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Engineering Point Spread Function of Two Zone Aperture Optical Imaging System under the combined influence of Defocus and Spherical Aberrations

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Abstract. *The point spread function of the optical system in the presence of defocus and primary, secondary and tertiary spherical aberration with Hanning amplitude filter and Connes amplitude filter is studied. A noted increase in the profile of the point spread function has been achieved. Employment of the Hanning and Connes amplitude pupil functions under higher degree of spherical aberration and defocusing effect helps the optical systems increases the resolution. The lateral resolution of the central peak is improved by the highest degree of the amplitude apodization parameter β. The presence of first minima with zero intensity is achieved which is necessary for Rayleigh criterion that can be used to study two-point resolution.*

Keywords:*Point spread function; Amplitude apodization; Primary, Secondary and Tertiary spherical aberration; defocus; two-zone aperture; super-resolution.*

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I. INTRODUCTION

Point spread function (PSF) engineering is the modulation of the light distribution in the focal region of the optical system, exploited for improving the performance of optical systems employed in numerous applications [1–18]. This mechanism, demonstrated by inserting suitable phase or amplitude filter masks in the Fourier plane of the optical system, results in changes of the focal spot size and level of its surrounding side lobes [1–4]. Presence of optical aberrations generally degrades the performance of the optical system [5, 6]. In general, the detrimental effects of aberrations can be reduced by inserting an optical element with a suitable optical transmittance function [7–23]. However, in this case sidelobes were completely suppressed on one side of the PSF at the cost of enhanced sidelobes on the counter side, and the resultant PSF, being asymmetric, plays a vital role in confocal imaging [3]. Further, the proposed technique opens up possibility for pupil filters design and can be used to develop the off-axis imaging system in the areas of microscopy, telescopy and spectroscopy.Apodization is the process for removal of secondary side-lobes or side-bands in the diffraction field also known as the point spread function (PSF) which is required for any optical system to act as super resolver. And this can be acquired by properly choosing the transmittance of the pupil function of the optical system, the intensity around the focused fields can be totally suppressed or at least considerably reduced without increasing the dimensions of the pupil.

When the optical system is defocused or under the influence of aberrations the response of the image due toa point defect is highly distorted and the intensity in the central lobe is scatterd into the optical side lobes.

The resultant intensity distribution is a point spread function with non-zero minima thereby rendering the image to be greatly of undesirable nature with an increase in the intensity in the ring structure of the diffraction pattern. The influence of Hanning amplitude filter when the optical system is highly defocused and suffering from aberration is found to radically improve the intensityin the central lobe with redistribution of the intensity, with zero first minima, which forms one of the merit functions of the point spread function

In the current study, the imaging characteristics of the diffracted field of rotationally symmetric optical systems with Hanning and Connes amplitude filters have been investigated in terms of the reduction of secondary side-lobes by modifying the two zone aperture with different degrees of amplitude apodization β using defocus and primary, secondary and tertiary spherical aberrations. To study the imaging properties of the optical systems, the knowledge of the PSF is an important parameter in designing optical imaging systems.

The present study provides a significant contribution to the resolution studies. We know that by employing suitable apodization function, the point spread function in the maximum out-of-focus image plane can be modified according to the axial shape requirements. A suitable aperture of shading is very helpful to correct the Seidel aberration effect in the image plane of the optical system. Based on the investigations done in the two zone apodization process, it can be inferred that the Hanning amplitude filter in the outer zone and Connes amplitude filter in the inner zone could be the solution for modifying the point spread function of the optical system under the strong combined influence of defect-of-focus and primary spherical aberration. In the present study, we studied the two zone aperture with the second order Hanning and Connes amplitude mask, to modify the distribution of light radiation in the focal plane of an aberration made optical systems.

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II. Theory And Formulation

The generalized expression for the amplitude impulse response of the pupil function in the presence of higher degree of spherical aberration and defocusing equation (1) can be written as

$S(\emptyset_d, \emptyset_s, Z) = [2\int_0^a f_1(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \emptyset_s\right)\right] J_0(Zx)xdx + 2\int_a^1 f_2(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} +$ *Øs]0Zxxdx]2***(1)**

Where $f_1(x)$ is Connes amplitude pupil function,$f_2(x)$ is Hanning amplitude pupil function of the optical system;Zis the dimension less variable which forms the distance of the point of investigation from the center of the diffraction field; and $J_o(Zx)$ is the zero order Bessel function of the first kind**; 'x'** is the reduced radial coordinate on the exit-pupil of aberrations influenced optical system. Here Φ_d, Φ_s, are the defocus and the primary, secondary, tertiary spherical aberration parameters respectively. In current study, the pupil functions we have considered are Connes amplitude filter and Hanning filter of second order respectively which can be represented by

$$f_1(x) = (1 - \beta^2 x^2)^2 \textbf{(2)}$$
$$f_2(x) = cos(\pi\beta x) \textbf{(3)}$$

Where 'β'is the amplitude apodization parameter controlling the non-uniform transmission of the pupil function. The intensity PSF *B(Z)* which is the measurable quantity can be obtained by taking the squared modulus of S(Z). Thus,

$$B(Z) = |\boldsymbol{S(Z)}|^{\mathbf{2}} \textbf{(4)}$$

III. Results and Discussion

The investigations on the effect two zone aperture shading on the images of point objects formed by coherent optical systems apodized by the Hanning and Connes amplitude filters in the presence of defocus and higher order spherical aberrations have been evaluated using the expression (4) by employing Matlab simulation.

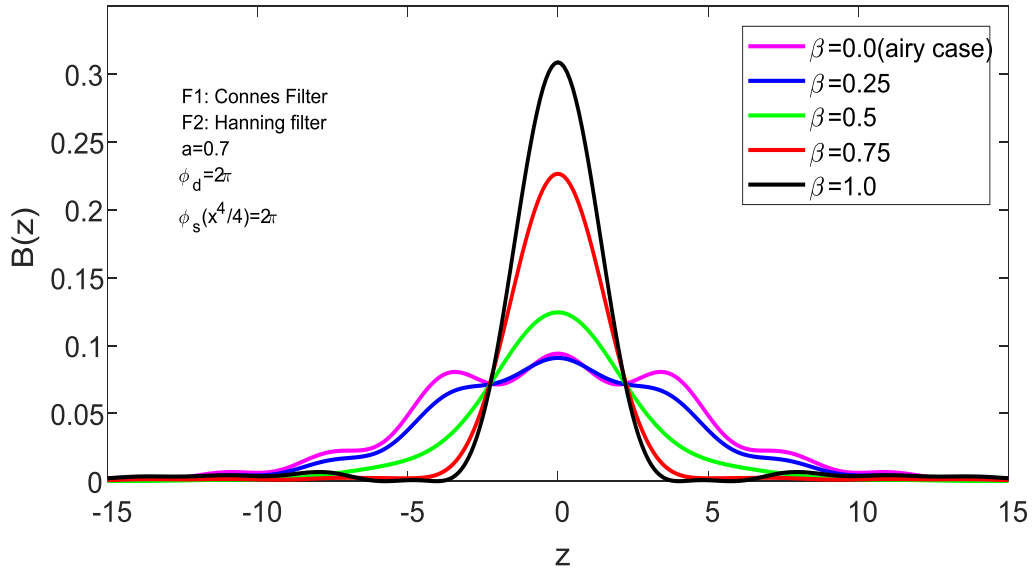

Figure 1

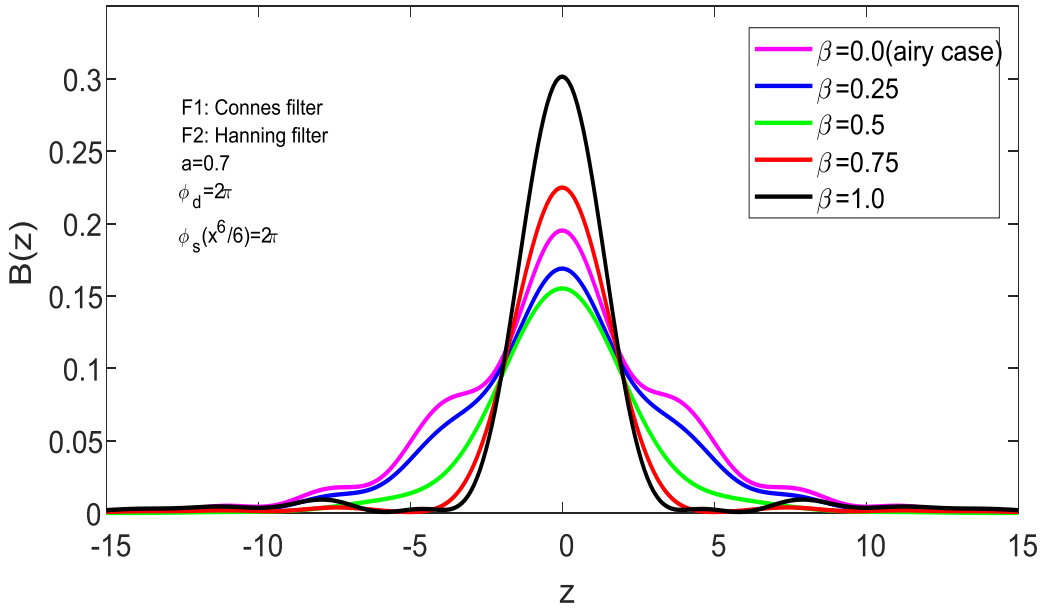

Figure 2

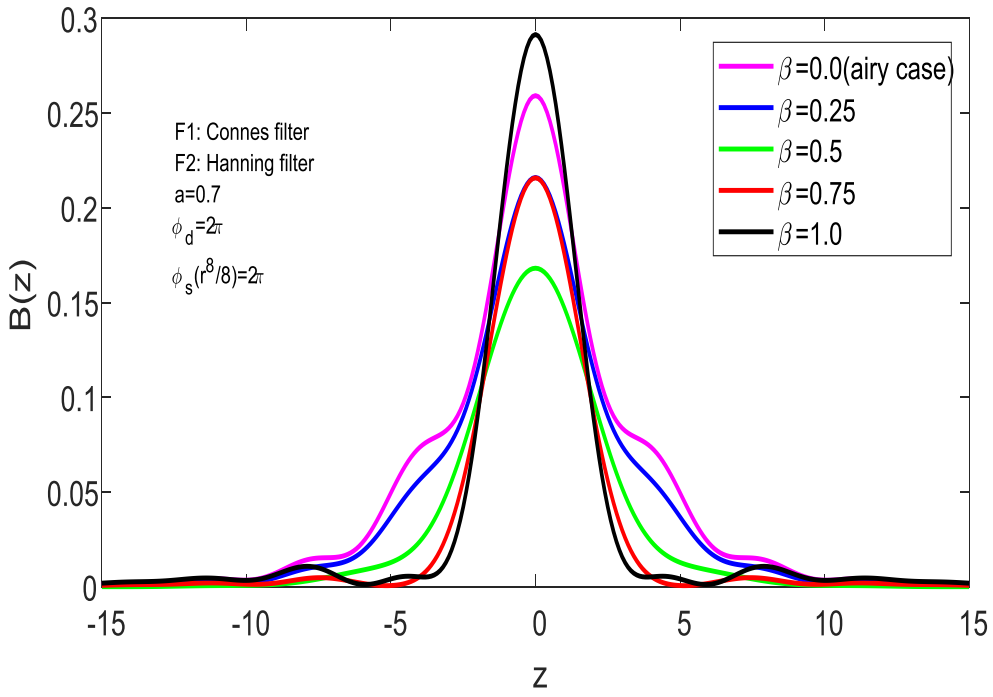

Figure 3

Figure (1-3):Variation in the axial shape of the point spread function of two zone aperture for different degrees of Connes filter(first zone) (0-0.7)and Hanning filter(second zone) (0.7-1)apodization for primary, secondary and tertiary spherical aberration.

From figures 1to 3, It is observed that for β = 0 (Airy), in the presence of high degree spherical aberration ($\phi_s = 2\pi$) the peak intensity of the central maximum is decreased for the maximum out-of-focus plane ($\phi_d = 2\pi$). The Airy PSF lost its axial shape or resolution and non-zero first minima. Similar pattern are noticed in the case of β = 0.25and β = 0.5. For β = 0.5, the main peak intensity starts to increase,whereas for β = 0.75, the first minima and the side-lobes on the both sides of the main peak reaches to zero intensity and the intensity of the main peak is considerably improved. It helps in detection of the direct image of the faint companion in every direction around the bright companion, known as two-point resolution studies. In the presence of defocusing effect and primary spherical aberration, as the degree of apodization increases from 0.5 to1 (as shown in the Figure 1, there exists a consistent improvement in the lateral resolution of the main peak .It is evident that for highest degree of amplitudeapodization (β = 1), the central light flux exhibit maximum intensity compared to that of Airy case (β = 0) and along with zero intensity in the first minima is measured, resulting in super resolved point spread function than in the presence of secondary and tertiary spherical aberration (Figure 2 -3).

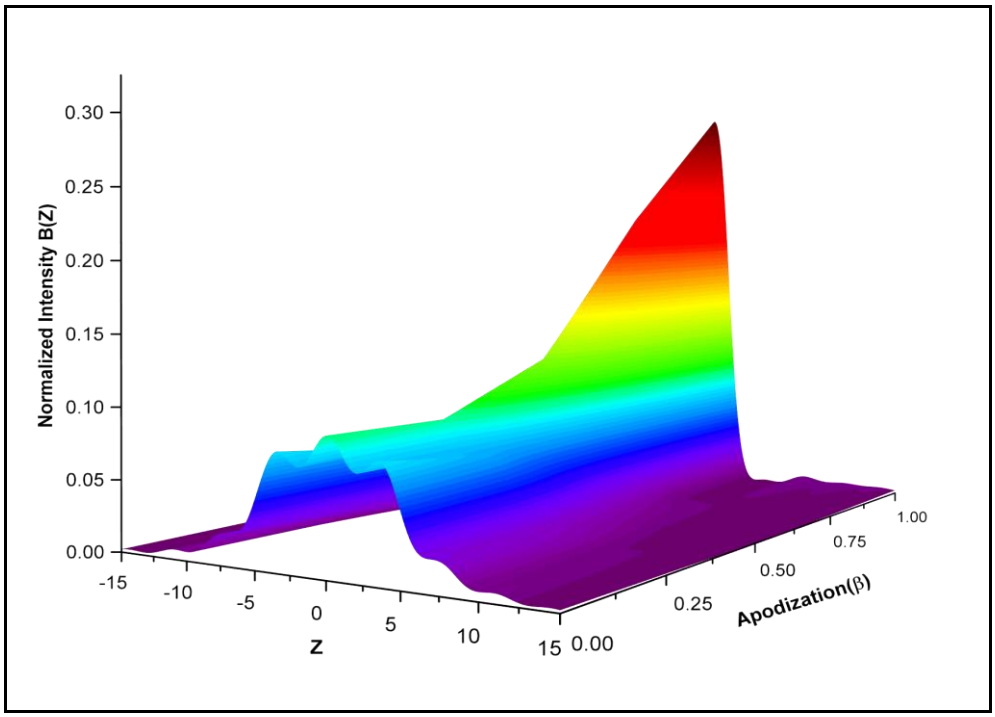

Figure 4

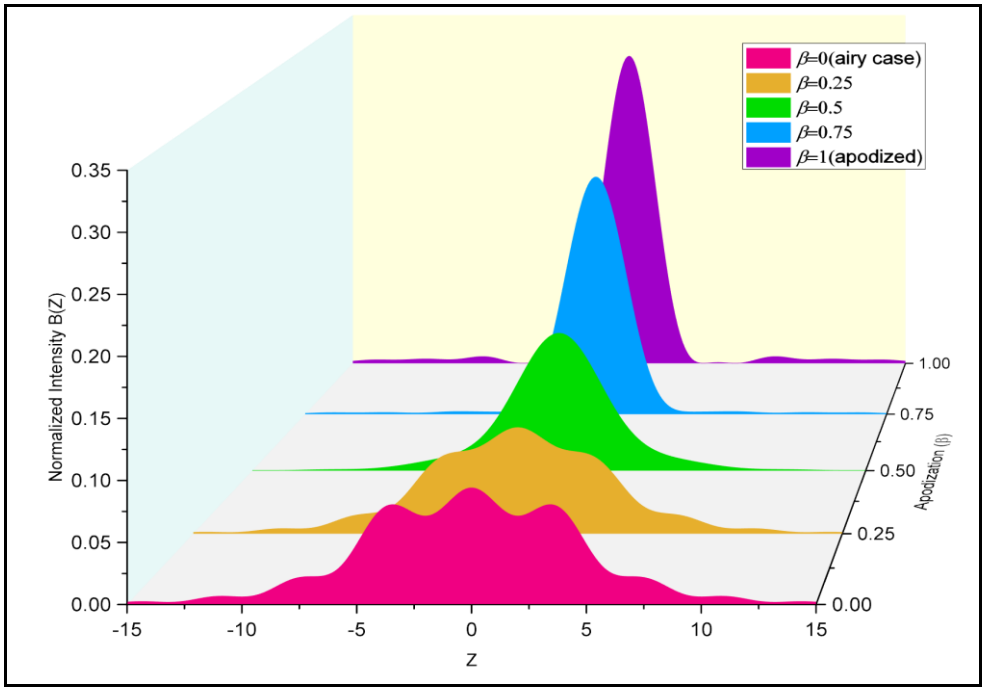

Figure 5

Figure (4-5): 3D graphs of the PSF for various values of apodization parameter *β* under the influence of high degree of defocus and primary spherical aberration

IV. Conclusions

From the present work, it is found that employing combination of Connes amplitude filter (from 0 to 0.7) and Hanning amplitude filter (from 0.7 to 1) is effective in achieving a super-resolved PSF for higher values of amplitude apodization ($\beta = 1$), even in the presence of high degree of defocus($\phi_d = 2\pi$) and primary spherical aberration ($\phi_s = 2\pi$). The process of apodizing the optical system, suppresses the optical side-lobes. For $\beta = 0.75$, the side-lobes are almost eliminated. For $\beta = 1$, the axial shape and the lateral resolution of the PSF is modified into the required module of maximum intensity and suppressed side lobes. On the whole it is emphasized that, the two zone aperture with the combined Connes and Hanning amplitude apodization filters has got good results in terms of the intensity of PSF under the combined influence of defocusing effect and the primary spherical aberration.

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