Evaluation of scaled and annular pupils within the framework of the Extended Nijboer-Zernike (ENZ) formalism

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Introduction:

Whenever an optical system is used below its maximum numerical aperture (NA), the effective aberrations, which limit the performance of the optical system, are different from those of the full NA case [1]. Here, we present a recently found concise formula to compute these altered aberrations in terms of Zernike coefficients [2]. This result is useful in those optical fields where one encounters reduced and annular pupils, such as lithography, ophthalmology and astronomy. In addition, we show how this result can be used to evaluate optical systems with scaled and annular pupils within the framework of the Extended Nijboer-Zernike (ENZ) diffraction formalism [3].

Conclusions:

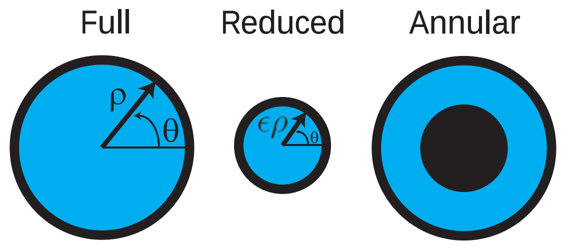
- A concise formula to obtain the aberration coefficients of a scaled or annual pupil has been presented.
- Based on this result we have shown the possibility to do aberration retrieval of optical systems with an annular pupil within the ENZ-formalism.
- We have highlighted some possible fields of application.

References:

[1] W. T. Welford, Aberrations of Optical Systems (Adam Hilger, 1986)
[2] A.J.E.M. Janssen, et al., JM³ **5** (2006), 030501.
[3] A.J.E.M. Janssen, et al., J. Mod. Opt. 55 (2008), pp. 1127-1157.

The main result:

We consider the following pupils



with a pupil distribution

$$P(\rho,\theta) = A(\rho,\theta)\exp\{i\Phi(\rho,\theta)\} \ ,$$

where $A(\rho,\theta)$ and $\Phi(\rho,\theta)$ are the amplitude and phase function, respectively. Next, this is written as a Zernike expansion

$$P(\rho,\theta) = \sum_{n,m} \alpha_n^m R_n^m(\rho)\exp\{im\theta\} \ ,$$

where α_n^m and $R_n^m(\rho)$ are Zernike coefficients and Zernike polynomials, respectively. A reduced pupil can be written as

$$P(\epsilon\rho,\theta) = \sum_{n,m} \alpha_n^m(\epsilon) R_n^m(\rho)\exp\{im\theta\} \ ,$$

where $\alpha_n^m(\epsilon)$ are Zernike coefficients describing the reduced pupil. An annular pupil is obtained by substracting a reduced pupil from a full pupil .

The main result presented in [2] gives a concise relation between the coefficients $\alpha_n^m(\epsilon)$ pertaining to the reduced pupil and the coefficients α_n^m describing the full pupil:

$$\alpha_n^m(\epsilon) = \sum_{n'} \alpha_{n'}^m \left[R_{n'}^n(\epsilon) - R_{n'}^{n+2}(\epsilon)\right] \ .$$

Optical system performance

When the NA of an optical system is varied below its maximum value, important parameters such as the aberration coefficients change. Using our results the influence of NA-variation can be efficiently calculated (see Fig 1).

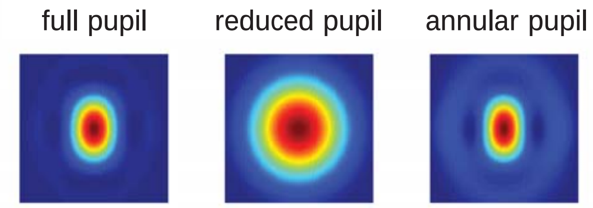


Fig 1. Image of a point-source generated with an aberration free high-NA optical system for a full, reduced and annular pupil.

Evaluation of optical systems

In [3] the main result is used in conjunction with the ENZ-formalism to perform full characterization of optical systems with an annular pupil. Below we show a reconstruction of an annular pupil having a Gaussian transmission function and a comatic phase aberration from through-focus intensity data.

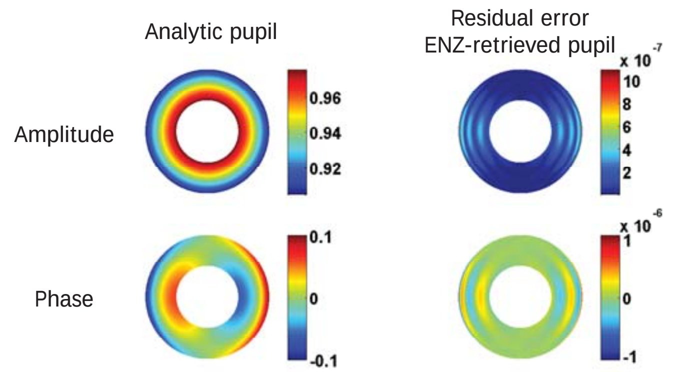


Fig 2. The left-hand column shows the analytic pupil distribution used to generate a through-focus intensity distribution. The right-hand column shows the residual error in the ENZ-retrieved pupil.

Fields of application

The results presented here are useful in many fields of optics such as lithography, ophthalmology and astronomy.

Lithography:

Contemporary lithographic systems allow the NA to be varied so as to optimize the image performance for certain lithographic features. Thus a variable fraction of the aberrations is actually involved in the imaging process. Our results allow efficient calculation of these effective aberrations.

Ophthalmology:

High resolution imaging of the retina is a complicated task due to constant variations in the pupil diameter of the eye. These variations are often compensated for using adaptive optics. Using our results an alternative adaptive system can be devised without the need for a wavefront sensor.

Astronomy:

In astronomy one has to deal with a centrally obstructed pupil. The results presented here simplify the analysis of such optical systems and enable the use of the ENZ-formalism in determining the atmospheric aberrations.

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