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Out-of-focus Point Spread Functions of Optical Systems in the Presence of Primary Spherical aberration

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Abstract
The out-of-focus point spread function of optical systems in the presence of primary spherical aberration has been investigated. Considerable reduction of the central maximum intensity and the presence of non-zero first minimum put a severe restriction for Rayleigh criterion to be applied for two-point resolution studies for these systems.
Key Words: *PSF, Primary Spherical Aberration, Defocusing.*

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I. Introduction

It is now well known that the diffraction image of a point never a point. It is a patch of light distributed over a finite region in the image plane. This is known as the Point Spread Function (PSF) of the optical system and is commonly known as Airy pattern when the optical system is purely diffraction-limited. The PSF of an optical system is an important parameter for studying its imaging characteristics. In other words, the performance of an optical system significantly depends on its PSF [1].

The study of imaging properties of optical systems suffering from aberrations from the knowledge of the PSF has become an important method in the design and testing of such systems [2]. In our present study, we have investigated the PSF of an optical system suffering from primary spherical aberration and in the presence of defect-of-focus.

II. Theory

The far-field effects due to a circular aperture in an optical system can be derived from its amplitude response or the amplitude PSF. The diffracted light amplitude associated with a rotationally symmetric pupil is given by [3],

$$A(Z) = 2\int_0^1 f(r)\exp\left[i\left(-Y\frac{r^2}{2} - Y_1\frac{r^4}{4}\right)\right] J_0(Zr)\,r\,dr \qquad (1)$$

where f(x) is the pupil function of the optical system; Y and Y_1 are respectively defocusing and primary spherical aberration parameters in dimensionless co-ordinates and $J_0(Zr)$ is the zero order Bessel function of the first kind. R is a reduced co-ordinate on the exit-pupil of the system. For our present analysis, we have considered the shaded apertures whose pupil function can be represented by

$$f(r) = \left(1 - \beta^2\, r^2\right) \qquad (2)$$

where β is the apodising parameter controlled the non-uniform transmission of the pupil. β=0 corresponds to a diffraction-limited system and in this paper; we have restricted ourselves to this case only. The intensity PSF B(Z) which is the real measurable quantity can be obtained by taking the squared modulus of A(Z). Thus,

$$B(Z) = \left|A(Z)\right|^2 \qquad (3)$$

III. Results and Discussions

Expressions (1), (2) and (3) have been used to compute the intensity PSF B(Z) by employing the standard twelve-point gauss quadrature method. In Figure 1, we have plotted the computed values of B(Z) versus Z for various values of the primary spherical aberration parameter Y_1=0, π/ 4, π/2, 3π/4, π, 5π/4 and for a fixed value of the defocusing parameter Y=2π. In the Tables 1 to 5, we have shown the locations and the intensity values of the central maximum, first and secondary maxima and also the first, second and the third minima for various values of Y and Y_1. In all these cases, β has been kept equal to zero.

This means that we have considered a diffraction- limited optical system suffering from both defocusing and primary spherical aberration. From the figure and the tables, we find that there is a significant effect of the combined influence of defocusing and spherical aberration on the PSF. For example, the central maximum reduces to 40% of its original peak value when Y=2π and even Y_1=0. The situation is still worse as the PSF drops from a value of 0.80016 when Y=0 and Y_1 =2π to a significantly low value of 0.09382 when Y=2π and Y_1 =2π. In general, for a fixed value of Y, the PSF central maximum reduces considerably as the spherical aberration increases.

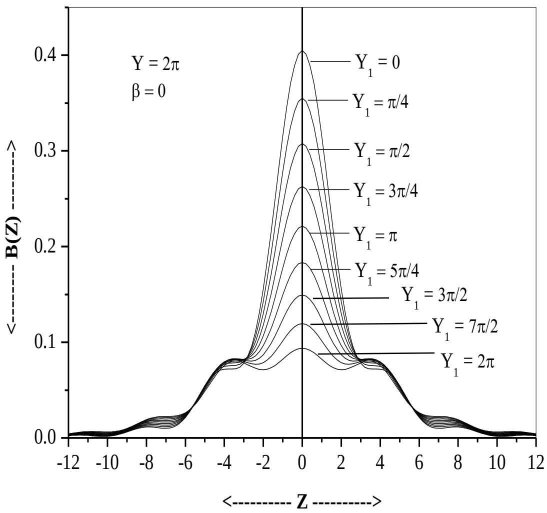

Fig.1 At defocused plane Y = 2π, intensiy distribution in the image of a point object in the presencwe of various amount of primary spherical aberration.

Table: 1

Y = 0, β = 0

Y1	Central Max		First Min		First Max		Second Min		Second Max		Third Min	
	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val
0	0.0000	1.0000	3.8317	0.0000	5.1339	0.0175	7.0155	0.0000	8.4066	0.0042	10.1732	0.0000
π/4	0.0000	0.9966	3.8336	0.0004	5.1307	0.0176	7.0138	0.0001	8.4050	0.0042	10.1721	0.0000
π/2	0.0000	0.9864	3.8393	0.0015	5.1164	0.0178	7.0086	0.0003	8.3899	0.0043	10.1670	0.0000
3π/4	0.0000	0.9695	3.8493	0.0034	5.0924	0.0181	6.9998	0.0006	8.3629	0.0045	10.1593	0.0001
π	0.0000	0.9464	3.8645	0.0059	5.0577	0.0187	6.9892	0.0010	8.3313	0.0047	10.1504	0.0002
5π/4	0.0000	0.9174	3.8863	0.0090	5.0094	0.0194	6.9736	0.0016	8.2947	0.0050	10.1358	0.0003
3π/2	0.0000	0.8829	3.9166	0.0127	4.9448	0.0203	6.9552	0.0022	8.2373	0.0054	10.1186	0.0005
7π/4	0.0000	0.8436	3.9606	0.0166	4.8569	0.0215	6.9301	0.0029	8.1812	0.0059	10.1103	0.0006
2π	0.0000	0.8002	4.0302	0.0208	4.7343	0.0230	6.9036	0.0038	8.1147	0.0065	10.0869	0.0008

Table: 2

$Y = \pi/2, \beta = 0$

Y1	Central Max		First Min		First Max		Second Min		Second Max		Third Min	
	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val
0	0.0000	0.9496	3.8316	0.0072	5.0268	0.0209	7.0149	.0004	8.3880	0.0045	10.1722	0.0001
$\pi/4$	0.0000	0.9220	3.8426	0.0107	4.9737	0.0221	7.0048	0.0008	8.3479	0.0047	10.1652	0.0001
$\pi/2$	0.0000	0.8887	3.8601	0.0147	4.9062	0.0236	6.9913	0.0013	8.3134	0.0051	10.1546	0.0002
$3\pi/4$	0.0000	0.8505	3.8862	0.0191	4.8244	0.0253	6.9765	0.0019	8.2676	0.0055	10.1437	0.0004
π	0.0000	0.8079	3.9273	0.0238	4.7166	0.0274	6.9568	0.0027	8.2183	0.0060	10.1304	0.0005
$5\pi/4$	0.0000	0.7615	3.9973	0.0286	4.5716	0.0299	6.9357	0.0035	8.1569	0.0065	10.1181	0.0007
$3\pi/2$	0.0000	0.7123	-----	-----	-----	-----	6.9132	0.0045	8.0853	0.0072	10.1074	0.0009
$7\pi/4$	0.0000	0.6608	-----	-----	-----	-----	6.8862	0.0055	8.0183	0.0079	10.0894	0.0012
2π	0.0000	0.6081	-----	-----	-----	-----	6.8553	0.0065	7.9475	0.0087	10.0697	0.0015

Table: 3

$Y = \pi, \beta = 0$

Y1	Central Max		First Min		First Max		Second Min		Second Max		Third Min	
	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val
0	0.0000	0.8104	3.8312	0.0263	4.7143	0.0320	7.0144	0.0018	8.2975	0.0055	10.1686	0.0003
$\pi/4$	0.0000	0.7651	3.8612	0.0316	4.6003	0.0349	6.9995	0.0026	8.2506	0.0060	10.1528	0.0004
$\pi/2$	0.0000	0.7166	3.9142	0.0369	4.4534	0.0381	6.9825	0.0035	8.1856	0.0066	10.1477	0.0006
$3\pi/4$	0.0000	0.6656	-----	-----	4.0762	0.0420	6.9633	0.0045	8.1164	0.0073	10.1285	0.0008
π	0.0000	0.6131	-----	-----	-----	-----	6.9422	0.0057	8.0433	0.0081	10.1164	0.0011
$5\pi/4$	0.0000	0.5597	-----	-----	-----	-----	6.9213	0.0069	7.9734	0.0090	10.1045	0.0014
$3\pi/2$	0.0000	0.5063	-----	-----	-----	-----	6.8922	0.0081	7.8863	0.0099	10.0876	0.0017
$7\pi/4$	0.0000	0.4536	-----	-----	-----	-----	6.8712	0.0094	7.8033	0.0110	10.0644	0.0021
2π	0.0000	0.4023	-----	-----	-----	-----	6.8412	0.0107	7.7153	0.0120	10.0466	0.0026

Table: 4

$Y = 3\pi/2 \;\; \beta = 0$

Y1	Central Max		First Min		First Max		Second Min		Second Max		Third Min	
	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val
0	0.0000	0.6147	3.8302	0.0507	4.2263	0.0512	7.0144	0.0049	8.1355	0.0076	10.1686	0.0007
$\pi/4$	0.0000	0.5618	------	------	------	------	6.9972	0.0061	8.0603	0.0085	10.1524	0.0010
$\pi/2$	0.0000	0.5086	------	------	------	------	6.9792	0.0075	7.9813	0.0095	10.1427	0.0013
$3\pi/4$	0.0000	0.4559	------	------	------	------	6.9613	0.0089	7.8956	0.0105	10.1288	0.0017
π	0.0000	0.4043	------	------	------	------	6.9412	0.0104	7.8033	0.0117	10.1055	0.0021
$5\pi/4$	0.0000	0.3546	------	------	------	------	6.9162	0.0119	7.7073	0.0129	10.0884	0.0025
$3\pi/2$	0.0000	0.3073	------	------	------	------	6.8922	0.0134	7.6053	0.0141	10.0665	0.0030
$7\pi/4$	0.0000	0.2630	------	------	------	------	6.8732	0.0149	7.5043	0.0154	10.0554	0.0035
2π	0.0000	0.2222	------	------	------	------	6.8513	0.0164	7.4034	0.0167	10.0245	0.0041

Table: 5

$Y = 2\pi, \beta = 0$

Y1	Central Max		First Min		First Max		Second Min		Second Max		Third Min	
	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val	Pos	Val
0	0.0000	0.4050	3.5942	0.0720	3.8293	0.0721	7.0166	0.0100	7.8779	0.0114	10.1691	0.0016
$\pi/4$	0.0000	0.3552	------	------	------	------	6.9952	0.0117	7.7763	0.0127	10.1475	0.0020
$\pi/2$	0.0000	0.3077	------	------	------	------	6.9822	0.0134	7.6733	0.0141	10.1255	0.0025
$3\pi/4$	0.0000	0.2629	------	------	------	------	6.9622	0.0150	7.5743	0.0155	10.1055	0.0030
π	0.0000	0.2214	3.1652	0.0820	3.4743	0.0821	6.9504	0.0167	7.4616	0.0170	10.0928	0.0036
$5\pi/4$	0.0000	0.1834	2.9182	0.0819	3.4723	0.0828	6.9334	0.0183	7.3345	0.0184	10.0756	0.0042
$3\pi/2$	0.0000	0.1494	2.6532	0.0803	3.4603	0.0828	6.9314	0.0198	7.2035	0.0199	10.0646	0.0048
$7\pi/4$	0.0000	0.1195	2.3552	0.0769	3.4444	0.0820	6.9356	0.0213	------	------	------	------
2π	0.0000	0.0938	2.0132	0.0712	3.4263	0.0805	------	------	------	------	10.0074	0.0062

As a consequence, the intensity values in the first and the second diffraction maximum increases with the increase in the values of Y_1. It is also observed that, not only the diffraction maxima, but also the various minima including the first minimum, show an increase in intensity values. Thus, as the value of Y_1 is increased, a perfectly dark minimum becomes a non-zero minimum even when Y=0. This imposes a severe restriction to the Rayleigh criterion to be applied for two-point resolution studies of these systems.

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