High-NA lens characterization by through-focus intensity measurement

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Summary

Based on the Extended Nijboer-Zernike (ENZ) formalism, we present a method that allows the determination of the main characteristics of a high-NA lens from through-focus intensity data.

Introduction

In optics, in general, and in high-resolution optics and micro-optics, in particular, the quality of optical components has to satisfy very stringent requirements. New applications not only demand enhanced quality, but also require exact specification of lens-characteristics. To obtain knowledge about the quality of an optical system, various methods are available. One could use an impulse response measurement, where the intensity pattern in focus is detected, or a frequency-based method that detects the image contrast as a function of spatial frequency. In both cases, intensity measurements provide a quality measure of the system but no direct access to the defects, described by the lens aberration function, of the lens system. Information about these defects is crucial to be able to do a 'repair' action on a lens system or to improve the manufacturing process. Therefore it seems advantageous to use an interferometric method as this allows a direct evaluation of the wavefront shape (Ref. [1]). Unfortunately, interferometry is also a rather elaborate method for lens quality measurement and its implementation in practical situations can be cumbersome. For that reason, methods have been developed to reconstruct the exit pupil aberration function from intensity measurement in the focal plane (inversion methods; for an overview, see Ref. [2]). Here we present such a method, based on the extended Nijboer-Zernike formalism (see Ref. [3]), that uses through-focus intensity point-spread data to reconstruct the aberration function. Such a method in the scalar approximation has been around for several years now (Ref. [3]). We will show that the method can be extended to the reconstruction of the aberration function of systems with high-NA.

Discussion

The method we propose is based on the ENZ-formalism. In this formalism an optical system, or its complex pupil function, is completely described by a set of Zernike-coefficients that can be directly attributed to aberrations and transmission variations of the system. This means that, in order to characterize a system, its Zernike-coefficients have to be determined. The ENZ-formalism allows retrieval of these coefficients by proposing a semi-analytic expression for the energy density in the focal region and matching these with measurement data.

Rather than matching the analytic expression directly point-by-point to measurement data, we perform a Fourier analysis on the measured and on the analytically proposed intensity data. A Fourier decomposition is carried out with respect to the order m harmonics in the azimuthal dependence of the through-focus intensity distribution. Ultimately, this results in the following system of equations to be solved in order to retrieve the Zernike-coefficients

$$\Psi^m(r, f) \approx \Psi^m_{an}(r, f) \; , \qquad (1)$$

where Ψ^m and Ψ^m_{an} are the measured and analytic expressions, respectively.

In order to restrain the computational burden associated with the retrieval scheme, a linearized version of the analytic expression for the energy density is used in Eq. (1), explaining the approximate sign. This simplification will imply that retrieval results will not be exact, but a so-called predictor-corrector mechanism is available to compensate for this error. This predictor-corrector procedure is an iterative process that will make the retrieval results converge to their exact values.

The ENZ-formalism was first described for systems of low-NA and later extended to high-NA, in which the full vectorial case has to be treated. The contribution of recent work consists of elaborating the formalism into a workable calculation scheme that can be used to test the high-NA version of the ENZ-formalism.

In Fig. 1 we show simulation of a through-focus intensity distribution containing some general aberration (top row Fig. 1). Next, in order to simulate an experiment, we add noise to this distribution with a signal to noise ratio (SNR) of 10. The result can be found in the second row of Fig. 1. Now this distribution serves as the input of the ENZ-retrieval process. Results for basic ENZ-retrieval (a single retrieval cycle) can be found in the third row and the result obtained through the predictor-corrector method, which uses the full power of the ENZ-formalism, is shown in the bottom row of Fig. 1.

A detailed description and examination of high-NA lens characterization using the ENZ-formalism can be found in Ref. [4].

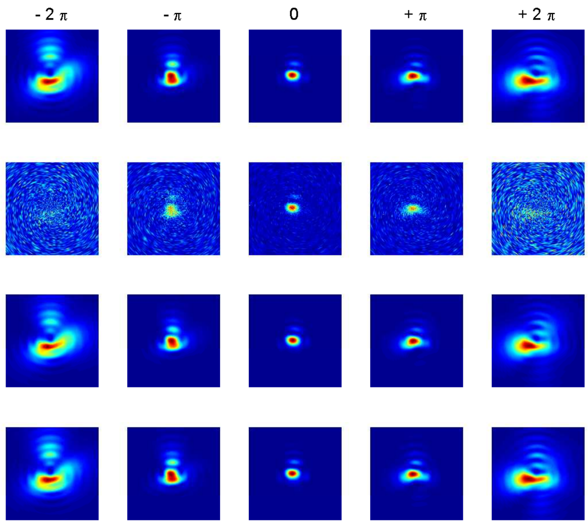

Fig 1. ENZ-retrieval example. The labels on top $[-2\pi..2\pi]$ correspond to the amount of defocus.

Conclusion

Based on numerical simulation we have shown that the full vectorial version of the ENZ-formalism can be used to retrieve lens characteristics of high-NA optical systems or lenses. This method can become a powerful tool for lens characterization. Research on high-spatial resolution through-focus intensity data measurements are ongoing.

References

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