Normal Incidence Two-mirror Reflecting Systems Designed at EUV and X-ray*

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Abstract: Based on the third-order aberration theory of two-mirror reflecting system, the influence of the geometrical aberrations on the performance of normal incidence telescopes was analyzed. The change trends of the angular size of the blur spot θ with the f-number and half-field angle u_P were concluded. The angular blur spot θ increased with the increase of the half-field angle u_P and the decrease of f-number, and the θ increased more sharply when the f-number was less than 10 or the half-field angle u_P was more than 0.005. And, four kinds of typical reflecting systems were discussed in detail. Comparing the results, it is found that the angular blur spots in a Dall-Kirkham system and an inverse Dall-Kirkham system are at the same order of magnitude, which is almost ten times of a Cassegrain system′s. The θ of an R-C system is the smallest, which is one tenth of a Cassegrain system′s. It is useful to estimate the size of the aberration blur by the formulae without going to the trouble of making a raytrace analysis.

Key words: Third order aberration theory; EUV and X-ray; Reflecting systems; Geometrical aberrations; Angular blur spot
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0 Introduction

Reflecting systems composed of two mirrors have been paid considerable attention owning to their interesting and useful properties. The aberration characteristics and the conditions of the absence of various aberrations of the optical systems were studied and a set of formulae was derived[1-6].

The great development of near-normal incidence multilayer reflective coatings allowed scientists and engineers to design and construct novel low-aberration optical instrumentations, including normal incidence optical systems, for soft X-ray microscopy, extreme ultraviolet EUV lithography, X-ray microanalysis, etc. The normal incident EUV and soft X-ray telescopes have a wide use owning to the advantages of good aberration characteristics and providing a much larger collecting area than a grazing-incidence mirror of the same diameter, such as the GOES SXI Telescope and the extreme ultra-violet imaging telescope on board SOHO[7-9]. The most complex array of multilayer X-ray/EUV telescopes ever flown in the Multi-Spectral Solar Telescope Array (MSSTA) and several papers are related to the MSSTA. The MSSTA includes two Cassegrain, seven Ritchey-Chrétien and five Herschelian telescopes that form images in narrow-wavelength bands in the XUV (4～35 nm) and FUV (122 ～ 160 nm)[10].

Note that due to short wavelength (λ<50 nm) a EUV/X-ray reflector enables us to achieve high spatial resolution limited by the value of its geometrical aberrations but not its diffraction effects. Unlike the visible light optics, in many cases soft x-ray optical systems can be analyzed from the viewpoint of geometrical aberrations only[11-12].

In this paper, the aberrations of four typical kinds of two-mirror reflecting systems are expressed in terms of the angular size θ (in radians) of the blur spot. It may also be converted to the linear diameter of the blur by multiplying by the system focal length. Where the blur size for more than one aberration is given, the sum of all the aberration blurs will yield a conservative estimate of the total blur.

1 Aberration analysis of two-mirror reflecting systems

The schematic diagram of two-mirror reflecting system is shown in Fig. 1.

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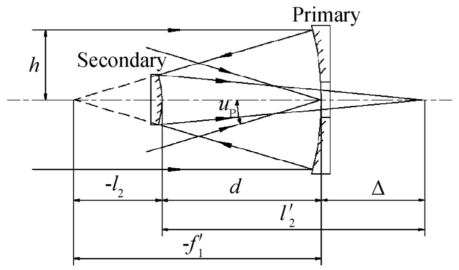


Fig. 1　The schematic diagram of two-mirror reflecting system

Where f is the focal length, u_P is the half-field angle in radians and h is the semi-aperture of primary. Assuming object to be at infinity, $l_1=\infty$, $u_1=0$, the stop is located at the primary, according to the third order aberration theory, we can find[13]

$$\begin{cases} \sum TSC=\dfrac{h^3[f(l'_2-f)^3+64d^3f^4K_1+l'_2(f-d-l'_2)(f+d-l'_2)^2-64l'^4_2d^3K_2]}{8d^3f^3} \\ \sum CC=\dfrac{Hh^2[2f(l'_2-f)^2+(f-d-l'_2)(f+d-l'_2)(d-f-l'_2)-64l'^3_2d^3K_2]}{8d^2f^3} \\ \sum TAC=\dfrac{H^2h[4l'_2f(l'_2-f)+(f-d-l'_2)(d-f-l'_2)^2-64l'^3_2d^3K_2]}{8l'_2df^3} \\ \sum TPC=\dfrac{H^2h[df-(l'_2-f)^2]}{2l'_2df^2} \end{cases} \quad (1)$$

The parameters used are: K = conic coefficient; $\sum TSC$ = transverse third-order spherical aberration sum; $\sum CC$ = third-order sagittal coma sum; $\sum TAC$ = transverse third-order astigmatism sum; $\sum TPC$ = transverse Petzval curvature sum.

1) As a spherical aberration-free system, a Dall-Kirkham system has a spherical secondary and all of the correction is accomplished by the aspheric primary. The system meets the requirement $\sum TSC=0$, thus

$$\begin{cases} \sum TSC=0 \\ \sum CC=Hh^2[2f(l'_2-f)^2+(f-d-l'_2)\cdot (f+d-l'_2)(d-f-l'_2)]/8d^2f^3 \\ \sum TAC=H^2h[4l'_2f(l'_2-f)+(f-d-l'_2)\cdot (d-f-l'_2)^2]/8l'_2df^3 \end{cases} \quad (2)$$

So the angular size of blur spot is

$$\theta=\{u_P[2f(l'_2-f)^2+(f-d-l'_2)(f+d-l'_2)(d-f-l'_2)]/32d^2f(f^{\#})^2\}+\{u_P^2[4l'_2f(l'_2-f)+(f-d-l'_2)(d-f-l'_2)^2]/16l'_2df(f^{\#})^2\} \quad (3)$$

From Eq. (3), get the change trend of the angular blur spot θ with the f-number ($f^{\#}$) and the half-field angle u_P (in radians). We set f = 4 060 mm, d=870 mm and l'_2=1 014.91 mm. In this case, the f-number changes from 5 to 30 and the half-angle in radian u_P changes from 0 to 0.008 73, and the change trend of θ is shown in Fig. 2(a).

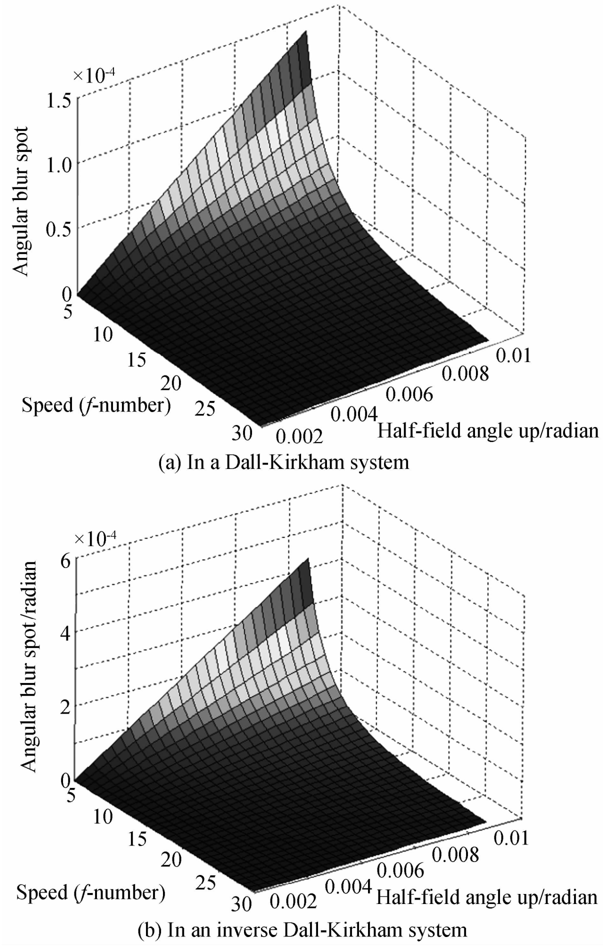


Fig. 2　The changes of θ with $f^{\#}$ and u_P in a Dall-Kirkham system and an inverse Dall-Kirkham system respectively

In order to compare the various two-mirror reflectors conveniently, the same parameters are used in the following design cases , and the θ is at the same order of magnitude in this paper.

2) A sort of inverse Dall-Kirkham system, whose $\sum \mathrm{TSC}=0$ also, has a spherical primary and an aspheric secondary. Thus

$$\begin{cases} \sum \mathrm{TSC}=0 \\ \sum \mathrm{CC}=\dfrac{Hh^2[2l_2' d^2-(l_2'-f)^3]}{8l_2' d^2 f^2} \\ \sum \mathrm{TAC}=\dfrac{H^2h[(f-l_2')^3+4l_2' d(d-f)]}{8l_2'^2 d f^2} \end{cases} \tag{4}$$

The angular size of blur spot is

$$\theta=\frac{u_P[2l_2' d^2-(l_2'-f)^3]}{32l_2' d^2(f^{\#})^2}+\frac{u_P^2[(f-l_2')^3+4l_2' d(d-f)]}{16l_2'^2 d(f^{\#})^2} \tag{5}$$

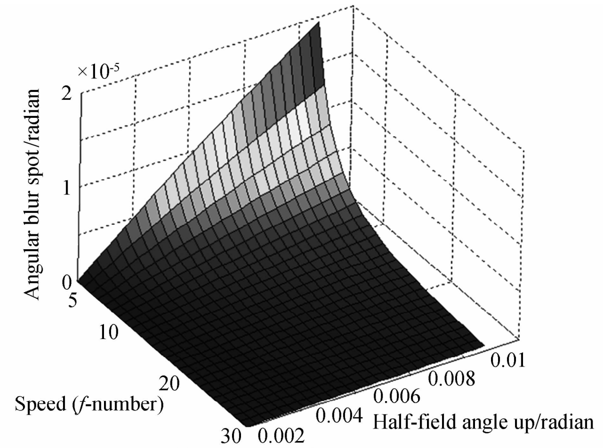
The change trend of the angular blur spot θ with the f-number and the half-field angle u_P (in radians) is shown in Fig. 2(b).

3) If both mirrors are independently corrected for spherical aberration, it is called the classical Cassegrain or Gregorian system. Let $\sum \mathrm{TSC}=0$, get the angular blur spot to

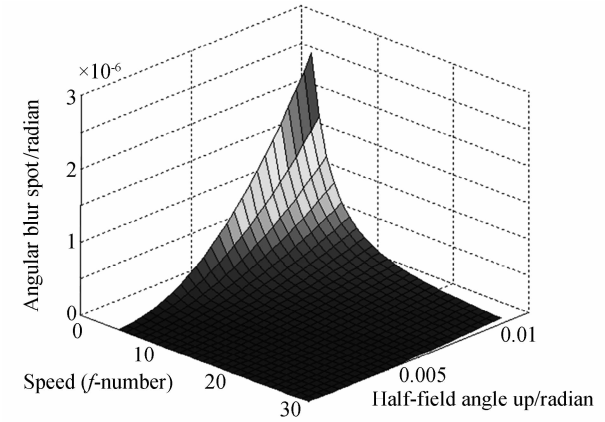
$$\theta=\frac{u_P}{16(f^{\#})^2}+\frac{u_P^2(d-f)}{4l_2'(f^{\#})^2} \tag{6}$$

The change trend of the angular blur spot θ with the f-number and the half-field angle u_P (in radians) is shown in Fig. 3(a).

The Cassegrain has a positive focal length and the Gregorian has a negative one. The Cassegrain objective system is used (usually in a modified form) in a great variety of applications because of its compactness and the fact that the second reflection places the image behind the primary mirror where it is readily accessible.



(a) In a cassegrain system



(b) In an R-C system

Fig. 3 The changes of θ with $f^{\#}$ and u_P in a Cassegrain system and an R-C system respectively

4) For a Ritchey-Chrétien system (R-C system), K_1 and K_2 can be solved to get both third-order spherical and coma corrected. So the angular blur spot is

$$\theta=\frac{u_P^2(d-2f)}{8l_2'(f^{\#})^2} \tag{7}$$

The change trend of the angular blur spot θ with the f-number and the half-field angle u_P (in radians) is shown in Fig. 3(b).

In Fig. 2 and Fig. 3, it is shown that the angular blur spot θ increases with the increase in the half-field angle u_P and the decrease in f-number. Moreover, the θ increases with the increase of the half-field angle u_P more sharply when the f-number is less than 10. In the same way, the θ increases with the decrease in f-number more sharply when the half-field angle u_P is more than 0.005.

The figures also show that the angular blur spots θ in a Dall-Kirkham system and an inverse Dall-Kirkham system are at the same order of magnitude and the θ of an R-C system is the smallest, which is one tenth of a Cassegrain system's.

Comparing the changes of θ with $f^{\#}$ and u_P in a Dall-Kirkham system with which in an inverse Dall-Kirkham system, the θ in an inverse Dall-Kirkham system is bigger than which in a Dall-Kirkham system, although they have the same parameters.

2 Conclusions

The influence of the geometrical aberrations on the performance of normal incidence telescopes for EUV and soft X-ray is analyzed on the base of the third-order aberration theory. Furthermore four kinds of typical reflecting systems are in detail discussed. From the minimal angular blur spots θ of reflecting systems, the change trends of θ with the f-number and the half-field angle in radians u_P are gotten.

Although the equations and the change trends come from the third-order aberration theory, there is a satisfactory agreement between them and the results which are derived from the optical design program. It is convenient to estimate the size of the aberration blur by the formulae without going to the trouble of making a raytrace analysis. This can play a valuable role in selecting the initial configuration on the beginning of the preliminary engineering work or the preparation of designing a normal incidence telescope for EUV and soft X-ray.

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极紫外与 X 射线波段正入射两镜反射系统的研究

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摘 要:基于三级象差理论,分析了几何象差对正入射望远镜性能的影响,总结了弥散斑角宽度 θ 随着系统 f 数和半视场角 u_P 的变化趋势.弥散斑的角宽度 θ 随着半视场角 u_P 的增大而增大,随着系统 f 数的增大而减小.当 f 数小于 10 或者半视场角 u_P 大于 0.005 弧度时,弥散斑角宽度 θ 变化比较剧烈.详细讨论了四种典型的反射系统,Dall-Kirkham 系统和反 Dall-Kirkham 系统的弥散斑角宽尺寸在一个数量级上,大约为卡塞格林系统的十倍.R-C 系统的弥散斑角宽最小,几乎是卡塞格林系统的十分之一.通过本文的结论公式可以估算一个光学系统的象差尺寸并避免进行光线追迹.

关键词:三级象差理论;极紫外与 X 射线;反射系统;几何象差;弥散斑角宽

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