Experimental Validation of the Extended-Nijboer-Zernike (ENZ) based Aberration Retrieval Method for Microscope Objectives

Axel Wiegmann*, Sven van Haver**, Nitish Kumar**, Silvania F. Pereira**

**Physikalisch-Technische Bundesanstalt,*
Bundesallee 100, 38116 Braunschweig, Germany
*** Delft University of Technology, TNW-IST,*
Optics Research Group, Lorentzweg 1, 2628 CJ Delft, The Netherlands

mailto:axel.wiegmann@ptb.de

The wavefront in the exit pupil of a microscope objective (NA=0.4) is obtained with a phase retrieval method based on the ENZ theory. The ENZ method calculates the wavefront from measured intensity distributions of through-focus planes. Comparison of this method with a direct interferometric method shows an agreement better than λ/70 (rms) for relative wavefront measurements.

1 Introduction

The quality of optical systems is conventionally assessed by interferometric tools requiring special setups and environmental conditions. The aberration retrieval method presented here relies only on intensity measurements in the focal region of the imaging system being tested. Hence, a simple setup for imaging the intensity distribution in the focal region is sufficient.
A brief description of the phase retrieval method is given in sec. 2, the setup for the through focus imaging is presented in sec. 3 and comparison measurements with an interferometric setup are shown in sec. 4. Finally, the results and the conclusion are presented in sec. 5 and 6.

2 Extended-Nijboer-Zernike (ENZ) based Aberration Retrieval

The field $P(\rho,\vartheta)$ in the exit pupil of an optical system is represented in polar coordinates by a Zernike expansion

$$P(\rho,\vartheta) = A(\rho,\vartheta)e^{\phi(\rho,\vartheta)} = \sum_{n,m} \beta_n^m Z_n^m(\rho,\vartheta) \qquad (1)$$

with complex coefficients β_n^m. The relationship between $P(\rho,\vartheta)$ and the field in the focal region is given by the Debye diffraction integral. A semi analytic solution to this integral is given by the extended Nijboer-Zernike theory. The intensity distribution in the focal region can be described by this theory in cylindrical coordinates as

$$I(r,\varphi,f) = \left| 2\sum_{n,m} i^{|m|} \beta_n^m V_n^{|m|}(r,f) e^{im\varphi} \right|^2, \qquad (2)$$

with the V_n^m functions as given in [1]. Equation (2) can be linearized with respect to the β_n^m coefficients and a system of linear equations is constructed from this linearized relationship between the measured intensity values I(r,φ,f) and the β_n^m coefficients. Hence, the field $P(\rho,\vartheta)$ can be reconstructed from the measurands I(r,φ,f) by solving the corresponding system of linear equations.

3 Measurement Setup

A diagram of the setup is shown in Fig. 1.

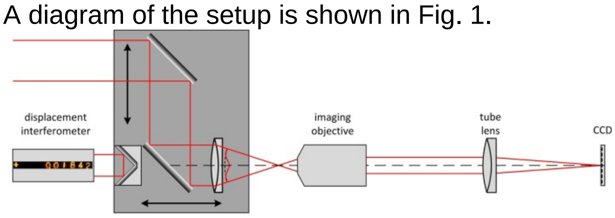

Fig. 1 *Diagram of the phase retrieval measurement setup.*

A collimated beam (λ=633 nm) is folded and passes the lens under test (microscope objective with NA=0.4). Images of the focal region (Fig. 2) are captured by an imaging objective with NA=0.9 and imaged with a tube lens on the CCD.

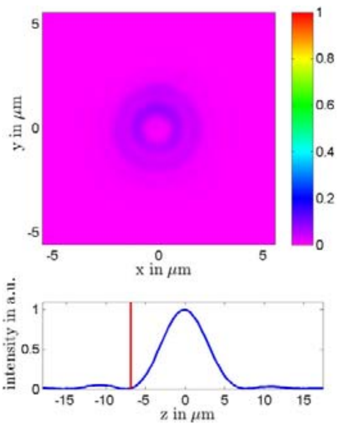

Fig. 2 *Measured intensity distribution in one of the through-focus planes (top). The graph on the bottom shows the measured intensity on the optical axis. The red line marks the position of the focal plane shown on the top.*

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The lens under test is mounted on a 2D scanning stage. By moving the stage along the optical axis, the intensity distributions in 30 focal planes are measured. In order to calibrate the magnification of the imaging part, the scanning stage is moved perpendicular to the optical axis before and after each through-focus scan. The magnification is calculated from the spot positions and the measured scanning stage positions.
Systematic errors of the setup are compensated by performing relative measurements. This means that one measurement with the single microscope objective and a second measurement with an additional aberration plate has been performed (Fig. 3).

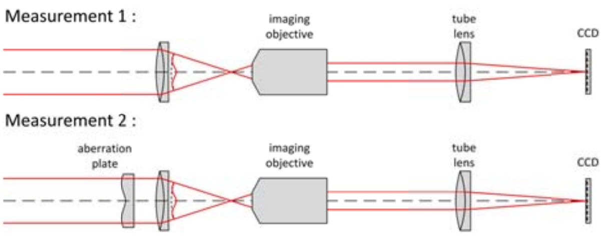

Fig. 3 *Measurement configurations of the phase retrieval setup.*

The difference of both measurements should only depend on the aberrations of the aberrations plate, since the systematic aberrations of the incoming wave front and the imaging part are canceled. In total, 59 Zernike coefficients β_n^m (n ≤12, |m| ≤5) have been reconstructed.

4 Comparison Measurements

The phase retrieval measurements have been validated by interferometric measurements.

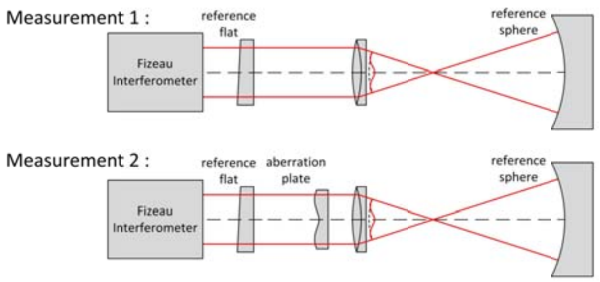

Fig. 4 *Measurement configurations of interferometric setup.*

A Fizeau interferometer with a flat reference surface (Zeiss Direct 100 [2]) has been used for the comparison measurements. The spherical wave formed by the microscope objective was reflected by a concave reference mirror. Again, two measurements have been performed (Fig. 4), one without and one with the aberration plate. Hence, all systematic errors of the reference surfaces are compensated for.

5 Results

A Zernike fit of the same number of coefficients was performed for the interferometric measurement data. The relative measurement results for two different aberration plates of both measurement methods and their difference is shown in Fig. 5. The results shown have not been compensated for possible orientation errors due to different mountings of the aberration plates in the setups. Tilt and defocus have been removed since these errors remain unknown in both measurement setups.

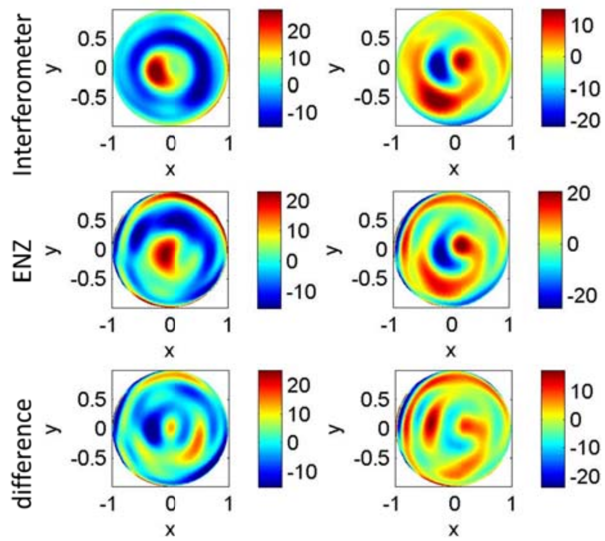

Fig. 5 *Measurement results of the phase of the wavefront of two aberration plates (left and right) for the interferometric setup (top), the phase retrieval setup (middle) and the difference between both measurement results (bottom). Lateral coordinates are normalized to a maximum radius of 1, phase values are given in nm.*

The rms difference is 7.4 nm (left in Fig. 5) respectively 7.0 nm (right in Fig. 5).

6 Conclusion

The phase retrieval results using the ENZ theory show a good agreement with the interferometric measurement results. The repeatability of the phase retrieval measurements is currently limited vibrations of the setup. However, absolute aberration measurement is possible but it requires a thorough calibration of the entire setup in the future.

References

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[2] M. F. Kuechel, „New Zeiss Interferometer“ in *Proc. SPIE* 1332, 655 (1991), DOI:10.1117/12.51116)