X-ray dark-field imaging with a single absorption grating

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Abstract
X-ray dark-field imaging is usually performed with a Talbot–Lau interferometer, but the quality of its analyser grating is limited by the fabrication process. This makes it difficult to achieve a large area and high aspect ratio. In this study, the analyser grating is abandoned and dark-field imaging is realized using only one absorption grating. The optimal grating position is derived theoretically in the single absorption grating x-ray dark-field imaging, and the conclusion is partially verified by the experiment. Meanwhile, the optimal object position for dark-field imaging has also been obtained from both the theory and experiment. In the process of comparing x-ray dark-field imaging with x-ray refraction imaging, it is found that both of them can be explained by geometric optics, showing the intrinsic relationship between them.

Keywords: x-ray imaging, dark-field imaging, phase contrast

(Some figures may appear in colour only in the online journal)
as x-ray energy increases, which was not good for the use of hard x-rays. Therefore, a single absorption grating incoherent x-ray dark-field imaging method is proposed in this study. This could not only prevent limitation of x-ray energy on the length of system, but also would simplify the system structure.

2. Theory and methods

In this section, we will derive the optimal position of the grating in a single absorption grating incoherent x-ray dark-field imaging system shown in figure 1(a). The system consists of a tungsten-anode x-ray source G (HAMAMATSU L9421-02) with a focus spot size of 5 µm, an absorption grating G1 with period of 42 µm and a flat panel detector D (Dexela 1207CL) with 864 × 1536 pixels of 74.8 × 74.8 µm². The distance from the source G to grating G1 was z1, and the distance from the grating G1 to detector D was z2. Projection of G1 will be represented by G2 with a period of p2 in the following discussion.

The intensity of each pixel on the detector will oscillate as G1 moves perpendicular to the beam propagation direction over one grating period. The intensity oscillation is named the phase stepping curve, which is a function of the relative position xg between the grating G1 and detector (figure 1(b)). The blue curve represents the phase stepping curve without an object, and the red curve represents the phase stepping curve with an object. The mathematical expression of the phase stepping curve can be written as

\[ I(x_g) = a_0 + a_1 \cos \left( \frac{2\pi}{p_2} x_g + \varphi \right) \] (1)

where \(a_0\), \(a_1\) and \(\varphi\) are the average intensity, amplitude and initial phase of the phase stepping curve, respectively. A beam of x-rays will be refracted with a refraction angle \(\alpha\) after passing through an object. The beam separation between the incident beam and refracted beam is \(l\) on the detector plane (figure 1(a)), and then the phase stepping curve with an object will produce a phase shift \(\Delta \varphi\) with the phase stepping curve without an object (figure 1(b)).

Since the refraction angle of x-rays is usually in the order of micro radians, by the small angle approximation, we can obtain

\[ l = z_2 \alpha. \] (2)

When beam separation \(l\) between the incident beam and refracted beam equals \(p_2\), the phase shift of the phase stepping curve is \(2\pi\) according to equation (3)

\[ \frac{\Delta \varphi}{l} = \frac{2\pi}{p_2}. \] (3)

Meanwhile, the geometric relations in figure 1(a) can be expressed by

\[ \frac{p_2}{p_1} = \frac{z_1 + z_2}{z_1} \] (4)

\[ L = z_1 + z_2 \] (5)

where \(L\) is the total length of the system.

In the case of the same refraction angle \(\alpha\) caused by an object, larger phase shift \(\Delta \varphi\) will lead to easy detection of the refraction angle \(\alpha\). Therefore, the system sensitivity can be defined as [22]

\[ S = \frac{\Delta \varphi \alpha}{L}. \] (6)

Substitution of equations (2)–(5) into (6) will yield

\[ S = \frac{z_2 (L - z_2)}{L p_1}. \] (7)

When the system length \(L\) and period of the absorption grating \(p_1\) are constant, the system sensitivity will reach its maximum at \(z_2 = L/2\) with value of

\[ S_{\text{max}} = \frac{L}{4p_1}. \] (8)

It can be seen from equation (8) that increased system length \(L\) and reduced period of grating \(p_1\) will increase the system sensitivity. However, the intensity on the detector plane will reduce when the system length increases. The decrease in period \(p_1\) will reduce the height of the absorption materials in
absorption grating, thus the absorption of x-rays by grating will decrease and it will degrade the quality of images.

In addition to refraction, a certain degree of scattering occurs when a beam of x-rays passes through an inhomogeneous object (figure 2(a)). A beam of x-rays will be split into several secondary beams after passing through an object, and each secondary beam will be refracted many times in the object due to inhomogeneity. Thus, each secondary beam will have different diffusion paths, resulting in a certain degree of divergence in emergent light. The intensity of the scattering signal can be represented by standard deviation $\sigma$ of angular distribution in emergent light. More inhomogeneous objects will result in greater probability of refraction and stronger scattering of x-rays.

Therefore, we assume that $\sigma$ and refraction angle $\alpha$ are positively correlated:

$$\sigma \propto \alpha. \quad (9)$$

For the single absorption grating incoherent imaging system, since the refraction signal reaches its maximum for absorption grating in middle of the system, the scattering signal will also reach its maximum at that position. However, the standard deviation $\sigma$ is not easily measured directly. We use the visibility of phase stepping curve to characterize the standard deviation $\sigma$. The visibility of the phase stepping curve is defined as

$$V = \frac{a_s}{a_0}. \quad (10)$$

To eliminate the adverse effects of uneven absorption grating on visibility, the visibility should be normalized by

$$V_n = \frac{V^r}{V^r} \quad (11)$$

where $V^r$ represents visibility with an object, and $V^r$ represents visibility without an object.

When a beam of x-rays is incident on a homogeneous object, it also will be split into several secondary beams (figure 2(b)). These secondary beams will travel in a straight line without being refracted inside the object due to the internal homogeneity of the object, and the emergent light will still be a beam of parallel light. In general, both refraction and scattering will occur simultaneously after x-rays are incident on an object. However, the intensity of the refraction and scattering signal differ from one object to another. For homogeneous objects, the refraction signals are more dominant and characterized by the refraction angle $\alpha$. By comparison, the scattering signals for inhomogeneous objects are more dominant and characterized by relative visibility $V_n$. The relationship between the scattering signal and relative visibility $V_n$ is: the larger the scattering signal, the smaller the relative visibility $V_n$.

3. Results and discussion

The aforementioned theory was validated by experiments using the experimental setup shown in figure 1(a). The voltage used in the experiment was 40kV and the current was 80 µA. The total length of the setup was set to 80 cm, and an amoxicillin capsule was used as the sample. Phase stepping was performed with $G_1$ grating in ten steps over one period of $G_1$ and each image was recorded with 4s exposure time. For each step, an image with the object in a beam and another image without the object in a beam were recorded. Three images were taken at each step in order to reduce the noise. The results are shown in figure 3.

In figure 3(a), the curve with the same color represents variations in the relative visibility of the object with distance from the object to detector. The curves with various colors represent different positions of grating $G_1$. The blue curve corresponds to grating $G_1$ placed 57.5 cm away from the detector, and period of $G_2$ is twice the size of detector pixel. The red curve corresponds to grating $G_1$ placed 65.1 cm away from the detector, and the period of $G_2$ is three times the size of detector pixel. The yellow curve corresponds to grating $G_1$ placed 68.8 cm away from the detector, and period of $G_2$ is four times the size of the detector pixel. The purple curve corresponds to grating $G_1$ placed 71.0 cm away from the detector, and the period of $G_2$ is five times the size of the detector pixel. The black boxes in figures 3(c) and (e) represent signals average areas with $50 \times 30$ pixels. From figure 3, we can see that the scattering signal in figure 3(e) is stronger than that in figure 3(c), and the noise in figure 3(e) is lower than that in figure 3(c). However, no obvious differences between the corresponding absorption images are observed. In figure 3(a), the lowest positions in blue, red and yellow curves are 53 cm, 60.5 cm and 64.5 cm from the detector, respectively. They are the closest object positions to the absorption grating in the experiment. At these positions, the absorption grating is gradually moved away from the middle of the system, and the relative visibility increases, which indicates the decrease of the scattering signals. When the grating is in the middle of system, i.e. 40 cm away from the detector, the period of $G_2$ is 1.12 times the size of detector pixel. The Moiré fringes will appear and low visibility of phase stepping curve will also cause great noise in images. Therefore, no data are shown at this position.

In summary, the above theoretical results are partially verified by experiments, that is, closer absorption grating to middle of the system will yield a stronger scattering signal, when the relative positions of the object and absorption grating are fixed. Meanwhile, figure 3 has shown that scattering signals can be successfully measured in a single absorption grating incoherent imaging system.

The system can not only reduce cost, but also improve the field of view because it does not need an analyser grating. Note that differences exist between the proposed single absorption grating imaging system and those reported by
In our proposed imaging system, a period of fringe on the detector plane can be resolved by only two pixels of detector [24], where conventionally at least five detector pixels are required to resolve the period of fringe. The difference in the scattering signal intensity between both methods has been shown in the yellow and purple curves of figure 3(a). The method used here greatly increases the scattering signal intensity compared to the conventional method.

It can also be seen from figure 3(a) that the intensity of the scattering signal is not only related to the position of the absorption grating, but also to the position of the object. In the blue, red and yellow curves, the scattering signals first increase linearly as the distance from the object to the detector increases. Then, near the position of absorption grating, the scattering signals decrease linearly as the distance from the object to the detector increases. A similar phenomenon was reported by Donath et al. [22] in 2009. They found that closer objects to phase grating resulted in a greater phase shift and higher system sensitivity. Donath successfully established a theoretical expression of system sensitivity as a function of position of the object using the refraction of x-rays, namely

\[ S = \left( \frac{1}{z_1} + \frac{1}{z_2} \right)^{-1} \frac{1}{p_1} f(r). \]  

(12)

With the function,

\[ f(r) = \begin{cases} 
 1 + \frac{r}{z_1}, & -z_1 \leq r \leq 0 \\
 1 - \frac{r}{z_2}, & 0 \leq r \leq z_2
\end{cases} \]  

(13)

where \( r \) refers to position of the object relative to phase grating. Note that \( r \) is negative when the object is between the source and phase grating and positive when the object is between the phase grating and detector.

Donath verified equation (12) by linear fitting of experimental data. Using the analytic method similar to Donath’s, we analyzed the variation of refraction signals with position of the object in the single absorption grating imaging system, and obtained equations (12) and (13) as well. As pointed out above, scattering can be regarded as multiple refractions of x-rays. Therefore, for inhomogeneous objects, stronger refraction will induce stronger scattering signals. Equation (12) suggests that closer objects to absorption grating will result
in higher system sensitivity and stronger scattering signals. For objects at both ends of the source and detector plane, the system sensitivity and scattering signals will be zero.

To clearly show the variation in scattering signals with position of the object, the absorption grating was placed at a distance of 57.5 cm from the detector. This time, the period of $G_2$ was twice the size of the detector pixel. The object was then placed at 12 different positions on both sides of the grating. The relative visibility was finally fitted linearly, and results were shown in figure 3(b). The linear fitting equations of both the left and right lines were determined as follows:

$$V_1 = -0.0057 \times x + 1.0038 \quad (14)$$
$$V_2 = 0.0125 \times x - 0.0085. \quad (15)$$

The correlation coefficients of the left and right lines are $r_1 = -0.9978$ and $r_2 = 0.9971$, respectively. The intersection of the two lines is $x = 55.62$, $V_n = 0.6868$, where the $x$-coordinate represents the position with the greatest relative visibility. The position of absorption grating is 57.5 cm, and relative error of two positions is only 3.3%. At the position of the source and detector, the scattering signal should be zero and relative visibility should be one. On the detector plane, $V_1 = 1.0038$ can be obtained by substituting equation (14) by $x = 0$, yielding relative error of 0.38%. On the source plane, $V_2 = 0.9915$ can be obtained by substituting equation (15) by $x = 80$, yielding relative error of 0.85%. The main source of the error is the inaccurate position of the object. For the different slopes in equations (14) and (15), the general expressions of equations (14) and (15) should be considered. After derivation, we can get:

$$V_1(x) = \frac{a - 1}{z_2} (x - z_2) + a, \quad 0 \leq x \leq z_2 \quad (16)$$
$$V_2(x) = \frac{1}{z_1} (x - z_2) + a, \quad z_2 \leq x \leq L \quad (17)$$

where $a$ represents the minimum relative visibility we can obtain in the system. $a$ depends on the period of the grating and the nature of the object. From equations (16) and (17), we can see that the slopes depend mainly on the position of the grating $z_2$, the period of the grating and the nature of the object. So far, the experimental results confirm the above theoretical analysis. At the grating position, the scattering signal is the strongest; at both ends of the source and detector planes, the scattering signal is the weakest. Scattering results from multiple refractions of x-rays.

Another experiment showed that scattering resulted from multiple refractions of x-rays, where both the scattering and refraction signal were inversely proportional to voltage. The employed experimental setup was the same as the previous one. The total length of the system was set to 80 cm with the sample and grating placed 53 cm and 57.5 cm away from the detector. The current was fixed to 100 $\mu$A and voltage ranged from 25 kV to 55 kV with an interval of 3 kV. The ten-step phase stepping was used to take 3 images at each step, and the exposure time of each image was 4 s. In figure 4(a), the relative visibility $V_n$ of the amoxicillin capsule increases with the increase of voltage, and scattering signal decreases accordingly. When the scattering signal reaches the maximum at 25 kV, the noise is also maximum. The error bar indicates the corresponding standard deviation. Since scattering of x-rays has a certain degree of symmetry, the refraction signal measured by the phase stepping method is not necessarily strong when the scattering signal is strong in the object.

Therefore, a homogeneous sample is utilized to measure the refraction signal. The homogeneous sample used in figure 4(b) is a PMMA rod with a diameter of 5 mm and the $y$-coordinate represents the peak-to-peak value of the cross-section of the refraction image. The peak-to-peak value of the cross-section of refraction image decreases as voltage increases, indicating that the refraction angle is inversely proportional to voltage.

4. Conclusions

In this paper, a single absorption grating incoherent imaging system is used to achieve x-ray dark-field imaging. The optimal positions of the grating and sample are obtained by theoretical analysis and experimental verification. By comparing the similarity between the scattering and refraction, we conclude that the scattering is caused by multiple refractions of x-ray in x-ray dark-field imaging. One advantage of
the proposed single absorption grating incoherent imaging system is that it consists of a large period of absorption grating that can be utilized, thus reducing the fabrication difficulties of absorption grating. On the other hand, there is no need for use of analyser grating, which makes it easier to improve the field of view. However, our proposed system is only a principle-validated system, in which the flux of micro-focal spot source is too small. This problem can be solved by combining a source grating with a large focal spot source or use of a structural source.

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