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Studies On Point Spread Function With Three Zone Complex Pupil Function

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Abstract
The point spread function of a complex three-zone pupil function is analyzed in the presence of primary spherical aberration and defocus. The second zone is phase-shifted by -π/5, and the third zone by +π/7. Apodization is applied using three filters: a Bartlett amplitude filter for the inner zone, a shaded amplitude filter for the second zone, and a Hanning amplitude filter for the third zone. The primary goal is to enhance the central maximum's intensity, eliminate side lobes, and reduce the radius of the first dark ring. A notable increase in the central maximum occurs when the apodization parameter is set to β = 1.0, and minimized the first dark ring's radius under high spherical aberration and defocus.

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I. Introduction

The main goal of any optical system is to create an image that closely replicates the object. However, in reality, the image of a point object is never truly a point but is represented by the point spread function (PSF), or the familiar Airy pattern, due to the diffraction of light [1]. The PSF is crucial for analyzing the image quality of an optical system [2-4]. Since the side lobes of the Airy pattern reduce image quality, suppressing these side lobes is key to enhancing PSF performance [5-7].

Apodization is a technique used to reduce the diffraction effects around an intensity peak, thereby improving focus. In this study, a complex three-zone aperture is utilized, with the second zone phase-shifted by -π/5 and the third by +π/7. The aperture is modified with three filters: a Bartlett amplitude filter for the inner zone, a shaded amplitude filter for the second zone, and a Hanning amplitude filter for the outer zone. This configuration helps analyze the intensity distribution, focusing on the width of the central lobe and reducing side lobes, all under the combined influence of defocus and primary spherical aberration [8-14].

Theory and Formulation

The far-field diffraction characteristics due to a circular aperture in an optical imaging 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

$$A(Z) = 2\int_0^1 f(r) J_0(Zr) r dr \qquad (1)$$

Where 'f(r)' is the pupil function of the optical system; 'Z' is the dimensionless variable which forms the distance of the point of observation from the Centre of diffraction head; and '$J_0(Zr)$' is the zero order Bessel function of the first kind; 'r' is the reduced co-ordinate on the exit-pupil of the system.

On introducing the wave aberrations such as defocus and primary spherical aberration. The complex amplitude impulse response of the optical system with one- dimensional amplitude filter is given as

$$A(Z) = \left\{ 2(\int_0^a f_1(r) \exp\left[-i\left(\phi_d \frac{r^2}{2} + \frac{1}{4}\varphi_s r^4\right)\right] J_0(Zr) r dr \right.$$

$$- Phase\int_0^a f_2(r) \exp\left[-i\left(\phi_d \frac{r^2}{2} + \frac{1}{4}\varphi_s r^4\right)\right] J_0(Zr) r dr$$

$$\left. + Phase\int_b^1 f_3(r) \exp\left[-i\left(\phi_d \frac{r^2}{2} + \frac{1}{4}\varphi_s r^4\right)\right] J_0(Zr) r dr \right\} \qquad (2)$$

In this context, ϕd and ϕs are the parameters for defocus and Spherical aberration parameters respectively. The current study focuses on considering pupil functions represented by the Barlett amplitude filter (first zone), the shaded amplitude filter (second zone) and the Hanning amplitude filter (outer zone) and a=0.3, b=0.6 are central-zone parameters. These filters can be represented as follows:

$f_1(r) = (1 - \beta r)$ Barlett amplitude filter (3)

$f_2(r) = (1 - \beta r^2)$ Shaded amplitude filter (4)

$f_3(r) = \cos^2(\pi \beta r)$ Hanning amplitude filter (5)

Where 'β' is the amplitude apodization parameter that controls the non-uniform transmission of the pupil function. The intensity Point Spread Function (PSF), denoted as B(Z), which is the measurable quantity, can be obtained by squaring the modulus of A(Z). Thus,

$B(Z) = |A(Z)|2$ (6)

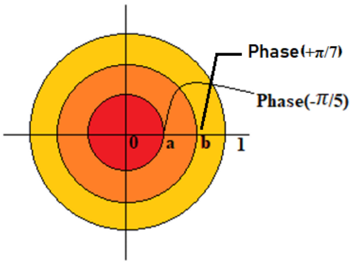

FiG:1 Three-Zone Complex Aperture

II. Results And Discussion

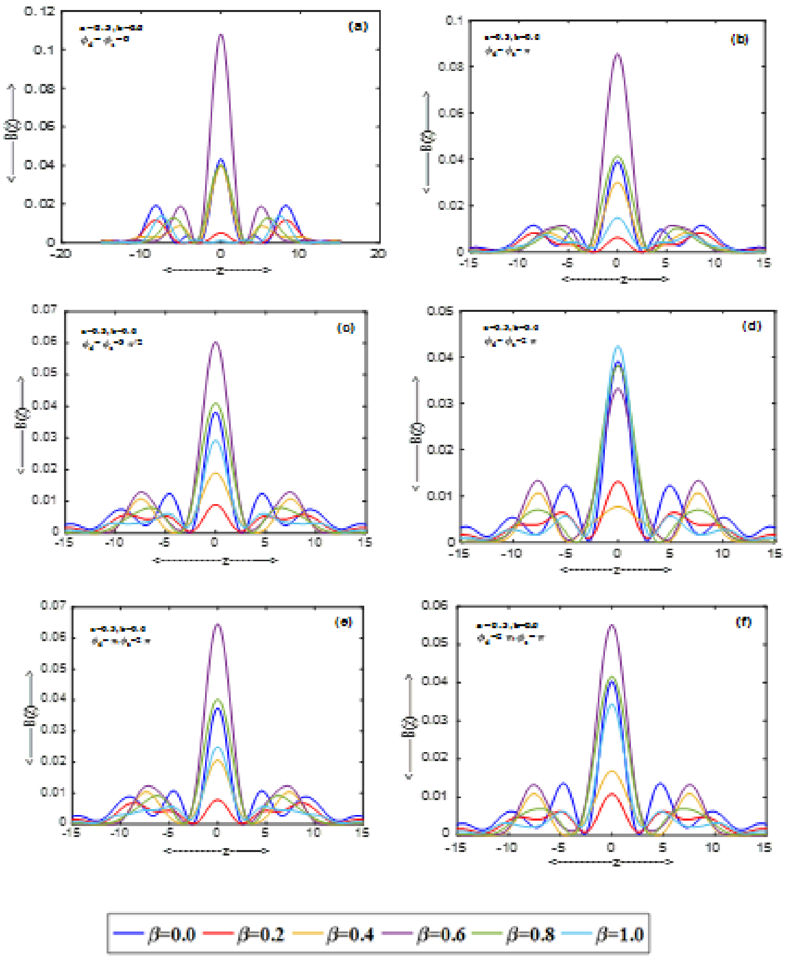

Fig:2 Intensity Distribution Curves Of Three Zone Complex Aperture

Figure 2 presents the intensity distribution profile of a three-zone complex aperture. In this configuration, the second zone is phase-shifted by -π/5, while the third zone is phase-shifted by +π/7. This phase variation between the zones plays a crucial role in modifying the diffraction pattern, significantly affecting the overall point spread function (PSF) of the optical system. By employing distinct apodization filters in each zone—such as Bartlett, shaded, and Hanning filters—the aperture is shaped to manipulate light transmission and enhance image quality.

Figure 2(a) illustrates the intensity distribution for the case where the aperture is free from defocus and primary spherical aberration. When the apodization parameter is set to β = 0.6, the central maximum intensity is significantly enhanced compared to the standard Airy pattern. Additionally, the optical side lobes are effectively diminished, contributing to improved image quality.

Figures 2(b) to 2(f) demonstrate that as aberration and defocus parameters increase, the intensity of the central maxima also rises with the corresponding increase in the apodization parameter.

When the aperture is significantly defocused and affected by aberration, with $\phi d = \phi s = 2\pi$, the central lobe's intensity reaches its maximum for the highest apodisation value (β = 1), as shown in Figure 2(d).

Thus, under conditions of high spherical aberration and defocus, the central maximum intensity increases with the apodisation parameter, achieving its peak at β = 1 while also narrowing the width of the central lobe.

Table: 1

Table 1 Maxima And Minima Values For Three Zone Complex Aperture

A=0.3,B=0.6	**B**	**Central Maxima**		**First Minima**		**First Maxima**		**Second Minma**		**Second Maxima**	
		Pos	**Value**	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
	0.0	0	0.0389	2.6171	0.0000	4.4154	0.0096	6.2422	0.0028	8.5455	0.0115
	0.2	0	0.0062	2.4341	0.0000	4.7825	0.0032	5.4605	0.0031	8.4244	0.0083
$\Phi_d=\Phi_s=\Pi$	0.4	0	0.0300	3.2868	0.0001	7.1945	0.0084	-	-	-	-
	0.6	0	0.0854	3.232	0.0003	5.5734	0.0115	10.7531	0.0002	11.6882	0.0004
Complex Aperture	0.8	0	0.0413	3.4873	0.0001	6.0904	0.0103	-	-	-	-
	1.0	0	0.0148	2.6077	0.0017	4.5160	0.0042	5.1043	0.0042	7.3906	0.0073
	0.0	0	0.0390	2.7834	0.0003	4.9442	0.0122	7.8058	0.0017	10.0807	0.0054
	0.2	0	0.0131	2.8274	0.001	5.353	0.0065	8.0861	0.0037	9.0496	0.0039
$\Phi_d=\Phi_s=2\pi$	0.4	0	0.0077	4.7038	0.0002	7.6147	0.0106	-	-	-	-
	0.6	0	0.0331	4.6126	0.0005	7.6581	0.0133	-	-	-	-
Complex Aperture	0.8	0	0.0381	3.9256	0.0000	7.6461	0.007	0.0000	-	-	-
	1.0	0	0.0423	3.1638	0.0013	5.0097	0.0057	7.9676	0.0017	10.1413	0.0028

Table- 1 shows that when the aperture is significantly defocused and affected by aberration, with $\phi d = \phi s = 2\pi$, the central lobe's intensity reaches its maximum for the highest apodisation value (β = 1) by reducing the width of the central lobe and achieved super resolved point spread function.

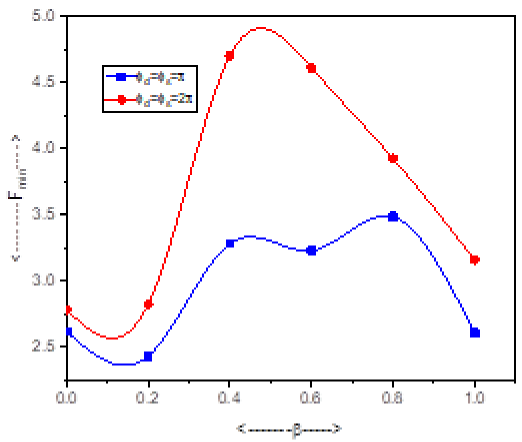

Fig: 3 Variation of Radius of First Dark Ring

Figure 3 depicts that when the aperture is significantly defocused and affected by aberration, with $\phi d = \phi s = 2\pi$, as apodisation increases the width of the central lobe decreases for high apodisation values.

III. Conclusions

The point spread function of a complex three-zone pupil function was studied in the presence of primary spherical aberration and defocus. Phase shifts of -π/5 in the second zone and +π/7 in the third zone were introduced, and apodization was applied using Bartlett, shaded, and Hanning amplitude filters in the respective zones. The objective was to enhance the central maximum's intensity, suppress side lobes, and minimize the radius of the first dark ring. The results showed a significant increase in central maxima intensity when the apodization parameter reached β = 1.0, when the aperture is highly defocused and affected by aberration, with $\phi d = \phi s = 2\pi$ and by effectively reducing the first dark ring's radius and also diminished side lobes.

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