Tailoring the point spread function of an aberrated optical imaging system with Hanning aperture

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Abstract

The point spread function of the optical system in the presence of defocusing effect and the third order wave aberration such as primary spherical aberration with the Hanning amplitude mask is investigated. A significant improvement in the profile of the point spread function has been achieved. Employment of the Hanning amplitude pupil function under the higher degree of spherical aberration and defocusing situation renders the optical systems to perform like a super-resolver. The lateral resolution of the central peak is made to be improved by the highest degree of the amplitude apodization β. The presence of first minima with zero intensity suits the optical system for Rayleigh criterion to be applied for two-point resolution studies.

Keywords: point spread function; amplitude apodization; primary spherical aberration; defocus; Hanning function; super-resolution.

1. Introduction

In the present scenario, where there is a huge surge of advancement of optics probing into all forms of technological development, especially in the field of imaging and communications, the suppression of secondary side-lobes or side-bands in the diffraction field also known as the point spread function (PSF) are highly desirable in measuring the ability of an instrument. The process of achieving this is known as apodization. By properly choosing the transmittance of the pupil function of the optical system, the intensity in the periphery of the focused fields can be totally suppressed or at least considerably reduced without increasing the dimensions of the pupil. In the current study, the imaging characteristics of the diffracted field of rotationally symmetric optical systems with the Hanning amplitude filters have been investigated in terms of the reduction of secondary side-lobes by modifying the circular aperture into the symmetric amplitude mask with different degrees of amplitude apodization β. Hence, the study of imaging properties of the optical systems from the knowledge of the PSF has become an important means in the design of optical imaging systems. There have been a number of studies involving apodization for different aberration considerations [1-20]. The present study provides a significant contribution to the resolution studies and restricted within the diffraction limits of the optical system. It is known that the wave aberrations are originated due to the deviations of light from geometrical optics. The monochromatic spherical aberrations may also produce from the pupils. It is understood 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 deep mechanism in the apodization process, we understood that the Hanning amplitude filter could 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 circular pupil with the second order Hanning amplitude mask, to modify the distribution of light radiation in the focal plane of an aberrations made optical systems.

2. Theory

The present study is projected to evaluate the effect of the Hanning amplitude filter on the optical system which is under the combined influence of high Seidel aberration and maximum defect of focus. The Hanning amplitude mask is placed over the exit of the circular pupil of the apodised optical system. The point spread function is subjected to a higher degree of defocusing and primary wave aberration effect. The far-field diffraction characteristics due to the shaded circular aperture in an optical imaging system can be derived from its amplitude response or the amplitude PSF. The diffraction field contributing by the symmetric amplitude filter is given by:

$$S(Z) = 2\int_0^1 f\left(x\right) J_0\left(Zx\right) x dx \qquad (1)$$

Where *f(x)* is the amplitude mask pupil function of the optical system; Z is the dimension less variable which forms the distance of the point of investigation from the centre of the diffraction field; and $J_0(Zx)$ 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.
The general expression for the Hanning amplitude mask of the circular pupil function is written as:

$$S(Z)=2\int_0^1 f(x)J_0(Zx)xdx \qquad (2)$$

The generalized expression for the amplitude impulse response of the pupil function in the presence of higher degree of primary spherical aberration and defocusing can be written as:

$$S(\phi_d,\phi_s,Z)=2\int_0^1 f(x)\exp\left[-i\left(\phi_d\frac{x^2}{2}+\frac{1}{4}\phi_s x^4\right)\right]J_0(Zx)xdx \qquad (3)$$

Here ϕ_d, ϕ_s are the defect-of-focus and the primary spherical aberration parameters. In the present study, we have considered the Hanning amplitude filter of second order, which is also known as Hanning window or aperture whose pupil function can be represented by:

$$f(x)=Cos(\pi\beta x) \qquad (4)$$

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

$$I(Z)=|S(Z)|^2 \qquad (5)$$

3. Results

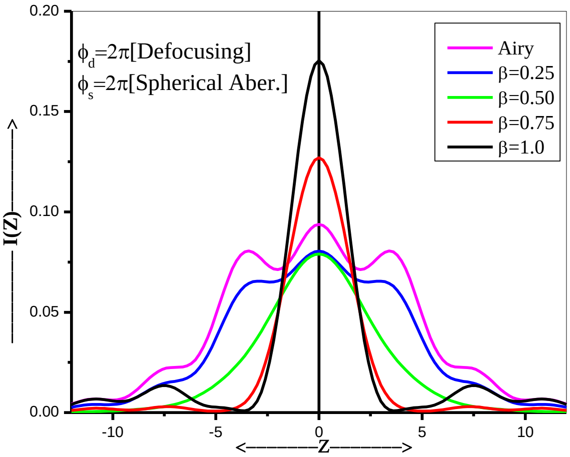

Fig.1. Variation in the axial shape of the point spread function for different degrees of Hanning amplitude apodization.

The investigations on the intensity distribution in the Point Spread Function of the apodised optical system has been obtained, using the equations (4) and (5) for the Hanning amplitude apertures, by using simulation program to study the effects of the Hanning amplitude apodization, defect-of-focus and the primary spherical aberration on the imaging efficiency of optical imaging systems. The Hanning amplitude apodization controlling parameter β varies from 0 to 1 in steps of 0.25. With β = 0 the optical system is said to be apodization free optical system and for the values of β ≠ 0 represents the apodised system. β = 0, corresponds to the Airy pattern (perfect lens). The influence of defect-of-focus (ϕ_d) on the optical system aberrated with the primary spherical aberration (ϕ_s) is investigated analytically for various degrees of the Hanning amplitude apodization β. Fig.1 explains the intensity distribution profile for the Hanning amplitude mask when the optical system is subjected to the combined influence of high degrees of the primary spherical aberration as well as defect-of-focus.

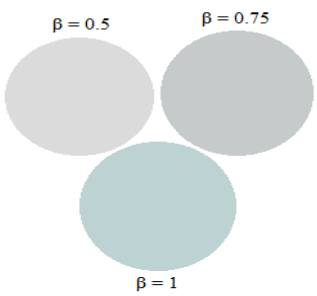

Fig.2. Scheme of Hanning amplitude masking in the pupil function.

It is observed that for β = 0 (Airy), in the presence of high degree spherical aberration (ϕ_s = 2π) the peak intensity of the principal maximum is decreased in low value for the maximum out-of-focus plane (ϕ_d = 2π). Here the Airy PSF is almost mislaid its axial shape or resolution and also found with non-zero first minima and similar trend results are noticed in the case of $\beta = 0.25$. For $\beta = 0.5$, the first minima and the side-lobes approaches to the zero level of intensity and the main peak intensity is starting to increase. Whereas for $\beta = 0.75$, the first minima and the side-lobes on the both sides of the main peak reaches the zero intensity level and the intensity of the main peak is considerably improved. It facilitates to the 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 third order wave-aberration, as the degree of apodization increases from 0.5 to1(as shown in the Fig.2), there exists a consistent improvement in the lateral resolution of the main peak It is clearly observed that for highest degree of apodization ($\beta = 1$), the central light flux exhibit high intensity compared to that of Airy case ($\beta = 0$) and along with zero intensity in the first minima is measured as Radius of the first dark ring, resulting in superresolved point spread function. For the highest degree of amplitude apodization ($\beta = 1$), The FWHM of the main peak obtains lower value than any other case in the Fig.1, concludes that the lateral resolution of the aberrations made PSF is technically improved by the optimum Hanning amplitude apodization.

4. Conclusion

It concludes that Hanning amplitude filter is effective in realizing a super-resolved PSF for higher values of amplitude apodization ($\beta = 1$), defocusing ($\phi_d = 2\pi$) and the primary spherical aberration ($\phi_s = 2\pi$). The process of apodising the optical system, suppresses fully or partially the optical side-lobes. For $\beta = 0.5$, these side-lobes are eliminated. For $\beta = 0.75$, the axial shape and the lateral resolution of the PSF is modified into the required component. On the whole it is emphasized that the Hanning amplitude mask pupil function has better response in terms of the intensity in the central lobe for the optical system under the combined influence of defocusing effect and the primary spherical aberration.

References

[1] Mills, JP. Thompson, BJ. Selected papers on apodization:coherent optical systems - Washington: “SPIE Optical Engineering Press” Publisher, 1996. – Vol.119.

[2] Jacquinot, P. Roizen-dossier, B. Apodization. Progress in Optics, 1964. - Vol.3. – P. 29-32.

[3] Barakat, R. Application of apodization to increase Two-point resolution by Sparrow criterion under incoherent illumination. J. Opt. Soc. Am., 1962. – Vol.52. – P. 276-283.

[4] Barakat, R. Solution to the Lunenberg Apodization problems. J. Opt. Soc. Am., 1962. – Vol.52. – P. 264-272.

[5] Khonina, SN. Ustinov, AV., and Pelevina, EA. Analysis of wave aberration influence on reducing the focal spot size in a High-aperture focusing system. J. Opt., 2011. – Vol.13. – 13pp.

[6] Falconi, O. The limits to which double lines, Double stars, and Disks can be resolved and measured. J. Opt. Soc. Am., 1967. – Vol.57(8). – P. 987.

[7] Hopkins, HH. Zalar, B. Aberration tolerances based on Line spread function. J. Mod. Opt., 1987. – Vol.34(3). – P. 371-406.

[8] Gupta, AK. Singh, K. Partially coherent far-field diffraction in the presence of primary astigmatism. Can. J. Phys., 1978. – Vol.56. – P. 1539-1544.

[9] Andrew Watson, B. Computing human optical Point spread functions. Journal of Vision, 2015. – Vol.15(2). – P. 1-25.

[10] Khorin, PA. Khonina, SN. Karsakov, AV. Branchevskiy, SL. Analysis of corneal aberration of the human eye. Computer Optics, 2016. – Vol. 40(6). – P. 810-817.

[11] Asakura, T. Resolution of two unequally bright points with partially coherent light. Nouv. Rev. Opt., 1974. – Vol.5(3). – P. 169-177.

[12] Asakura, T. Ueno, T. Apodization for increasing two-point resolution by the sparrow criterion under the partially coherent illumination. Nouv. Rev. Opt., 1974. – Vol.5(6). – P. 349-359.

[13] Karuna Sagar, D. Sayanna, R. and Goud, SL. Effects of defocusing on the sparrow limits for apodized optical systems. Opt. Commun., 2003. – Vol.217. – P. 59-67.

[14] Naresh Kumar Reddy, A. Karuna Sagar, D. Point spread function of optical systems apodised by a semicircular array of 2D Aperture functions with asymmetric apodization. Journal of Information and Communication Convergence Engineering, 2012. – Vol.12(2). – P. 83-88.

[15] Keshavulu Goud, M. Komala, R. Naresh Kumar Reddy, A. and Goud, SL. Point spread function of asymmetrically apodised optical systems with complex Pupil filters. Acta Physica Polonica A, 2012. – Vol.122(1). – P. 90-95.

[16] Kowalczyk, M. Zapata-Rodriguez, CJ. Martinez-Corral, M. Asymmetric apodization in confocal scanning systems. Applied Optics, 1998. – Vol.37(35). – P. 8206-8214.

[17] Siu, GG. Cheng, L. Chiu, DS. Improved side-lobe suppression in asymmetric apodization. J. Phys. D: Applied Physics, 1994. – Vol.27(3). – P. 459-463.

[18] Cheng, L. Siu,GG. Asymmetric apodization. Measurement and Technology, 1991. – Vol.2(3). – P. 198-202.

[19] Naresh Kumar Reddy, A. Karuna Sagar, D. Defocused point spread function of asymmetrically apodized optical systems with slit apertures. Journal of Biomedical Photonics & Eng., 2016. – Vol.2(3). – P. 1-6.

[20] Naresh Kumar Reddy, A. Karuna Sagar, D. Spherical aberration of point spread function with Asymmetric pupil mask. Advances in Optical technologies, 2016. – Vol.2016. – P.1-5.