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Analysis of Intensity Distribution in the Image Plane for Various Focus Errors in an Optical System Illuminated by Coherent Light Utilizing a Circular Aperture

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ABSTRACT

One common kind of aberration in optical systems that can seriously impair the quality of the images that are taken is focus errors. The objective of this study is to assess the impact of focus errors on the distribution of intensity in the image plane of the optical system, which is composed of a circular area nature. The Zernike coefficient W20 is used to compute quantitatively defined focus errors, and the results are verified both experimentally and through simulations that use the Fresnel diffraction integral. In excellent agreement with the theoretical prediction, the measurement results confirm that the fault-free optical system generates a central peak of higher intensity (Airy disk) surrounded by a Pearly ring structure of lower intensity (Airy rings). The phenomenon of Airy rings becomes more noticeable as the central peak tends to smear more and lose intensity from W20 = 0.25 to W20 = 1.25. The image quality consequently deteriorates over time. With an NRMS error of less than 0.1 for every position error condition, the experimental results exhibit a trend that is comparable to the modulated (simulated) intensity distributions. Low-quality imaging is caused by focus errors, which play a critical role in the design, optimization, and characterization of optical systems. This offers a variety of approaches to enhance computational imaging methods and create the best possible optical designs.

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1. Introduction

Numerous applications, from imaging and microscopy to optical metrology and laser material processing, depend on an understanding of the intensity distribution in optical systems. An optical system's performance level in terms of resolution, clarity, and the quality of the image it produces is determined by intensity distributions in the image plane (Zuo et al., 2015).

There are various optical systems with apertures, but one element that demands attention is the circular aperture. This part regulates the spot size in the image plane and modifies the distribution of light. Because of their symmetry and capacity to regulate the spatial frequencies of light, lenses with open-ended metrical implementation are a common feature (Reddy et al., 2016). From the middle to the edge, the aperture's size and light intensity decrease, which is typically too much for the human brain to process. As a result, the image that the subject sees will differ from the actual image.

It is very important to examine the intensity distribution in the image plane of an optical system that is illuminated by coherent and has a circular aperture for a number of reasons. In the first place, it provides invaluable insights into optics, helping to explain how light travels and how images are formed when aberrations and apertures are present (Zuo et al., 2017). Researchers and engineers can increase the accuracy of their predictions and simulations of optical systems and the efficacy of their solutions by understanding those principles. Furthermore, precise measurement establishes the basis for the system's adjustment to sophisticated imaging technologies and algorithms that can correct for all focusing errors and improve the quality of the images. In particular, ptychography is used to correct aberrations in lenses by modulating phase information by measuring the light's intensity (Picazo-Bueno et al., 2023; Ou et al., 2015). To obtain better spatial and quantitative images, they are based on a thorough understanding of the superposition grain distribution rather than being a qualitative indetermination.

Applications like structured illumination microscopy, laser material processing, and optical trapping that demand exact control over the light intensity profile depend on an understanding of the intensity distribution (Tian & Waller, 2015). Astigmatism generation and aperture hiding are achieved in such a way that an accurate spot can be produced with sufficient efficiency for most, if not all, visible purposes. In light of this, understanding the intensity distribution in the presence of aberration errors and circular apertures will be beneficial as it will aid in the creation of new optical tools and applications. In other words, the aperture function of the system could be changed to improve its resolution, depth of focus, or light efficiency by using the apodization mask or the phase mask (Naresh & Khonina, 2018; Dubey et al., 2020). However, these discoveries have the potential to have a substantial impact on a number of fields, including scientific research, medical imaging, and optical metrology.

Because of their symmetry and capacity to regulate the spatial frequency content of light, circular apertures are frequently employed in optical systems. The optical pattern of the core of the Airy disk, which consists of a central bright spot encircled by intricate rings of dimming intensity, is made possible by a circular aperture transmitted with coherent light (Yang et al., 2016).

These studies have also contributed to the development of optical systems, such as imaging and computing techniques, which have improved the quality and resolution of images. We can't let both exist simultaneously. In a similar vein, anisotropic crystals and circular polarizers have brought sophisticated new optical components and techniques. As an example, the apodization technique is used to reduce side lobes, enhance contrast, or extend focus depth in imaging systems. It is achieved by altering the aperture opening using amplitude or phase masks (Reddy et al., 2024).

The study aims to investigate the effects of various focus errors and examine the intensity distribution in an image plane of an optical system in terms of coherent illumination and focusing. Undefined

1. To depict diagrammatically the intensity distribution of an aberration free optical system, i.e., system operating with a circular aperture and illuminated by coherent light. In this way, a reference will be made to demonstrate the influence of focus errors on the assemblage of intensity.

2. To investigate the influence of several optical aberrations, characterized by the Zernike coefficient W20, on the distribution of the intensity in the image plane. The research will carry out a comprehensive study on this topic by exploring w20 values which include values like 0, 0.25,0.5,0.75,1, and 1.25.

2. Method

The purpose of optical systems is to control and manipulate light in order to create images, take measurements, or carry out particular tasks. The basic laws of optics—refraction, diffusion, refraction, and interference—are the basis for the phenomena underlying optical systems and image formation (Born & Wolf, 2013). Understanding the rules makes it easier to predict the resulting light patterns and analyze how light affects optical systems. Wavefront propagation theory is the key to operating optical systems. According to Goodman (2017), light is a figurative surface with a constant phase that is oriented perpendicular to the direction of motion. The distance between the optical components (lenses, mirrors, and apertures) affects how the wavefront behaves when light passes through an optical system. These changes are the basic processes that give the wavefront's form and characteristics on the image plane their shape. Ultimately, this is what regulates the image's intensity distribution.

According to the Huygens-Fresnel principle, each point on a wavefront functions as a secondary source of spherical waves, and the wavefront at any given time is the envelope of these secondary waves. This principle is one of the fundamentals of image formation (Born & Wolf, 2013). This principle describes the algorithm for determining the diffracted field anywhere in space using an initial wavefront that is supplied along with the characterization of the optical system. One option is to maintain the complex amplitude of the diffracted field intact when using the Huygens-Fresnel principle to solve the Fresnel diffraction integral (Goodman, 2017). The point spread function (PSF) is another element that consumes a large share of image formation theory. PSF shows how the optical system works with a point source of light, demonstrating a type of impulse response of that system. (Mahajan, 2011). In an ideal scene, the PSF would be an essentially small point of light, resulting in a perfect image. Nevertheless, considering the wave nature of light and Internet aberrations, the PSF will have a finite shape and not zero dimension, which restricts the formed image resolution and quality. At the same time, the Fourier transform of PSF gives such overall system characterization as optical transfer function (OTF), which describes the system's ability to pass spatial frequencies from an object plane to an image plane (Goodman, 2017).

In the creation of images, coherence is essential, particularly when working with coherent light sources like lasers. According to Mandel and Wolf (1995), coherence is the ability of wavelets to interfere with one another in either a constructive or destructive way, depending on how they phase. Temporal coherence is the correlation between the waves at a single point in time, while spatial coherence is the correlation between the various points on the wavefront. The type of interference patterns that are seen on the image plane are determined by the level of coherence, which also affects resolution and contrast. As a result, the quality of the image that is created may suffer (Zuo et al., 2015).

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In the presence of coherent illumination, the image formation process is described by the complex amplitude of the wavefront rather than just the intensity (Born & Wolf, 2013).

2.2: Focus Errors and Their Impact on Image Quality

One common aberration in optical systems that can seriously impair image quality is focus errors, also referred to as defocus aberrations. When these errors happen, the light wavefront is distorted away from the spherical or even profile, which leads to poor imaging quality (2001). To effectively design highly functional optical systems, it is essential to understand the nature of undesired diffraction and spherical aberration effects and how they affect image quality. According to Booth (2014), variations in the optical path length brought on by unfavorable environmental conditions can also cause focus errors, in addition to manufacturing flaws in optical elements and misalignment of optical components. If all of the rays, which start in the object plane as points, converge to a single point in the image plane, a sharp and clear picture will be formed. Unfortunately, in the presence of photon glitches, the rays do not converge ideally causing an image to be blurry and out of focus.

The severity of focus errors is often quantified using Zernike polynomials, a set of orthogonal functions that describe the wavefront aberrations in a standardized manner (Thibos et al., 2002). The Zernike coefficient W20 also called the defocus term, reflects how much defocus has been incorporated into the system. A positive W20 value indicates positive defocus, where the focal plane is located within the optical system. In contrast, a negative value usually stands for negative defocus, where that focal plane is beyond the optics system. Focus errors are unavoidable; this can be realized by the study of the Point Spread Function (PSF) of the imaging optics. Deviation from the Airy disk in defocus gives PSF a blurred look, with diameter thinner and broader (Mahajan, 2011). As a result of the enlargement of the image field limit, the resolution is reduced significantly because the object appears less defined. The greater the bokeh, the more pronounced side effects like image blurring and lessened clarity.

Focus errors also affect the contrast and clarity of the image. Due to the widening of the PSF beam width, the contrast of the nearby features in the image gets reduced, making the task more complex (like distinguishing between them) (Booth, 2014). This decreases the contrast when focusing on high-frequency details, as it's common for the edges and textures to be more influenced by the blur effect.

Not only can focus errors affect contrast and resolution, but they can also cause distortions and artifacts in the image. For example, when imaging with coherent light, defocus may result in the formation of fringes or halos from the white light surrounding the bright objects (Born & Wolf, 2013). The resolution of the image may be decreased as a result of these pixels obstructing important information. Focus errors frequently coexist with other aberrations, such as spherical aberration, coma, and astigmatism, in real optical systems (Mahajan, 2011). However, these distortions and defocusing weaken each other in a combined sense, increasing the image distortion. When there are many errors at the same time, they can cause a drastic decrease in the lens's overall quality, which means it cannot be used to produce quality images.

2.3: Circular Apertures and Their Role in Optical Systems

In optical systems, circular apertures are frequently employed to modulate the spatial frequency content of the image and regulate the spatial extent and shape of the light beam. The aperture quickly and effectively affects depth of field, flicker-free image resolution, and system performance (Mahajan, 2011). A solid understanding of the properties and advantages of circular apertures is essential for the efficient design, improved functionality, and use of optic systems in a variety of applications. This kind of task can be completed by the spheric lens sot. It restricts the angular range of light rays that pass through the optical system. The system's efficiency in gathering light is determined by the aperture's size in relation to the focal length (Born & Wolf, 2013). The NA is a definition of the light-gathering ability of the system, the proportional product of the refractive index of the medium, and the half-angle of the cone of light on which the laser works. More enormous numerical aperture light cones and maximum safe zones increase; however, the depth of focus simultaneously gets smaller.

The point spread function (PSF) of an ideal, aberration-free optical system is the Airy disk pattern, which is created when light is diffraction by a circular aperture (Airy, 1835). The center bright lobe of the Airy disk is encircled by a ring of bands of alternating brightness and darkness. The wavelength of the light and the NA of the system determine the size of the Airy disk. Airy disks are larger when the apertures are smaller. The Airy disk represents the ultimate limiting resolution of the optical system, which is the minor point at which a light beam can be focused.

When the center of one point's Airy disk falls on the first dark ring of the other point's Airy disk, two points are just resolvable, according to the Rayleigh criterion, which controls the resolving power of an optical system with a circular aperture (Rayleigh, 1879). This is used as a source to determine the minimum distance between two points of measurement, and it also depends on the system's NA and the light's wavelength. A shallow depth of field is a drawback of increasing the NA by increasing the focal length f or the medium's refractive index (n), which results in an improved resolving power. In addition, when the pupil is disc-shaped, i.e. temporally, the apertures act as a low-spatial frequency filter, which blocks or attenuates frequencies higher than it and lets low frequencies pass through (Goodman, 2017). This is precisely why the image's depth of contrast and sharpness are critical points, as they may change the entire ecosystem. Narrow apertures are characterized by reduced cutoff frequency, having more considerable attenuation of high-frequency information, and producing pictures with softer focus and blur. Next, the differences between a small and large aperture are addressed. In this case, the small aperture will only allow low-frequency components to pass, while the large aperture will permit more high-frequency components to pass through, creating pictures with better contrast and sharpness.

Circular apertures have an effect on the optical system's depth of field in addition to resolution and spatial frequency filtering. According to Merklinger (1992), field depth can be defined as the range of object distances over which the corresponding objects can be focused. This is a more comprehensive range of focus position because the cone of light from each point has a narrower opening. In addition, the wider aperture leads to a reduced depth of field and, as a result, more significant effects on focusing to attain sharpness throughout the image plane. The wavefront is formed and light propagation is controlled by a circular aperture in conjunction with other optical components such as lenses and mirrors. Take, for instance, the circular aperture of the system, which is located at the entrance pupil plane; the image of the aperture stop is seen as observed from the object space (Born & Wolf, 2013). The entrance pupil size and its position, in combination, determine the field of view and the angular resolution of the system.

In order to accomplish particular optical effects, the circular aperture is occasionally purposefully altered. Apodization is among them. This happens when you avoid the airy disk by using an indirect or patterned aperture. It improves the image by decreasing the intensity of the side lobes and increasing the contrast and dynamic range (Jacquinot & Roizen-Dossier, 1964). Furthermore, apodization techniques can only be used to control the side lobes when forming the system for a particular task (Martinez, 1986). According to Pawley (2006), Gustafsson (2000), and Betzig et al. (2006), the pupils are also an essential component of the system of optical factors that create circular apertures and are used in a variety of applications, such as confocal microscopy and structured illumination microscopy. Instead of using circular apertures, brain imaging devices use more complex apertures. To improve the system's resolution, contrast, or depth sectioning, they could be shaped like circles, annular rings, or spirals. Additionally, circular apertures and coherent illumination can aid in the realization of advanced imaging modalities like coherent diffractive imaging and Fourier ptychography as other astrophysical imaging modalities are induced (Miao et al., 1999; Zheng et al., 2013). These methods generate high-resolution images of the object by utilizing the diffraction patterns the circular aperture produces. When the aperture is less than the wavelength, though, that is not the case.

3.1 Experimental Setup:

Two major research methods include performing experimental measurements, combining them with computational simulations, and performing thorough validation. Through this, it is possible to understand the effect of focus errors on the intensity distribution in the image plane. Using this approach, we can perform a detailed analysis of the abnormality of the relationship between the abnormality in the main focus error and the pattern of formation of an intensity. It comes in handy when designing and fine-tuning optical systems.

The following essential elements make up the experimental setup for examining the intensity distribution in the image plane of an optical system with focus errors. Because of its high spatial and temporal coherence, the original light source was a helium-neon (He-Ne) laser with a wavelength of 632.8 nm (Siegman, 1986). The beam has been expanded and separated using a beam expanding system that consists of a 200mm focal length plano-convex lens and a 10× microscope objective lens. All of the circular aperture area is covered by these lenses, which increase the beam diameter by up to 20 mm.

The circular aperture is a 1 mm diameter precision pinhole that is positioned precisely by being mounted on a three-axis translation stage. The compromise between the maximum intensity of the transmitted light and the spatial size of the diffraction pattern where the light is to pass through is used to estimate the size of the pinhole (Born & Wolf, 2013). To provide continuous illumination for the incident beam, a work coil positioned perpendicular to the seed beam is used. The focusing errors are shown onto the optical system to introduce an apparent aberration curve using a set of optical aberration plates. This set of glass plates replicates various errors defined by the Zernike co-efficient W20 because it has an identical surface profile (Mahajan, 2011). A thorough investigation of the intensity distribution levels caused by and associated with focus errors is made possible by the aberration plates that are positioned between the image plane and the circular aperture.

The image plane detector is a high-resolution CMOS camera with a sensor size of 2048 × 2048 pixels and a pixel size of 5.5 μm. In order to control the distance between the apertures with respect to the image plane, the camera is fixed on a linear translation stage, which allows for precise movement. Cables are used to collect and process data between the computer and the camera.

3.2: Data Acquisition and Processing

A high-resolution CMOS camera operating in linear response mode, where the pixel values are directly proportional to the incident light intensity, is used to measure the intensity distribution in the image plane. In order to avoid noise and overall saturation, the exposure time is adjusted to fall within the dynamic range of the camera, staying close to the maximum amount of light. Through a series of measurements using the aberration plates inside the optical path, the optical ray will be tracked in order to fix the intensity distribution at various focus error conditions. Two plates with W20, -1, and 1 values in increments of 0.25 are made for every diaphragm. In order to improve the signal completion through an average, multiple images are identified for every focus error scenario. Calibration data is additionally created for comparison when there is no aberration plate in the system that gives the ideal intensity distribution.

MATLAB software that was specially created is used to process the obtained images (MathWorks, 2021). The background noise in each image is eliminated separately. The laser is turned off when the image and noise are taken. Following that, each image is normalized by dividing it by the total intensity, which accounts for variations in laser output or camera sensitivity. Quantitative information on the distribution of intensities is obtained by normalizing the figures. The analyzed images are shown as one-dimensional radial profiles and two-dimensional intensity maps to show how focus errors affect the distribution of intensity.

3.3: Simulation and Modeling

Computational simulations by using the Quick Basic programming language are performed to complement the experimental results and gain further insights into the impact of focus errors on the intensity distribution. The simulations are based on the Fresnel diffraction integral, which allows us to calculate the complex field in the aperture and the image by taking into account the distance of the propagation and the wavelength of the light (Goodman, 2017).

The point of light is represented in the simulation as a circular function with a diameter equal to the pinhole size, and it is defined as the complex field in the aperture plane. According to Mahajan (2011), these errors arise because of the way the multiplication operation operates, which affects both the aperture function and a single Zernike term related to the meaning of W20.By using the Fast Fourier Transform algorithm, the Fresnel diffraction integral is numerically evaluated to determine the field of complex numbers on the image plane. By raising the field to the square and calculating the absolute value, the intensity mapping is determined. In order to test the input set of W20 values in experiments, the program performs simulation trials. Simulated outcomes are contrasted and validated by experimental measurement data, though. The parameters of the simulations are then carefully selected to be consistent, i.e., acting as the wavelength, aperture size, and propagation distance with the experimental conditions.

The simulated intensity distributions obtained from the simulation are assessed by comparing them with experimental data qualitatively by observing the intensity maps and radial profiles created by the two and quantitatively by assessing the normalized root mean square error (NRMSE) between the simulated and experimental data. The NRMSE is the root mean square of absolute errors in simulated versus actual intensities divided by the range of experimented intensities or the formula of Chai and Draxler (2014). A relatively small NRMSE value at the end of the experiment shows that the model and measured data are close to each other. In contrast, a value of 1 indicates that deviations could be present due to measurement errors and model deficiencies. For instance, the Pearson correlation coefficient and the Bland-Altman analysis provide us with a way of determining the agreement of the experiment and the results we produced from simulations (Bland & Altman, 1999). Given this fact, the metrics will likely expose the relevant information and ties that account for the correlation and any systematic disparities between the two datasets.

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3. Results and Discussion

4.1: Intensity Distribution for Aberration-free Optical System

Figure 1 shows the intensity distribution for an aberration-free optical system with a circular aperture illuminated by coherent light. The graph demonstrates the intensity, which is normalized as a function of z's reduced distance and is a dimensionless parameter proportional to the distance from a point of zero. The angular intensity distribution displays a bright disk, called an Airy disk, the central peak. Then, there are the Airy rings, a set of concentric rings that diminish in intensity (Born & Wolf, 2013).

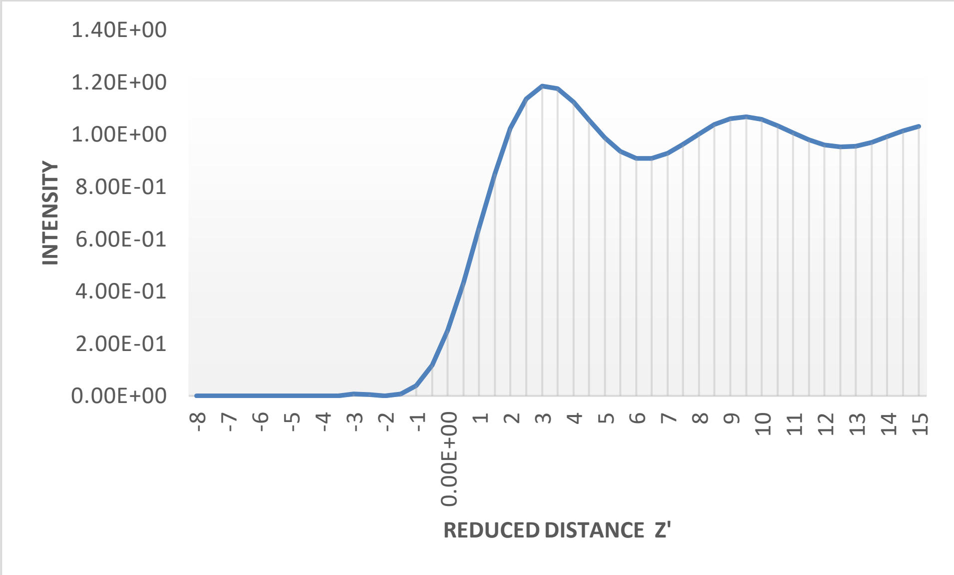

Figure 1:

Calibrated intensity of a parallax-illuminated optical system operating with a circular aperture and free of aberration

3.1. 4.2: Impact of Focus Errors on Intensity Distribution

Figure 2 shows the intensity distribution for an optical system with a focus error characterized by a Zernike coefficient of W20 = 0. This illustration mirrors the same aberration-free state not affected by any kind of focusing error in Figure 1, which was used as the benchmark to observe the influence of the non-zero focus errors. Figure 2 also shows the same important features as Figure 1: a sharp central peak and series (waved-out circles).

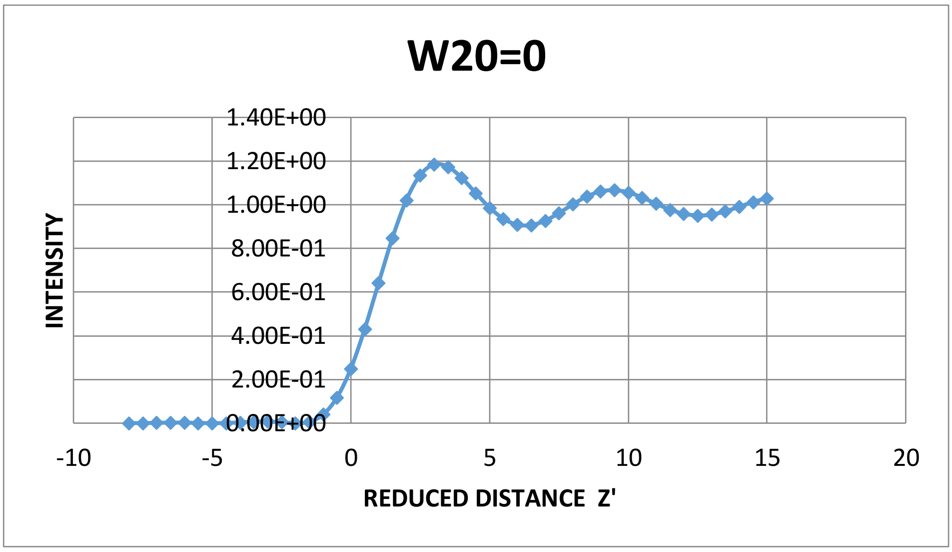

Figure 2:

W20=0

The intensity distribution for a focus error of W20 = 0.25 is presented in Figure 3. Adding a minute defocus aberration causes a slight broadening of the central peak and a gradual decrease in the maximum peak intensity. Consequently, the size of the aberration-free resolution will be smaller. The width at the full maximum height of the center peak creases, and therefore, the system's resolving power is decreased (Mahajan, 2011). The Airy rings seen at very high magnification appear shallower, and their intensity increases minimally, with the first Airy ring getting slightly more prominent. The shape symmetry of the distribution is top med, but the unclearness between the central peak and the side rings is also tiny. This influence may be seen in the tuned way the ray intensity passes through the focus alternative, similar to introducing a phase shift in the wavefront of the light (Born & Wolf, 2013).

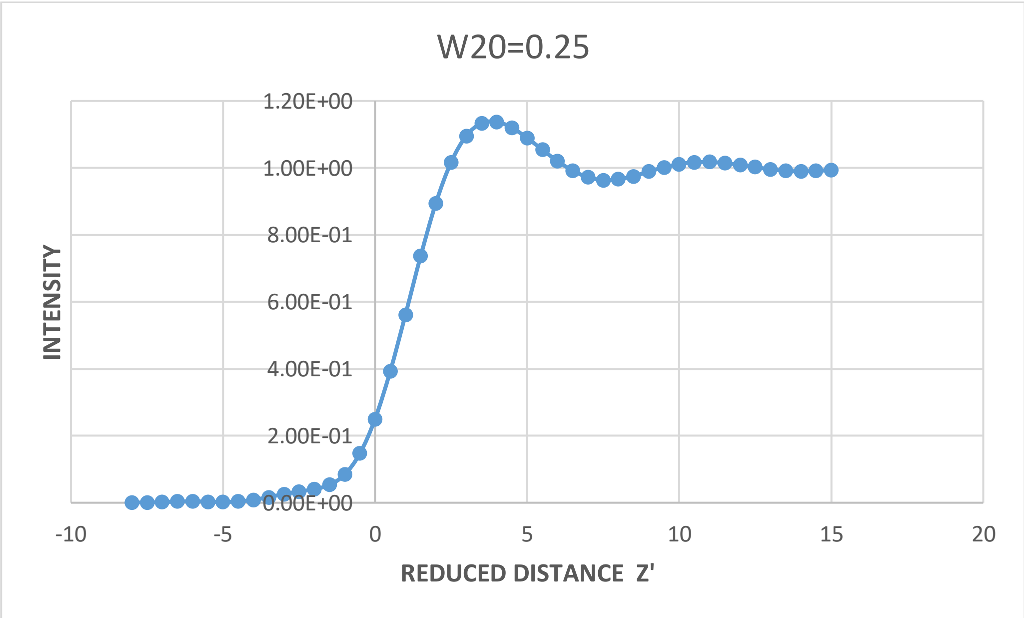

Figure 3:

W20=0.25

As shown in Fig. 4, the uniformity of intensity has been reduced for non-zero aberration of W20 = 0.5. In this focus error situation, the central peak becomes broader and less noticeable than in the previous cases. The incoming FWHM of this central peak also increases, thus signifying that the system's resolving power is steeply deteriorating. The order of the Airy rings is more complicated; the first ring is highlighted, becoming more pronounced, and the other ones are becoming distinct. The black and white central peak becomes a grey cloud bounding the rings, making them appear at the same color level, complicating the discovery of fine details in the image (Mahajan, 2011).

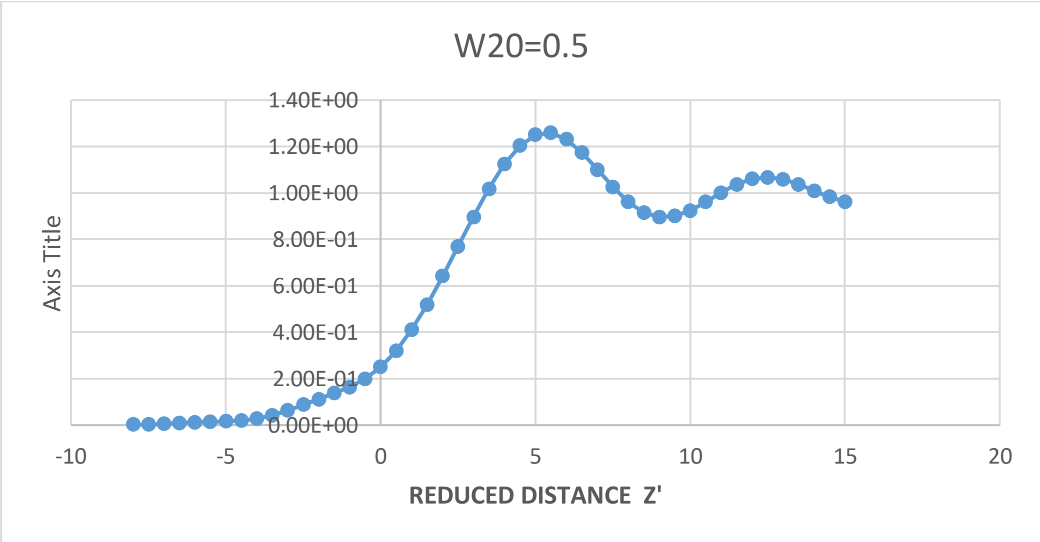

Figure 4:

W20=0.5

The broadening of the central peak and the increase in the intensity of the Airy rings result from the phase distortions introduced by the focus error. As the wavefront deviates from the ideal spherical shape, the constructive and destructive interference patterns that give rise to the Airy disk and rings are altered, leading to a degradation of the intensity distribution (Born & Wolf, 2013).

The intensity distribution for a focus error of W20 = 0.75 is shown in Figure 5. At this level of focus, astigmatism error results in a broader, less intensive central peak compared to the aberration-free case. The width of the central peak is now noticeably broader, so the resolution power of the system is highly deteriorated. The Airy rings gradually get brighter, and the first Airy ring approaches the central peak in brightness. The outer segments of the rings are prominent, further decreasing the picture's visibility and quality. The central peak and rings are more challenging to see as the level of symmetry is maintained but switched. The increase of the width of the central peak and more light intensity of the Airy rings result from more over the blur phase that distorts focus accuracy. The more significant the deviation from the ideal shape of the spherical wavefront is, the greater the complexity of the interference patterns, which leads to a broader spread of the intensity distribution of the airy disk (Mahajan, 2011).

3.2. 4.3: Implications for Optical System Design and Optimization

The results presented in this study have significant implications for the design and optimization of optical systems, particularly those that rely on coherent illumination and circular apertures. With this data, we clearly show that the focus errors are essential in increasing the image's brightness and, therefore, the image quality. Among the critical consequences is the necessity of having fewer focusing errors that ultimately positively impact the output quality of the imaging. In the w = 0.25 case plot, system characteristics, such as the resolving power and contrast, will be significantly reduced, but the system will become worthless in the $w \geq 1$ case. This emphasizes the necessity of doing the optics in careful design, production, and space of optical elements during the launching into space (Mahajan, 2011).

Another implication is the potential for using intensity distribution as a diagnostic tool to assess the presence and magnitude of focus errors in an optical system. The actual intensity distribution pattern could be compared with the ideal one of zero aberrations (Figure 1), which allows quick detection and quantification of focus errors in the setup. These parameters can then be incorporated into the optimization loop of the optical system either via manual adjustments or an adaptive optics technique. In addition, the findings would also be relevant for the design of digital imaging methods as compensation programs for focus blunders. Apart from knowledge about aberration-induced error, a proper solution can be constructed based on the idea that the original aperture distribution free of aberration can be restored by applying algorithms and enhancing the imaging quality (Shechtman et al., 2015). This method is beneficial when it is impossible to erase the luminous haze using only software.

Furthermore, the findings of this study can inform the design of optical systems for specific applications that require high resolution, contrast, or depth of field. This knowledge lets us know why we have limited resolution due to focus errors, which will help us decide what aperture size, wavelength of illumination, and other system parameters should be to meet the needs for the proper application (Mahajan, 2011). Lastly, the findings indicate that it is incumbent upon the researchers to consider the correlated effects of the other aberrations and, hence, the imaging conditions. Nevertheless, this study is only concerned with optical systems having focus errors. However, other types of aberrations can appear on the optics used in a system, such as spherical aberration, coma, or astigmatism (Born & Wolf, 2013). The crosstalk between these distortions and the magnification irregularities can precipitate a compound shift in the intensity distribution and the image's overall appearance. Consequently, a detailed knowledge of the varied aberrations and their mutual interactions is mandatory to understand how optical systems can be designed or optimized.

Conclusion

a. In this study the presented findings showed that the aberration-free optical system produced an intensity distribution with an Airy disk (concentric rings with ultimate limit) near the focus and intensity distribution in excellent agreement with the theoretical prediction from the diffraction theory of light. Including the first two modes of wave aberration is known as focus errors in the Zernike polynomial, constituting W20, which determines the progressive defeatism of the beam intensity distribution.
b. The Airy disc broadens and diverges as the simulation begins with the focus error set at W20 = 0.25 and then becomes even broader at the maximum focus error of W20 = 1.25. Meanwhile, the Airy rings, which were not visible initially, are visible with growing focus errors.
c. The total resolution power of the optical system measured through the FWHM of the central peak reduction is directly related to the focal adjustment. At a high depth of focus, (W20 >= 1) errors, the resolving power drops to a very low level, and the structure of the Airy knuckle and rings become indistinguishable.
d. The experimental values of the patterns are in perfect agreement with those simulated using the formula for Fresnel diffraction integral, with NRMSE ≤ 0.1 for all focus error situations.

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e. The findings of this study have significant implications for the design, optimization, and characterization of optical systems that rely on coherent illumination and circular apertures.
f. This study shows how the aberration of focusing errors affects the intensity distribution in the output and eventually leads to poor imaging performance. This has fundamental implications for the corresponding field design. These results helped researchers and engineers understand the link between aberration intensity and focus error forms well, and hence, they could define critical and unwanted error levels for special applications.
g. The research further demonstrates an appealing feature of optics in its ability to use the spatial distribution of intensity as a diagnostic tool. This could facilitate the analysis of formation errors and give rise to improvements in system optimization. Consequently, the results generated from this research could be helpful for building imaging techniques based on computation, which would eliminate the existing focusing errors, and individual optical systems that the user desires can be designed for some instances that would require high resolution, contrast or depth of field.
h. The research studies of the next wave could widen the discussion of the influence combinations of focus errors and other aberrations on imaging, mathematical optics techniques development, using non-circular apertures, studying of the role of partial coherence and searching of the optimal imaging systems design parameter sets for given applications.

References

[1] Born, M., & Wolf, E. (2013). Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light. In Google Books. Elsevier.

[2] Cohen, N., Yang, S., Andalman, A., Broxton, M., Grosenick, L., Deisseroth, K., Horowitz, M., & Levoy, M. (2014). Enhancing the performance of the light field microscope using wavefront coding. Optics Express, 22(20), 24817–24839. https://doi.org/10.1364/OE.22.024817

[3] Dubey, N., Rosen, J., & Gannon, I. (2020). High-resolution imaging system with an annular aperture of coded phase masks for endoscopic applications. Optics Express, 28(10), 15122–15122. https://doi.org/10.1364/oe.391713

[4] Mahajan, V. N. (2011). Optical imaging and aberrations. Pt. 2 Wave diffraction optics. Spie.

[5] Naresh, A., & Khonina, S. N. (2018). Apodization for improving the two-point resolution of coherent optical systems with defect of focus. Applied Physics. B, Lasers and Optics, 124(12). https://doi.org/10.1007/s00340-018-7101-z

[6] Ou, X., Horstmeyer, R., Zheng, G., & Yang, C. (2015). High numerical aperture Fourier ptychography: principle, implementation and characterization. Optics Express, 23(3), 3472. https://doi.org/10.1364/oe.23.003472

[7] Picazo-Bueno, J. Á., Granero-Montagud, L., Sanz, M., García, J., & Micó, V. (2023). Multiplexed super resolution phase microscopy with the transport of intensity equation. Optics and Lasers in Engineering, 166, 107601–107601. https://doi.org/10.1016/j.optlaseng.2023.107601

[8] Reddy, A. N. K., Shailaja, P., & Sagar, D. K. (2016). Resolution of Two Unequally Bright Points of Apodized Optical Systems with Asymmetric Circular Antenna Arrays. Optics and Photonics Journal, 06(03), 39–46. https://doi.org/10.4236/opj.2016.63006

[9] Reddy, A. N. K., Dev, V., Pal, V., & Ganeev, R. A. (2024). The Effect of a Parabolic Apodizer on Improving the Imaging of Optical Systems with Coma and Astigmatism Aberrations. Photonics, 11(1), 14. https://doi.org/10.3390/photonics11010014

[10] Shechtman, Y., Eldar, Y. C., Cohen, O., Chapman, H. N., Miao, J., & Segev, M. (2015). Phase Retrieval with Application to Optical Imaging: A contemporary overview. IEEE Signal Processing Magazine, 32(3), 87–109. https://doi.org/10.1109/msp.2014.2352673

[11] Tian, L., & Waller, L. (2015). 3D intensity and phase imaging from light field measurements in an LED array microscope. Optica, 2(2), 104. https://doi.org/10.1364/optica.2.000104

[12] Yang, H., Raphaël Trouillon, Gergely Huszka, & Martin. (2016). The Waist of Its Photonic Nanojet governs Superresolution Imaging of a Dielectric Microsphere. Nano Letters, 16(8), 4862–4870. https://doi.org/10.1021/acs.nanolett.6b01255

[13] Zuo, C., Chen, Q., Tian, L., Waller, L., & Anand Asundi. (2015). Transport of intensity phase retrieval and computational imaging for partially coherent fields: The phase space perspective. Optics and Lasers in Engineering, 71, 20–32. https://doi.org/10.1016/j.optlaseng.2015.03.006

[14] Zuo, C., Sun, J., Li, J., Zhang, J., Anand Asundi, & Chen, Q. (2017). High-resolution transport-of-intensity quantitative phase microscopy with annular illumination. Scientific Reports, 7(1). https://doi.org/10.1038/s41598-017-06837-1