivity, such as flat-field correction methods [10] or pre-scanning methods with a known object to estimate detector non-uniformity, but none can completely compensate for the non-uniformity. Therefore, most projection measurements involve a certain level of detector sensitivity inhomogeneity [11].

When one or several detector elements have defects or different gains compared to others, distinct ring patterns are formed during the reconstruction process, known as ring artifacts [12–15]. When almost all detector elements have different gains, which is the case for inhomogeneous detector sensitivity, ring patterns are formed everywhere as distributed rings in reconstructed images. Figure 1 shows an example of sinograms for a uniform disk phantom placed in the center of rotation of CT scanning geometry. The detector sensitivity was randomly perturbed to induce inhomogeneity in the detector elements in simulation studies. Figure 1(a) is the sinogram with homogeneous detector sensitivity and (b) is the sinogram with inhomogeneous detector sensitivity. Because inhomogeneity in detector sensitivity is very subtle in this example, the existence of inhomogeneous artifacts is barely noticeable in this projection data (sinogram); (c) and (d) are reconstructed images of (a) and (b), respectively. It is clearly observed that there are widespread ring patterns everywhere in the reconstructed image (d) due to inhomogeneity in detector sensitivity.

Fig. 1. Inhomogeneous detector sensitivity and resultant distributed ring artifacts. (a) and (c) are the sinogram and reconstructed image, respectively, for a uniform disk phantom when detector sensitivity is homogenous. (b) and (d) are the sinogram and reconstructed image, respectively, when detector sensitivity is inhomogeneous.
2.2 Properties of ring artifacts

Ring patterns are formed as concentric circles centered at the center of detector rotation. The ring with a radius \( r \) is caused by inhomogeneity in the detector element, which is at a distance \( r \) from the center of the detector. Because the inhomogeneity of a single element is spread along the circle of radius \( r \), strong rings are formed when \( r \) is small, whereas weak rings are formed when \( r \) is large. Figure 1(d) shows distributed multiple ring patterns throughout the reconstructed image. Strong rings are observed at and near the center of the image. Ring artifacts seem to be negligible in the peripheral area.

The severity of ring artifacts depends on the location of the reconstructed images and can be investigated by multiple simulation studies with different realizations of inhomogeneous detector sensitivities. A thousand realizations of a randomly perturbed detector sensitivity were simulated using a uniform disk phantom, as shown in Fig. 1, and the severity of the ring artifacts was calculated by summation of the absolute difference between the true uniform disk phantom and reconstructed images of each inhomogeneity realization. Figure 2 shows the severity of ring artifacts assessed from 1,000 realizations. The artifacts are strongest at the center of the image (\( r = 0 \)) and decrease as \( r \) increases toward the peripheral area of the image. When these ring artifacts are combined with other aliasing artifacts, such as view aliasing streaks due to view undersampling, interfering artifacts such as moiré patterns can be formed.

2.3 Moiré patterns

In general, moiré patterns are interference patterns produced by overlaying more than two different periodic patterns [16]. Several examples of moiré artifacts have been reported with respect to computed radiography images, where interfering moiré patterns are formed due to combination of improper use of grids during x-ray exposure to remove scattered x-rays and a digital display of the images on a computer monitor [17, 18]. Figure 3 shows examples of moiré patterns formed by the overlay of two sets of line patterns with different angles, and (b) the overlay of two sets of ring patterns [19].
In computed tomography, there are generally two types of aliasing artifacts: ray aliasing and view aliasing. Ray aliasing occurs when sampling within the projection is insufficient, and view aliasing occurs when the number of projections over scanning angles is insufficient [2, 20]. When these two different aliasing patterns are combined, another type of moiré pattern can be formed. In most cases, ray aliasing effects are well controlled either by using high-resolution techniques, such as quarter-detector shift or flying focal spot methods [2], or by using interpolation methods or appropriate reconstruction kernels while sacrificing spatial resolution of the reconstruction [8]. In contrast, view aliasing effects are sometimes not sufficiently controlled because of practical limitations, such as limited scanning duration or x-ray dose constraints, which can result in streak patterns in the reconstructed images. Figure 4 shows an example of streak patterns in a reconstructed image due to insufficient view sampling; (a) is the reconstructed image with sufficient view sampling (1800 view projections over 180°, 0.1° interval between adjacent views). Streak patterns are not observed. In contrast, when the number of projections is reduced to 90 (90 view projections over 180°, 2° interval between adjacent views), several streak patterns occur in the reconstructed image, as shown in (b). Streaks are negligible near the center of the image in this case, but can be easily observed around its peripheral area.
In most scanners, aliasing effects are adequately controlled to minimize the visibility of these artifacts by using the aforementioned reduction techniques. However, complete rejection of these artifacts is very difficult, and therefore, subtle aliasing effects remain even though they are not easily recognizable in reconstructed images.

Even if a single aliasing artifact is too weak to be observed in reconstructed images, when more than two different aliasing effects are combined, noticeable artifacts may be formed, which can appear as noise in images, degrading the overall quality of the reconstructed images.

In this paper, we examine a new finding that artifacts due to inhomogeneous detector sensitivity, as explained in Section 2.1, can cause a small-scale moiré pattern and result in noisy reconstructed images. Figure 5 shows a diagram that explains the interference condition which results in noise-like moiré patterns in reconstructed tomographic images. In the radial direction, the aforementioned distributed ring artifacts due to inhomogeneity in detector sensitivity occur, whereas aliasing effects due to insufficient number of views occur in the azimuthal direction. In the following sections, we describe simulation studies and real experiments used to examine the properties and patterns of these artifacts and noise.

2.4 Mathematical description of Moiré patterns

The interference phenomenon illustrated in Fig. 5 can be mathematically described as follows. Let’s consider a detector that has a fluctuating sensitivity profile in Eq. (1)

\[ g(s) = 1 + \alpha \cos(2\pi v s) \]

where \( g(s) \) is the sensitivity function, \( s \) is the coordinate in detector space, \( \alpha \) and \( v \) are the amplitude and the spatial frequency of sensitivity variation, respectively. Since we are interested in the interference phenomenon due to the sensitivity variation, we disregard the object dependency in our derivation, and then the parallel-beam projection becomes the same over all projection angles as in Eq. (2)

\[ p(s, \theta) = g(s) = 1 + \alpha \cos(2\pi v s) \]
The reconstructed image \( f(x,y) \) from \( p(s,\theta) \) can be obtained using the filtered-backprojection algorithm [1, 11] as follows:

\[
f(x,y) = \int_0^\pi q(x\cos\theta + y\sin\theta, \theta)d\theta
\]

where \( q(s,\theta) \) is the ramp-filtered projection [1] and it becomes \( q(s,\theta) = \beta \cos(2\pi \nu s) \) since \( p(s,\theta) \) has only a single frequency component.

\[
f(x,y) = \beta \int_0^\pi \cos(2\pi \nu (x\cos\theta + y\sin\theta))d\theta
\]

If the total number of projection views is \( N \), the angular sampling interval is \( \Delta \theta = \pi / N \), and

\[
f(x,y) = \gamma \sum_{i=0}^{N-1} \cos(2\pi \nu(x\cos(i\Delta\theta) + y\sin(i\Delta\theta))). 
\]

When \( N \) is sufficiently large, there will be no view-aliasing artifacts and there remain only the ring artifacts as shown in Fig. 6(a). However, when \( N \) is not sufficiently large, the view-aliasing occurs and the interference phenomenon happens as shown in Fig. 6(b) and magnified in Fig. 6(c). The maximum \( R \) for the aliasing-free region is given by Eq. (6) [11]

\[
N = \pi Rv_M,
\]

where \( v_M \) denotes the spatial resolution of the image [11].

![Fig. 6. Interference phenomena. (a) Only rings occur due to detector sensitivity variation when \( N \) is large. (b) rings and interference patterns occur when \( N \) is small. \( R \) denotes the radius for aliasing-free region (c) magnified image of the boxed area in (b) showing oscillating patterns in the azimuthal direction](image)

When the distance between the point \((x,y)\) and the center of the image is larger than \( R \), the interference artifacts become noticeable and they have oscillating patterns along the azimuthal direction. In order to verify the oscillating pattern along the azimuthal direction, we can evaluate the reconstructed values on two different points \((x_1,y_1)\) and \((x_2,y_2)\) that have the same radius, \( r \), from the center and different angles, \( \phi_1 \) and \( \phi_2 \). Then,

\[
f(x_1,y_1) = f(r \cos \phi_1, r \sin \phi_1)
\]

\[
= \gamma \sum_{i=0}^{N-1} \cos(2\pi \nu(r \cos \phi_1 \cos(i\Delta\theta) + r \sin \phi_1 \sin(i\Delta\theta)))
\]

\[
= \gamma \sum_{i=0}^{N-1} \cos(2\pi \nu r \cos \phi_1 - i\Delta\theta))
\]
Let $\Delta \phi = \phi_1 - \phi_2$, then

$$f(x_2, y_2) = \gamma \sum_{i=0}^{N-1} \cos(2\pi v (r \cos \phi_2 \cos(i\Delta \theta) + r \sin \phi_2 \sin(i\Delta \theta)))$$

$$= \gamma \sum_{i=0}^{N-1} \cos(2\pi vr \cos \phi_2 - i\Delta \theta))$$ (8)

If $\Delta \phi = \Delta \theta$, then

$$f(x_2, y_2) = \gamma \sum_{i=0}^{N-1} \cos(2\pi vr (r \cos(\phi_1 - \Delta \phi - i\Delta \theta)))$$ (9)

Therefore, it has been shown that $f(r \cos \phi, r \sin \phi)$ is periodic in the azimuthal direction with the angular period of $\Delta \phi = \Delta \theta$, which is the angular sampling interval. Now let’s consider points between $\phi_1$ and $\phi_2$ where $\Delta \phi < \Delta \theta$. To simplify the equations without loss of generality, $\gamma$ can be set to be 1, and $\phi_1$ can be set to zero and then $\phi_2 = -\Delta \phi$, where $0 < \Delta \phi < \Delta \theta$. Then, $f(x_2, y_2)$ becomes

$$f(x_2, y_2) = f(r \cos(-\Delta \phi), r \sin(-\Delta \phi)) = \sum_{i=0}^{N-1} \cos(2\pi vr \cos(i\Delta \theta + \Delta \phi))$$ (11)

Figure 7(a) shows four examples of the evaluation of Eq. (11) over $0 < \Delta \phi < \Delta \theta$, when $\Delta \theta = 1$, $v = 1$ and $r = 60,80,100,200$. All of them are periodic with $\Delta \phi = 1$, but have various patterns depending on different values of $r$. These oscillating patterns over ranges of $r$ can form 2-dimensional moiré patterns. Figures 7(b)-7(d) show 2-dimensional sets of the oscillating patterns over $0 < \Delta \phi < \Delta \theta$ and $0 < r < 100$ for three different combinations of $\Delta \theta$ and $v$. 
Fig. 7. Visualization of oscillating patterns in the azimuthal direction due to the interference between the detector sensitivity variation and the view-aliasing effect. (a) various oscillating patterns depending on $r$. (b)-(d) show 2-dimensional moiré patterns with different sets of $\Delta \theta$ and $v$.

In Figs. 7(b)-7(d), it can be observed that there is no variation over $\Delta \phi$ when $r$ is less than $R = 57.3$, 19.1, and 9.55, respectively, calculated by Eq. (6). However, when $r$ is larger than $R$, the view-aliasing starts to occur and various oscillating patterns are generated as $r$ increases. These oscillating patterns result in the interfering moiré patterns observed in Figs. 6(b) and 6(c). When the detector sensitivity contains random variation, a variety of moiré patterns can be formed based on this interfering mechanism. In the following sections, noise-like moiré patterns caused by the random sensitivity distribution are presented.
3. Simulation studies

3.1 Simulations

Simulations were designed to determine whether noise-like moiré patterns along ring artifacts are due to actual noise or due to other factors. First, an elliptic uniform phantom was designed as an object to be scanned and its projection data were calculated mathematically. The conditions of the simulation were similar to those of the CT system used for actual data acquisition. For convenience, we considered only the central slice in the cone-beam geometry, which corresponds to that of parallel-beam CT, instead of cone-beam CT. The number of detector bins was 2048, and 360 projection data points were acquired over 360° with a 1° interval. The elliptical phantom was placed in the lower part of the scanning field-of-view. Figure 8 shows (a) the projection data and sinogram of this phantom, (b) the reconstructed image from the projection data, and (c) a magnified image of the boxed area in (b). It can be observed that the original elliptical uniform phantom was well reconstructed without any artifacts.

Fig. 8. Simulated projection data and its reconstruction. (a) is the projection data and (b) is the reconstructed image. (c) is the magnified image of the region of interest indicated by a box in (b).

Next, subtle inhomogeneity in detector sensitivity was introduced in all detector elements. Random sensitivity gains were generated for each detector element with a Gaussian probability distribution, as shown in Fig. 9(a). The minimum sensitivity was 0.9965 and the maximum sensitivity was 1.003. This inhomogeneous sensitivity profile, as shown in Fig. 9(b), was applied to the detector elements or the sinogram in Fig. 8(a). The maximum deviation of the affected sinogram was 0.3% of the original values. Figure 10 shows the reconstructed images compared with the original image. Figure 10(a) is the reconstructed image with homogeneous detector sensitivity, showing uniform intensity inside the phantom, whereas Fig. 10(b) is the reconstructed image with inhomogeneous detector sensitivity (Fig. 9(b)), showing certain patterns or texture inside the phantom. The number of projection views is the same for both images. This distinct difference suggests that the subtle sensitivity inhomogeneity in the detector induced the artifactual texture in the image. If this artifactual texture is seen from a distance or if the image is downsampled, it can appear as noise. Figure 11 shows an example of the downsampled version of the image in Fig. 10(b). The image now looks as if it has lots of noise rather than an artifactual texture, as seen in the previous image.

On the other hand, when the elliptical phantom was placed at the center of rotation, the result could be quite different. Figure 12 shows the reconstructed image with the same phantom as in the previous example but placed at the center of rotation and with the same inhomogeneous sensitivity profile for the detector elements. The artifactual pattern in the reconstructed image due to inhomogeneous sensitivity is now only a ring artifact pattern, as previously shown in Fig. 1. In this case, the noise-like pattern is not observed.
Fig. 9. (a) Sensitivity distribution for all detector elements and (b) simulated sensitivity values for each detector element along the detector location.

Fig. 10. Reconstructed images with and without inhomogeneity in detector sensitivity. (a) is the reconstruction with homogeneous detector sensitivity showing uniform intensity inside the phantom. In contrast, (b) is the reconstruction with inhomogeneous detector sensitivity, which causes moiré patterns when combined with the aliasing effects due to an insufficient number of views. The number of projection views is the same for both images.

Fig. 11. Downsampled reconstructed image with noise-like moiré patterns.
3.2 Effect of the number of views on moiré pattern

Because noise-like texture occurred when the phantom was placed away from the center of rotation and this texture was not observed when the phantom was placed at the center, we hypothesized that the aliasing effect due to an insufficient number of views combined with sensitivity inhomogeneity in the detector produced a noise-like moiré pattern. To investigate this hypothesis, we first reconstructed the images from the limited number of projections. The phantom was the same elliptical phantom and placed at the center of rotation. Figure 13 shows the reconstructed images from the projection data set with a limited number of views; (a), (c), (e), and (g) were reconstructed from 4, 8, 18, and 36 views, respectively. When the number of views is small, the shape of the elliptical phantom is inaccurate and artifacts occur outside the phantom. However, the interior of the phantom is homogeneous for all numbers of views. In contrast, (b), (d), (f), and (h) are the reconstructed images with 4, 8, 18, and 36 views, respectively, but with inhomogeneous detector sensitivity. If the number of views is small, it can be seen that the lines due to difference in detector sensitivity constitute the lattice. When the number of views increases, it can be seen that the lattices are superposed many times and deform into a noise-like pattern.
In the case of parallel beam projection, the minimum number of angular samples required to prevent aliasing is given by Eq. (6). According to this equation, aliasing does not occur if the object is located near the center of rotation even when the number of views, $N$, is small. However, if the object is located away from the center, as $R$ increases, the minimum number of views to prevent aliasing also increases. However, there is a limit to increasing the number of views, and if the number of views remains the same, the aliasing artifact becomes stronger with increasing object distance from the center of rotation.

Therefore, when aliasing artifacts and the weak ring artifacts caused by difference in sensitivity of detector elements are present simultaneously, a noise-like pattern can be created, as shown in Figs. 10(b) and 11. As suggested in the diagram in Fig. 5, the ring...
artifacts in the radial direction and the aliasing artifacts in the azimuthal direction overlap each other like a lattice to form a noise-like pattern, which has considerable similarity to the moiré pattern. The moiré pattern is an interference pattern created when two or more periodic patterns overlap, as explained previously. This interference process occurs during CT reconstruction where inhomogeneous sensitivity-affected data projected at different angles are added to each other when backprojection is performed. For verification of this interference process, sensitivity difference extracted from actual CT data (Fig. 14(a)) was backprojected into the image space, as shown in (b), and the moiré pattern was created through backprojections over many angles, as shown in (d). The generated moiré pattern (d) was very similar to the artifactual patterns that appear as noise in the actual CT images in (c). We confirmed that the ring artifacts were widely distributed and the artifactual small lattices overlapped along each ring artifact. Hence, the subtle difference in sensitivity of the detector eventually created weak ring artifacts, and when they occurred throughout the entire image (as distributed rings because inhomogeneous sensitivity is distributed randomly over all detector elements, as shown in Fig. 1), it was confirmed that a noise-like moiré pattern emerged when combined with the aliasing effect due to insufficient view sampling.

To investigate the effect of the number of views on the cause of the noise-like moiré patterns, we increased the number of views up to 3600. Figure 15 compares the reconstructed images with 360 views and those with 3600 views. Figure 15(a) shows the noise-like moiré patterns due to both the distributed ring artifacts and the aliasing effect caused by an insufficient number of views. In contrast, when the number of views increased up to 3600 views, the noise-like moiré patterns were not formed, and only distributed subtle rings remained, as shown in (b).

Fig. 14. Moiré patterns generated by actual sensitivity variation. (a) sensitivity values for all detector bins, (b) line images of detector sensitivity (a single backprojection), (c) actual CT reconstruction image, and (d) moiré patterns generated by backprojections of (b) over many angles.
3.3 Effect of ring artifact reductions on moiré pattern

There are several methods to reduce ring artifacts in reconstructed images. We investigated how these correction methods can reduce noise-like moiré patterns. The conventional moving average-based method (MA) \[13\] and recently introduced line-ratio method \[15\] were used as ring artifact-correction methods in this study. The MA method uses a mean curve that is the averaged profile of all projection data. If a certain detector element has a different sensitivity than that of neighboring detector elements, the mean curve may have a distinct peak or trough at that corresponding element, and this peak or trough can be reduced by a moving average filter. This method is effective in reducing one or several distinct ring artifacts, but not very effective in reducing distributed ring artifacts or when peaks in the mean curve are obscured by structural variation in objects. In contrast, the line-ratio method tries to estimate sensitivity difference between every adjacent detector element and find the correction factors for all detector elements considering statistical aspects of sensitivity difference from each projection data. Therefore, this method can be effective in reducing distributed ring artifacts due to inhomogeneous sensitivity of all detector elements.

Figure 16 shows (a) the numerical phantom image with ring artifacts, (b) the magnified view of the area indicated by a white box in (a), (c) reconstructed image with MA method, and (d) with line-ratio method. Strong noise-like moiré patterns were successfully reduced by the MA method. However, two distinct ring artifacts are observed in the bottom of (c). Several weak oscillating patterns are also observed throughout the image. In contrast, the line-ratio method reduced the distributed rings very effectively without any significant side artifacts, and the resultant image did not contain the noise-like moiré patterns. The subtle aliasing effects were not observable either. For quantitative comparison, root-mean-square-error (RMSE) and variance on two regions-of-interest (ROI) indicated by black boxes in (a) were calculated. Table 1 suggests that the line-ratio method outperforms the MA method. Both the MA and line-ratio methods significantly reduced RMSE and variance, which is consistent with visual evaluation on (c) and (d).

| Region of Interest | Ring (Fig. 16(b)) | MA (Fig. 16(c)) | Line-ratio (Fig. 16(d)) |
|-------------------|------------------|----------------|------------------------|
| RMSE              | ROI1             | 2.18E-03       | 0.59E-03               | 0.32E-03               |
|                   | ROI2             | 2.32E-03       | 0.67E-03               | 0.34E-03               |
| Variance          | ROI1             | 4.78E-06       | 3.49E-07               | 1.03E-07               |
|                   | ROI2             | 5.41E-06       | 4.55E-07               | 1.17E-07               |

Fig. 15. The effect of the number of views on moiré patterns. Left: The number of views is 360. Right: the number of views is 3600.
4. Experimental Results

4.1 Data Acquisition

Three sets of raw projection data were obtained on an industrial CT system. One set of data was obtained from a polymethyl methacrylate object, and the other set was obtained from an aluminum object. The first data set was acquired using a 2048 × 2048 flat panel detector. The detector element was 0.198 mm in width. The number of views was 400 over a range of 360°. The second data set was acquired using a 1200 × 1200 flat panel detector. The detector element was 0.085 mm in width. The number of views was 200. The third data set was acquired using a 1024 × 1024 flat panel detector with the element width of 0.2 mm. The number of views was 200.
Figure 17(a) shows the reconstructed image without ring artifact correction (a magnified version of the upper part of the full field of view focusing on the noise-like moiré pattern). This area should be uniformly flat, but there are noise-like dark and bright dots along subtle rings, as indicated by arrows. These noise-like features are not seen in the reconstructed image with line-ratio ring artifact correction in (b). The subtle weak rings are well removed, and hence, the noise-like moiré pattern is not formed. Overall, the image (b) looks much less noisy than the image (a).

Figure 18 shows the distinct differences in noise-like moiré pattern between the reconstructed images with and without line-ratio ring artifact correction. The image (a) appears to contain a large amount of noise. Dark and bright dots are observed along the distributed subtle weak rings and these are believed to be formed by inhomogeneous sensitivity of the detector elements combined with the weak aliasing effects, which are not clearly observed in the image. In contrast, the image (b), which is reconstructed using the line-ratio ring artifact reduction method shows much less noise. The subtle weak rings are completely removed and the noise-like dark and bright dots completely disappear. No weak aliasing effects are observed. Because the widespread noise-like patterns are removed, the underlying structure of the object becomes clear. In particular, the thin stripes indicated by arrows are now clearly noticeable.
Figure 19 shows the distinct interfering moiré patterns. The image (a) appears to contain a large amount of noise and strong rings. Three distinct rings are indicated by white arrows. Other rings appear to be subtle. However, various oscillating patterns in the azimuthal direction are clearly observed as indicated by three white ellipses. Interestingly, these oscillating patterns are not seen in the image (b) that was reconstructed with ring artifact correction. This comparison suggests that the oscillating patterns in (a) are caused by the detector sensitivity variation interfering with the view-aliasing effect as mathematically described in Section 2.4. The angular period of the oscillating patterns has been calculated based on the locations of two points indicated by black arrows, being 1.83 degree, which is almost the same as the sampling interval of this data set, 360/200 = 1.8 degree. Another example of interfering moiré patterns is shown in Fig. 20.

![Image](image.png)

Fig. 20. Examples of interfering moiré patterns observed in actual CT reconstructed images. (a) Original reconstructed image without ring artifact correction. (b) Reconstructed image with ring artifact correction. Noise-like moiré patterns are not observable and the thin stripe indicated by an arrow is clearly noticeable in (b).

5. Discussion and conclusions

In this study, we examined noise-like moiré patterns caused by inhomogeneous detector sensitivity combined with aliasing effects due to an insufficient number of views. It has been known that defects in one or a few detector elements can cause artifactual rings in reconstructed images. However, there has been no study on more widely distributed ring artifacts due to inhomogeneous detector sensitivity in all detector elements and their interfering effect with different types of aliasing artifacts. This study demonstrates that inhomogeneous detector sensitivity can cause widespread distributed rings in reconstructed images, and when combined with subtle aliasing effects due to an insufficient number of views, small-scale noise-like moiré patterns are formed and appear as noise in the image. Interestingly, even though the aliasing effect is not very noticeable in the reconstructed image when a fairly large number of views is obtained (the aliasing artifacts are very subtle), it can still cause noise-like artifacts if it is combined with distributed weak ring artifacts due to inhomogeneous detector sensitivity.

In the current state-of-the-art CT systems, appropriate techniques to address issues related to the number of views and detector sensitivity have been incorporated into the whole system, including the hardware and reconstruction methods. However, complete rejection of the aliasing artifacts or ring artifacts is very difficult, and subtle aliasing or ring artifacts often remain even though they are not easily recognizable. Smoothing kernels during reconstruction or post-processing are often applied to reduce these artifacts so that they are unnoticeable but this comes at the cost of spatial resolution of the reconstructed images. However, with high-resolution CT systems, such as micro-CT with flat-panel detectors, it becomes more difficult
to reject these types of artifacts, especially when it is intended to keep the original resolution without applying smoothing kernels.

Our study results suggest that even if aliasing effects appear to be sufficiently well controlled so as to be unnoticeable or ring artifacts are effectively reduced, these efforts may not be enough to produce good quality images. A combination of both types of artifacts, even though they are very subtle individually, can cause interference artifacts that we refer to as noise-like moiré patterns that degrade image quality and render the images noisier than they should be.

In Section 2.4, the mathematical description of the cause and phenomena of the interfering patterns has been provided. The amplitude of the interfering patterns can be much higher than that of the ring artifacts as shown in Fig. 6(c) and Figs. 7(b)-7(d), which may explain why noticeable moiré patterns can be formed by the combination of two subtle ring and aliasing artifacts.

Further development of artifact-correction methods should be performed to remove even these interfering noise-like moiré artifacts. Conventional ring artifact-reduction techniques, such as the MA method, are effective in reducing a single or a few distinct ring artifacts but not very effective for distributed ring artifacts because subtle low-frequency band-type ring patterns remain, which, in turn, caused another type of moiré pattern when combined with subtle aliasing effects due to the insufficient number of views. Two bright and dark ring artifacts observed in the bottom of Fig. 16(c) were caused because the MA method removed peaks in the mean curve to compensate for ring artifacts, but some of those peaks were induced due to the shape of the object, not due to the detector sensitivity. When the object-induced peaks are removed in the MA method, artefactual rings can occur [13, 15]. In contrast, the line-ratio method does not depend on the mean curve and thus, is less affected by the object than the MA method [15]. However, the line-ratio method would fail when circular objects are placed near the center of rotation of the scanner. Otherwise, the line-ratio based ring artifact correction method is very effective in reducing distributed rings caused by inhomogeneous detector sensitivity, and therefore, noise-like moiré patterns are not formed in the reconstructed images as demonstrated in the simulation and experimental studies.

In recent years, textural analysis of computed tomography has received increased interest [21–25], and machine-learning techniques to recognize patterns of textures of tissues or objects in an image have emphasized the importance of fine detail and subtle textures of the image [26, 27]. However, this subtle textural information can be obscured or distorted by aliasing or ring artifacts and further by noise-like interfering moiré patterns shown in our study. Therefore, proper remedies for individual artifacts and for interfering artifacts caused by a combination of more than two underlying different artefactual patterns should be carefully and extensively developed. This aspect will become more important in the future when higher-resolution flat-panel detectors are used in CT systems, where subtle textural information should remain intact during the reconstruction process, which precludes using smoothing kernels to reduce noise or the aforementioned artifacts.

**Limitation of the mathematical analysis on moiré patterns**

The mathematical description on moiré patterns in Section 2.4 does not consider the object dependency, which may induce additional characteristics on the final formation of moiré patterns.

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