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Optimization Of Central Zone Parameter For Defocused Optical System With Astigmatism And Primary Spherical Aberration

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Abstract:
To optimize the central zone parameters for minimizing the combined effects of astigmatism and primary spherical aberration, we employ a systematic approach involving numerical optimization techniques. We introduce a novel merit function that quantifies the extent of image degradation caused by defocus, astigmatism, and spherical aberration. This function serves as a comprehensive metric for evaluating system performance. Through an iterative optimization process, the central zone parameters are systematically adjusted to minimize the merit function, thereby enhancing image quality and correcting aberrations. The highest degree of the amplitude apodization parameter β leads to an enhancement in the lateral resolution of the central peak.

Keywords: *Point spread function, Optical aberrations, defocus, Primary Spherical aberration, Astigmatism, Central zone parameter.*

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I. Introduction

Point spread function (PSF) engineering refers to the purposeful manipulation of the light distribution within the focal region of an optical system. This methodology is employed to optimize and enhance the performance and efficiency of optical systems across a diverse array of applications. In recent years; researchers have been focused on the optimization of optical systems to mitigate the impact of these aberrations. One particular area of interest lies in the central zone parameter of defocused optical systems. The central zone parameter refers to the configuration and characteristics of the central portion of an optical system, which can have a profound influence on the behaviour of astigmatism and primary spherical aberration. Astigmatism occurs when different meridians of an optical system have different focal lengths, resulting in elongated or distorted images. On the other hand, primary spherical aberration arises due to the variation in focal lengths for rays passing through different zones of a lens or mirror. This leads to a deviation from the desired point focus, affecting the overall image quality. This study investigates the interplay between defocus, aberrations, and the Hanning amplitude filter in optical systems. By examining the effects of these factors on the PSF and subsequent image quality, we aim to demonstrate the utility of the Hanning amplitude filter in mitigating the negative impact of defocus and aberrations. Through theoretical analysis, computational simulations, and potentially experimental validation, we seek to contribute to the development of techniques for enhancing image quality in challenging optical scenarios [1-4]. These aberrations can result from manufacturing limitations, material properties, or misalignments in the optical system [5-11].

Optical aberrations come in various forms, including spherical aberration, chromatic aberration, coma, astigmatism, and distortion. Each type of aberration introduces specific distortions to the image, often leading to a cumulative effect that severely impacts the overall image quality [12-13]. Aberrations, as deviations from ideal optical behaviour, introduce distortions and imperfections in images. This research endeavours to delve into the intricate relationship between astigmatism, primary spherical aberration, and the central zone parameter in defocused optical systems. By comprehensively investigating the interplay between these factors, we aim to develop strategies for optimizing the central zone parameter to minimize aberration-induced image degradation and enhance overall system performance. Through a combination of theoretical analysis, this study seeks to contribute to the advancement of optical system design, with potential applications in fields where precise imaging and accurate diagnostics are crucial.

The outcome is an intensity distribution characterized by a point spread function exhibiting non-zero minima. Consequently, this leads to an undesirable image quality, marked by heightened intensity in the ring-like structure of the diffraction pattern. When the optical system encounters partial defocus and aberration, the impact of the highest value of the central zone parameter is observed to significantly enhance the intensity within the central lobe. This enhancement is accompanied by a redistribution of intensity. Importantly, this adjustment results in the emergence of a zero-intensity first minima, a key criterion in evaluating the quality of the point spread function.

II. Theory and Formulation

The amplitude impulse response of the pupil function in the presence of higher degrees of spherical aberration and defocusing, as described by equation (1), can be expressed in a generalized form as follows:

$$B(z) = \left\{2\left(\int_0^a f_1(r)e^{-i(\phi_d+\phi_s+\phi_a)}J_0(Zr)rd\right) + (Phase)\int_a^1 f_2(r)e^{-i(\phi_d+\phi_s+\phi_a)}J_0(Zr)rdr\right\} \quad [1]$$

Where $f_1(r)$ represents the Shaded amplitude pupil function, $f_2(r)$ represents the Hanning amplitude pupil function of the optical system. The variable Z is dimensionless and signifies the distance of the point of investigation from the centre of the diffraction field. $J_0(Zr)$ stands for the zero order Bessel function of the first kind, and 'r' denotes the reduced radial coordinate on the exit-pupil of the aberration-influenced optical system.

In this context, ϕ_d, ϕ_s and ϕ_a are the parameters for defocus, spherical aberration and astigmatism parameters, respectively. The current study focuses on considering pupil functions represented by the Shaded amplitude filter and the Hanning amplitude filter of the second order. These filters can be represented as follows:

$$f_1(r) = 1 - \beta r^2 \quad [2]$$

$$f_2(r) = cos(\pi\beta r) \quad [3]$$

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 A(Z), which is the measurable quantity, can be obtained by squaring the modulus of B(Z). Thus,

$$A(Z) = |B(Z)|^2 \quad [4]$$

III. Results and Discussion

The impact of a two-zone aperture shading on the images of point objects formed by coherent optical systems, which have been apodized by the Shaded and Hanning amplitude filters, has been explored. This investigation includes scenarios with the presence of defocus and higher-order spherical aberrations. The evaluation was conducted using the expression (4) and was facilitated through MATLAB simulations

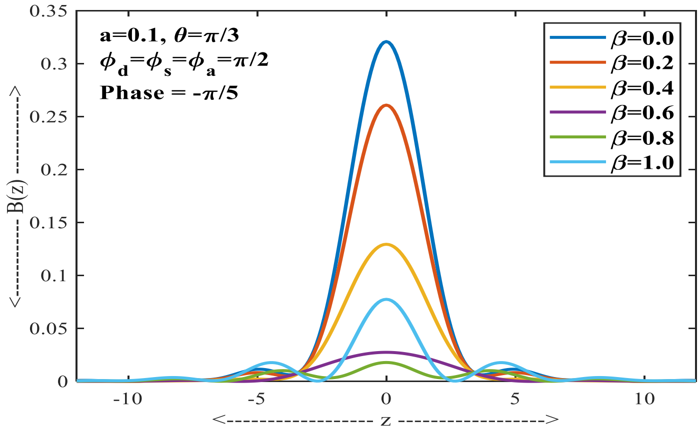

Figure (a)

Figure (b)

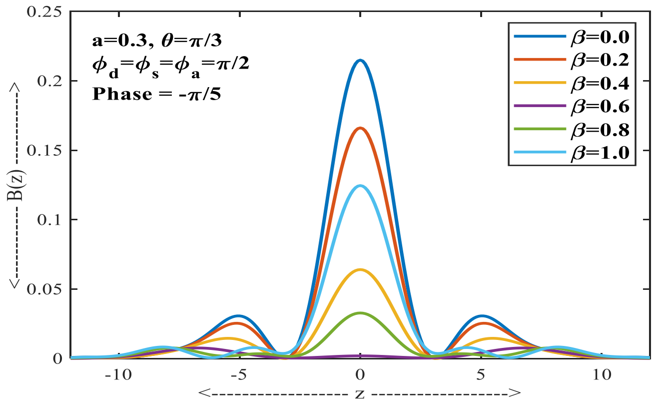

Figure (c)

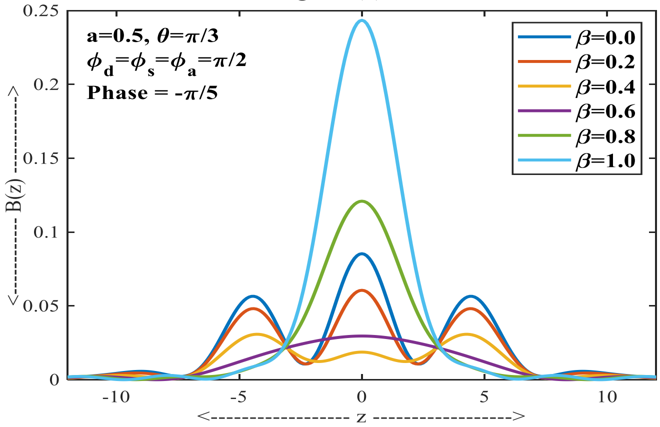

Figure (d)

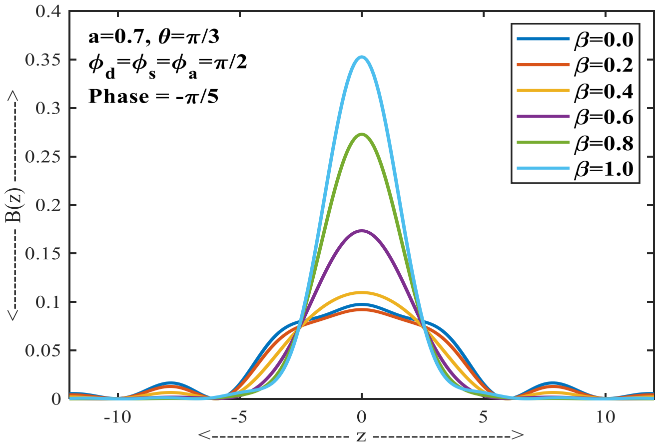

Figure (a),(b),(c) and (d) - Variation in the axial profile of the point spread function (PSF) is observed within a two-zone aperture configuration for different degree of apodization applied through Shaded filtering in the first zone and Hanning filtering in the second zone, all in the context of astigmatism and primary spherical aberration.

From the figures (a) to (d), a consistent pattern is observed that, when β is set to 0 (Airy pattern), and in the context of partial degrees of defocus, primary spherical aberration and astigmatism ($\phi_d = \phi s = \phi a = \pi/2$), accompanied by a phase change of $-\pi/5$, variations in the central zone parameter ('a'= 0.1, 0.3, 0.5 and 0.7) lead to a notable reduction in the peak intensity of the central maximum. As the central zone parameter 'a' increases, a notable enhancement in the intensity of the central maxima with minimised optical side-lobes, especially in the scenario where the highest degree of apodization, β =1, is applied.

IV. Conclusions

The findings of this study reveal that employing a combination of a shaded amplitude filter in the first zone and a Hanning amplitude filter in the second zone, along with a higher value of the central zone parameter (**a=0.7**), proves to be an effective strategy for achieving a super-resolved Point Spread Function (PSF). This effectiveness holds true even when dealing with elevated values of amplitude apodization ($\beta = 1$), and in the presence of factors such as defocus ($\phi_d = \pi/2$), primary spherical aberration ($\phi_s = \pi/2$), and astigmatism ($\phi_a= \pi/2$) with a phase change of $-\pi/5$ and an angle of $\theta = \pi/3$. In conclusion, it is emphasized that the two-zone aperture, characterized by a central zone parameter 'a' of 0.7 and the combined application of shaded and Hanning amplitude apodization filters, yields favorable outcomes concerning the intensity of the PSF, even when confronted with the combined influences of defocusing, primary spherical aberration, and astigmatism.

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