Evaluation of disturbing effect of mesh holes in wide-acceptance-angle electrostatic mesh lenses

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A B S T R A C T
A curved mesh electrode introduced into an electrostatic lens enables spherical aberration correction over a wide acceptance angle. This technique has great advantages in X-ray photoelectron spectroscopy and related techniques, allowing considerable increase in photoelectron intensity and efficient measurement of photoelectron angular distribution. However, the use of meshes severely limits spatial resolution, as the image produced through each mesh hole is blurred by the lens action of the hole. This feature is studied in detail in this paper, in order to determine the best possible resolution that can be attained in electrostatic mesh lenses with wide acceptance angles. A simple way to evaluate the mesh-hole effect is to use the Davisson–Calbick formula, which expresses the focal length of a single-aperture lens. To make this approach more feasible, we take into account the influence of the angle of incidence to a mesh hole. We characterize the image blur due to each mesh hole in two orthogonal directions, considering the discrepancy in focal length in tangential and sagittal planes. After the demonstration of the validity of our approach in a simple example, the mesh-hole effect of a wide-acceptance-angle electrostatic mesh lens is evaluated.

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1. Introduction
Electron-transparent foils or meshes can be used for spherical aberration correction in electron lenses, as first suggested by Scherzer [1]. The simple way is to use flat foils, which was studied in detail by several authors [2–6]. While it can correct third-order spherical aberration, it cannot correct higher-order ones simultaneously. Thus, its applications were limited to systems with small acceptance angles like transmission electron microscopes [7], in which fifth- and higher-order spherical aberrations are negligibly small. To increase acceptance angles, possibilities of the use of curved meshes have been explored [8–14]. Kato and Sekine showed that a spherical mesh can be used to correct spherical aberration for electrostatic lenses with acceptance angles up to ±30◦ [10]. Furthermore, it was shown by Matsuda et al. that the use of an ellipsoidal mesh enables us to correct spherical aberration over a wide acceptance angle up to around ±60◦ [12–15]. Following this method, a wide-acceptance-angle electrostatic lens has been developed [16–19]. This lens can serve not only as an objective lens for electron energy analyzers, but also in itself, as an energy analyzer like a cylindrical mirror analyzer.

Wide angular acceptance is a key feature of advanced photoelectron spectroscopy systems, because it allows considerable increase in photoelectron intensity and efficient measurement of photoelectron angular distribution. The wide-acceptance-angle electrostatic lens has a great advantage in this regard, and further, it allows two-dimensional (2D) angular distribution analysis like a display-type spherical mirror analyzer (DIANA) [20–22]. The lens, used as an objective lens of a certain photoelectron spectroscopy system, enables us to advance the 2D angle-resolved photoelectron spectroscopy (see, e.g., [23–27]) developed by DIANA. While DIANA can measure 1sr sr (±60◦) 2D angular distribution at a time, information of 2D angular distribution may be mixed for non-uniform sample because the obtained data are averaged over an irradiation spot size. In the case of the use of the wide-acceptance-angle electrostatic lens, it is possible to perform projection imaging and then to select small sample areas using a field-limiting aperture. In this way we can introduce the selected-small-area analysis to the 2D angle-resolved photoelectron spectroscopy. However, such applications of the wide-acceptance-angle electrostatic lens have the disadvantage that spatial resolution is severely limited by the disturbing...
effect of mesh holes. Thus, for such applications, careful evaluation of the mesh-hole effect is required in order to determine the best possible spatial resolution.

In this paper, we describe a practical way to evaluate the mesh-hole effect in the wide-angle regime. Our approach follows the approach of Kato and Sekine [11]. They showed that the Davisson–Calbick formula [28,29], which gives the focal length of a single-aperture lens, can be applied for spherical mesh lenses [10] and then be used to evaluate the image blur due to the mesh-hole effect. Although their blur expression was appropriate for the considered geometrical situation, it should be modified for more general situations including the case of the wide-acceptance angle electrostatic lens. We take into account the influence of the angle of incidence to a mesh hole (i.e., of the chief ray angle). Here we describe the difference in focal length between tangential and sagittal planes, which becomes more marked when the chief ray angle increases. Then we characterize the image blur due to each mesh hole in two orthogonal directions.

2. Mesh-hole effect and its simple evaluation

2.1. Mesh-hole effect

We consider an electric field produced by two concentric spherical shells \( S_0 \) and \( S_1 \) of which the inner one is a mesh, as shown in Fig. 1. It is almost the same as a spherically symmetric field except for a region close to \( S_0 \). Some examples of electron trajectories in spherically symmetric fields are shown in Fig. 1. The trajectories in each figure start from a point source \( P_0 \) on the \( z \) axis, which is specified by \( z = z_0 \). They have emission angles \( \theta \) from \( 0^\circ \) to \( 50^\circ \) with an interval of \( 5^\circ \). The center of \( S_0 \) and \( S_1 \) is the origin of the coordinates and the radii of \( S_0 \) and \( S_1 \) are set to \( r_0 = 20 \) mm and \( r_1 = 40 \) mm, respectively. The electric field is determined by the potential \( V_1 \) applied to \( S_1 \), with that of \( S_0 \) being set to 0 V. We consider only the case of decelerating fields, i.e., \( V_1 < 0 \). The kinetic energy of electrons at \( P_0 \) is set to 1 keV. The trajectories are terminated at \( S_1 \) and virtual images are formed by drawing tangential lines from there.

Fig. 1(a) is a special case where all virtual rays are focused to a point in the mathematical sense, i.e., with zero spherical aberration, which can be seen analytically for \( z_0 = -20 \) mm and \( V_1 = -500 \) V (see Ref. [13]). In Fig. 1(b)–(d), three different sample positions \( z_0 \) are considered for \( V_1 = -700 \) V; this voltage gives a field strength at \( S_0 \) similar to that of the wide-acceptance-angle electrostatic lens. Negative and positive spherical aberrations are produced in Figs. 1(b) and (d), respectively. This is seen more clearly in Fig. 2, which shows the spherical aberration at the virtual image plane (VIP) for some variations of \( z_0 \). Good focusing is found in the case of \( z_0 = -17 \) mm and \( V_1 = -700 \) V (see Fig. 1(c)), while there remains a certain amount of spherical aberration, as shown in Fig. 2.

Now we deal with the problem of the mesh-hole effect in the above example. The electric field in a region close to \( S_0 \) is disturbed by the presence of mesh holes in practice. An example of the disturbed field around a mesh hole is given in Fig. 3. The action of the field on incident electrons is indicated by some arrows in the figure. Each mesh hole on \( S_0 \) causes such diverging action, i.e., acts as a local divergent lens, which makes a certain amount of image blurring unavoidable. We investigated the effect of each mesh hole in the wide angle regime.

The investigation was carried out under the following calculation conditions. Since electric fields with axial symmetry can be calculated with high accuracy using the charge simulation method (CSM), we used CSM for calculation of disturbed electric fields as shown in Fig. 3. Here spherical shells with a single circular hole were considered, assuming that electron trajectories passing through each mesh hole would be much less influenced by its neighboring

Fig. 1. Formation of a virtual image by a spherically symmetric field between two spherical surfaces \( S_0 \) and \( S_1 \). Electron trajectories starting from the on-axis object point \( P_0 \) with initial angles up to \( 50^\circ \) are shown. The spherical aberration can be controlled by changing the object position \( z_0 \) and the voltage \( V_1 \) applied to \( S_1 \). (a) Case of no spherical aberration. (b) Case of negative spherical aberration. (c) Case of small spherical aberration. (d) Case of positive spherical aberration.
holes. Another point to be mentioned is the condition of the mesh thickness. Our calculations were done considering thin meshes with thickness of \(1/150\) of the hole diameter. We note that trajectories passing through a mesh may become trapped when the mesh thickness increased. However, we confirmed that trajectories obtained by changing only the mesh thickness have no significant change as long as they are not trapped. Thus, after investigating such thin-mesh cases, it is sufficient to consider only the trapping of trajectories for cases of increased mesh thickness geometrically.

We evaluated the mesh-hole effect by the change in electron trajectories at the virtual image plane. This evaluation was made along two directions: one is the \(x\) direction (see Fig. 1), which is taken in the plane including the \(z\) axis and the center of a considered mesh hole, and the other is the \(y\) direction, which is perpendicular to the \(xz\) plane. Results of the evaluation for the four cases considered in Fig. 1 are shown in Fig. 4. Here, mesh holes with a diameter of 1 mm, put at \(\theta = 0°~50°\) with an interval of 5° are considered. For each mesh hole and for each direction, eleven trajectories that uniformly cover 98% of the hole were calculated, as shown in Fig. 3. Each set of eleven lined-up marks is the result and shows blurring due to the mesh-hole effect. The center point for each mark set is the result for the trajectory directed toward the center of each corresponding hole. In each figure for the \(x\) direction of Fig. 4(b)–(d), all of the center points agree well with each corresponding curve in Fig. 2. That is, the trajectory directed toward the center of each hole is practically not affected by the lens action of the hole. Some detail of this feature is mentioned in the following section. Fig. 4 also indicates that blur due to each mesh hole is distributed uniformly.

![Fig. 2. Spherical aberration at VIP for the case \(V_1 = -700\ \text{V}\). The aberration can either be positive or negative depending on the object position \(z_0\).](image)

![Fig. 3. Electric field around a mesh hole.](image)

![Fig. 4. Image blurring in two orthogonal directions \(x\) and \(y\) at the virtual image plane. (a)–(d) are for the cases corresponding to Fig. 1(a)–(d), respectively.](image)
2.2. Evaluation using the Davison–Calbick formula

We now review a simple method for evaluating the image blur due to the mesh-hole effect. Each mesh hole in $S_0$, having a circular shape, can be regarded as a single-aperture lens and its focal length $f_M$ can be given by the Davison–Calbick formula \cite{28,29}

$$f_M = \frac{4\Phi_0}{E_a - E_b},$$  \hspace{1cm} (1)

where $\Phi_0$ is the kinetic energy of an incident electron in equivalent volts and $E_a$ and $E_b$ are, respectively, the strengths of electric fields at the object and image sides in the case where there is no aperture.

In the case considered in Section 2.1, $E_a = 0$ and $E_b = E(r_0)$, with $E(r)$ the field strength of the spherically symmetric field produced by two concentric spherical shells, which is generally given by

$$E(r) = \frac{r_1 r_0 (V_1 - V_0)}{r_1 - r_0} \frac{1}{r^2},$$  \hspace{1cm} (2)

where $V_0$ $(V_1)$ is the potential at $r = r_0$ $(r_1)$. Inserting $r = r_0 = 20$ mm, $r_1 = 40$ mm, $V_0 = 0$, and $V_1 = -700$ V into Eq. (2), we obtain $E_b = 70$ V/mm. In this case, the focal length of Eq. (1) is given by $f_M = -400/7$ mm for $\Phi_0 = 1000$ V.

The nature of single-aperture lenses was studied in detail in Ref. [11], taking the dimensionless quantity $Q = \Phi_0/E_a D$ as a basic parameter, where $D$ is the diameter of the aperture. It was shown that when $Q$ is greater than around 10, the single-aperture lens can be replaced with a thin lens with the focal length given by Eq. (1). For each case in Fig. 4 $(D = 1$ mm), the quantity becomes $Q = 1000/70 \approx 14$. An important feature of the thin lens is that electrons going toward the center of the lens receive no lens action. This behavior was just observed in Fig. 4.

Consider the virtual image of a point source by the thin lens. Then, using the thin-lens object–image relationship, i.e., the relationship in the form $1/f_M = -1/s_0 + 1/b$, one can simply express the diameter of the image blur caused by a mesh hole as follows:

$$\Delta d_0 = s_0 D / f_M$$  \hspace{1cm} (3)

where $s_0$ is the distance between the point source and the center of the mesh hole.

We confirmed the validity of the formula for the example in Section 2.1. For the case of on-axis mesh hole, $s_0 = 20 - z_0$ and we have $\Delta d_0 = (20 - z_0) D(400/7)$. This gives $\Delta d_0 = 0.525D$ for the case $z_0 = -10$ mm. This result is plotted in Fig. 5 and compared with corresponding results from ray tracing. Here electron trajectories were calculated in the same manner as in Section 2.1. The blur diameter for each $D$ obtained in this manner was multiplied by the factor of 100/98 to take into account the contribution of the entire hole. The diameter was also divided by the magnification of image, since the formula (3) characterizes the blur at the object plane. As is shown, the ray-tracing results are in good agreement with the evaluation by the formula (3).

3. Formulae for evaluation of off-axis mesh-hole effect

3.1. Modified formulae

The formula (3) can be suitably applied for mesh holes located within the paraxial region. However, for mesh holes distant from the $z$ axis, the expression should be modified taking into account the incidence angle $\theta$ and the angle of incidence to a mesh hole, i.e., the chief ray angle, which we denote by $\theta_M$ (see Fig. 6). The chief ray angle $\theta_M$ can be large for mesh holes other than those close to the $z$-axis. If $\theta_M$ is large, astigmatism needs to be considered for the lens action of a mesh hole. For astigmatism, a lens has two characteristic planes: the tangential plane (also called the meridional plane), which includes the chief ray and the optical axis of the lens, and the sagittal plane, which includes the chief ray and is perpendicular to the tangential plane. In general, focal length is shorter in the tangential plane than in the sagittal plane. This discrepancy becomes more marked when the chief ray angle increases. We take into account this feature in the evaluation of the mesh-hole effect.

We consider blur diameters $\Delta d_x$ and $\Delta d_y$ for the $x$ and $y$ directions (see Fig. 6). A simple geometrical consideration gives

$$\Delta d_x = \Delta d_0 \cos \theta_M \cos \theta;$$  \hspace{1cm} (4)

$$\Delta d_y = \Delta d_0.$$  \hspace{1cm} (5)

Introducing correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ depending on $\theta_M$, we express the focal lengths in the tangential and sagittal planes, respectively, by $f_M/k(\theta_M)$ and $f_M/\tau(\theta_M)$, where $\kappa(0) = \tau(0) = 1$. Then we modify the expressions (4) and (5) as follows:

$$\Delta d_x = \Delta d_0 \kappa(\theta_M) \cos \theta_M \cos \theta;$$  \hspace{1cm} (6)

$$\Delta d_y = \Delta d_0 \tau(\theta_M).$$  \hspace{1cm} (7)

For the case of an on-axis mesh hole, $\theta$ and $\theta_M$ are both zero, and thus both $\Delta d_x$ and $\Delta d_y$ lead to $\Delta d_0$. Anisotropic blur such as seen in Fig. 4 can be characterized by $\Delta d_x$ and $\Delta d_y$, which is demonstrated in Section 3.2.
blur diameters $\Delta d_x$ and $\Delta d_y$ evaluated by Eqs. (4) and (5) are represented by the solid and dashed lines, respectively. The closed and open squares represent results of the ray-tracing evaluation of $\Delta d_x$ and $\Delta d_y$, respectively. Each curve in Fig. 7(a) is in good agreement with the corresponding ray-tracing result. However, this is the case only when $z_0$ is small (i.e., the point source $P_0$ is close to the origin $O$ of the coordinates), which is just the case where the chief ray angle $\theta_M$ is small for all $\theta$. In this case, $\kappa(\theta_M)=\tau(\theta_M)=1$ is a good approximation. Fig. 7(b) and (c) considers cases with large chief-ray angles; when $z_0=-20$, the chief-ray angle $\theta_M$ is equal to the incidence angle $\theta$. Considerable difference between $\Delta d_x (\Delta d_y)$ and the corresponding ray-tracing result is observed in the figures. This means that the expressions (4) and (5) are not valid for large chief ray angles.

Here, we mention the ray-tracing evaluation of $\Delta d_x$ and $\Delta d_y$. They were obtained in a similar manner as mentioned in Section 2. This evaluation requires that the blur diameters $\Delta d_x$ and $\Delta d_y$ obtained at the virtual image plane be correctly converted to those at the object plane. This can be done by dividing $\Delta d_x$ and $\Delta d_y$ by their corresponding magnifications. This assumes that $\Delta d_x$ and $\Delta d_y$ are simply due to the lens action of mesh holes and the magnification by the field following the mesh. However, there is a contribution of spherical aberration in some degree. In the thin lens approximation for mesh holes, the electric field between $S_0$ and $S_1$ is purely the spherically symmetric field and the action of mesh holes are replaced by the refraction at the boundary $S_0$, as described in Fig. 6. That is, the incidence angle to the spherically symmetric field is changed by the thin lens. If there is spherical aberration, the change causes the aberration that contributes to $\Delta d_x$ and $\Delta d_y$. To avoid this complication, the three cases considered in Fig. 7 are those with sufficiently small spherical aberration.

Now we consider the correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$. They can be determined by taking the ratio of the blur diameters $\Delta d_x$ and $\Delta d_y$ given by ray-tracing calculation to those given by Eqs. (4) and (5). In this manner, the results shown in Fig. 7(c) allows us to determine $\kappa(\theta_M)$ and $\tau(\theta_M)$ over a wide angle range up to $\theta_M=50^\circ$. However, we determined $\kappa(\theta_M)$ and $\tau(\theta_M)$ in another system to show the generality of our formulation. We considered two parallel flat plates perpendicular to the $z$ axis, instead of the two concentric spherical shells, as shown in Fig. 8(a). A similar calculation as in Fig. 7 was carried out, locating a circular hole in the direction of $\theta$ up to $50^\circ$. Diamonds and circles in Fig. 8(b), respectively, show the correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ determined through this calculation. The parameter $Q$ (see Section 2.2) was set to $Q=1000$, assuming that $\kappa(\theta_M)$ and $\tau(\theta_M)$ practically does not depend on $Q$ for $Q \approx 10$. Diamonds and circles in Fig. 8(b) are well approximated by polynomials of the form $f(\theta_M) = 1 + a_1\theta_M + a_2\theta_M^2 + a_3\theta_M^3 + a_4\theta_M^4$. The values of the parameters $a_i$ for each of $\kappa(\theta_M)$ and $\tau(\theta_M)$ are shown in Table 1.

Table 1

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<th>Parameter values</th>
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<tr>
<td>$a_1 \times 10^{-4}$</td>
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<tr>
<td>$\kappa$</td>
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<td>$\tau$</td>
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It is indicated in Fig. 8(b) that the focal length in the tangential plane, defined by $f_M|\kappa(\theta_M)$, considerably decreases with increasing $\theta_M$. The focal length in the sagittal plane, $f_M|\tau(\theta_M)$, also decreases with increasing $\theta_M$, but it is much milder than in the tangential plane. The correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ shown in Fig. 8(b) were applied to the three cases considered in Fig. 7. The results of the correction of $\Delta d_x$ and $\Delta d_y$ are shown in Fig. 9, with Fig. 9(a)–(c) corresponding to Fig. 7(a)–(c), respectively. In each figure, the curves of the corrected blur diameters are in good agreement with the results of the ray-tracing evaluation.

Fig. 7. Comparison of the blur diameters $\Delta d_x$ and $\Delta d_y$ evaluated by ray-tracing calculation and those evaluated by the formulas (4) and (5). (a) Case where the chief-ray angle $\theta_M$ is small for all the range of the incidence angle $\theta$. (b) and (c) Case where large chief-ray angles are involved. In each case, the hole diameter $D$ is 1 mm.

The above two expressions give two diameters of an elliptic blur. Assuming a uniform distribution for the elliptic blur, the full width at half maximum (FWHM) of the distribution obtained when considering all azimuth angles is $\sqrt{2}d_x \Delta d_y/\sqrt{\Delta d_x^2 + \Delta d_y^2}$, which gives

$$\Delta d = \Delta d_0 \frac{\sqrt{2}(\theta_M)^2 \cos \theta_M}{\sqrt{\tau(\theta_M)^2 \cos^2 \theta_M}}. \quad(8)$$

Naturally, Eq. (8) leads to $\Delta d_0$ when $\theta = 0$.

3.2. Examination of the formulae

We examined the validity of the formulae (4)–(7) applying them to the example in Section 2. We first consider the case where the focal length $f_M$ is not corrected, i.e., the evaluation by Eqs. (4) and (5). Fig. 7 shows results for three particular cases of $(z_0, V_1)$. Here the hole diameter $D$ was set to 1 mm. In each of Figs. 7(a)–(c), the
4. Practical application

Fig. 10 is a schematic view of a wide-acceptance-angle electrostatic lens (WAAEL) we have developed. The lens, which is composed of seven electrodes, has an ellipsoidal mesh as the major part of the entrance electrode EL1. This electrode and the sample are grounded and there is no electric field between them. The lens allows us to completely or almost completely correct spherical aberration over a wide range of incident angles $\theta$ (up to around $\pm 50^\circ$). The full acceptance angle of the lens is around $\pm 60^\circ$.

We evaluated the mesh-hole effect of WAAEL by applying the approach described in Section 3. Fig. 11(a) shows the quantity $QD (= \Phi_0/\Phi_2)$ calculated as a function of the incident angle $\theta$. The quantity $Q$ increases with increasing $\theta$, since the field strength at the mesh surface becomes smaller with increasing $\theta$. It is very marked in the range of around $\alpha = 50^\circ$–$60^\circ$, which can be seen from the equipotential lines shown in Fig. 10. If we choose $D = 1$ mm ($D = 0.1$ mm), we have $Q \approx 14.9$ ($Q \approx 149$) at $\theta = 0^\circ$, which seems to be sufficiently large to use the thin-lens approximation. The absolute value of the focal length of Eq. (1) is given by $|f_0| = 4QD$ and thus the blur diameter of Eq. (3) is $\Delta d_0 = s_0/4Q$. Fig. 11(b) shows the relationships of the distance $s_0$ and the chief ray angle $\theta_M$ with the incidence angle $\theta$. The distance $s_0$ considerably decreases with increasing $\theta$, as seen in Fig. 10. The chief ray angle $\theta_M$ has a broad maximum around $\theta = 30^\circ$.

Fig. 8. (a) A system in which the correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ are determined. A decelerating field is produced between two parallel flat plates, of which the left one is a mesh. (b) Determined correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ as functions of the chief ray angle $\theta_M$. Results for $\kappa(\theta_M)$ and $\tau(\theta_M)$ are plotted as open diamonds and circles, respectively. They are approximated by fourth order polynomials (solid and dashed curves).

Fig. 9. Comparison of the blur diameters $\Delta d_x$ and $\Delta d_y$ evaluated by ray-tracing calculation and those evaluated by the formulas (6) and (7) with the correction factors $\kappa(\theta_M)$ and $\tau(\theta_M)$ shown in Fig. 8(b). The three cases correspond to those in Fig. 7.

Fig. 10. Schematic view of wide-acceptance-angle electrostatic lens. Electrode arrangement, equipotential lines, and electron trajectories with initial angles up to $\pm 50^\circ$ are shown.
Fig. 11. Evaluation of the mesh-hole effect of wide-acceptance-angle electrostatic lens. (a) Dependence of the quantity \( QD \) on the incidence angle \( \theta \). (b) Angular dependence of the chief-ray angle \( \theta_M \) and the distance \( s_0 \). (c) Angular dependence of the blur diameters \( \Delta d_x \), \( \Delta d_y \), and \( \Delta d \).

Fig. 11(c) shows the angular dependence of the blur diameters \( \Delta d_x \), \( \Delta d_y \), and \( \Delta d \) evaluated by Eqs. (6) to (8). We remark that they are greatly decreased with increasing \( \theta \). As seen from Eqs. (6) to (8) and \( \Delta d_0 = s_0/4Q \), this is caused by two factors: the increase with \( \theta \) of the quantity \( Q \) and the decrease with \( \theta \) of the distance \( s_0 \). As a result, the blur diameter \( \Delta d \) decreases from 81 to 31 \( \mu \text{m} \) (2 \( \mu \text{m} \)) for \( D = 0.1 \text{mm} \) when \( \theta \) increases from 0° to 50° (60°). Considering all contributions from \( \theta = 0° \) to 50° (60°), the blur diameter is estimated to be 49 \( \mu \text{m} \) (32 \( \mu \text{m} \)) (FWHM) for \( D = 0.1 \text{mm} \).

5. Conclusion

A practical way to evaluate the mesh-hole effect in electrostatic lenses with meshes in a wide range of incidence angles has been described, based on the approach of using the Davisson–Calbick formula. Considering the influence of the angle of incidence to a mesh hole, we introduced correction factors to express the focal lengths in the tangential and sagittal planes. As a result, we obtained the expressions for blur diameters in two orthogonal directions. The validity of these expressions was confirmed in a simple example after the correction factors were determined in a single aperture lens. The blur diameters evaluated by the expressions agree well with the results of ray-tracing calculation. As a practical example, we evaluated the mesh-hole effect of a wide-acceptance-angle electrostatic lens. It was revealed here that the mesh-hole effect considerably decreases with increasing the incidence angle.

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