36 Adaptive Aberrometer for Acuity Measurements and Testing

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Summary. We present the novel instrument combining the Shack–Hartman wavefront sensor, compensator of low order aberrations and bimorph adaptive mirror for high order aberration correction. We have tested the developed instrument in the clinical environment on human subjects. The measurement rate was 77 frames per second. The typical residual error of correction was between 0.1–0.15 microns was achieved. The wavefront can be reconstructed in form of up to 36 Zernike polynomials. Automatic low order aberration compensator allows introduction of spherical and astigmatic terms with amplitudes up to ±15 D and ±6 D correspondingly and accuracy of 0.05 D. An 18 electrode bimorph deformable mirror corrector makes it possible to model Zernike aberrations up to the 3-th order + Spherical aberration with RMS amplitudes up to 1 micron. The results of measurements were compared with clinical refraction and good correspondence was found.

36.1 Introduction

Several groups in the world are working under implementation of the systems for measuring and correction of the human eye aberrations. The Shack–Hartmann (SH) wavefront sensor consisting of micro-lens array (lenslet) and CCD camera seems to be most widely used for eye aberration measurements [1,2]. Haro and Dainty proposed the original implementation of such a sensor where the reference point source is created by retinal fluorescence under laser radiation [3]. This sensor ensures true single-pass measurements of aberrations. Hamam introduced [4] a direct numerical method to reconstruct the aberration curve from SH image, without passing through a wavefront fit. The method does not require precise knowledge of the position of the pupil center of the eye.

Hofer et al. [5, 6] recently reported that they constructed a real-time (video-rate) SH wavefront sensor to measure the dynamic of eye aberration. They experimentally compared the quality of eye aberration correction in cases of static and dynamic control of a 37-electrode monolithic mirror. The Shack–Hartmann wavefront sensor used in experiments measured aberrations with the 30-Hz rate. The analysis showed that the dynamic compensation increases the Strehl ratio by a factor of three and contrast of observable photoreceptors by 33% compared to the static compensation.
Other techniques for eye aberration measurements, such as phase retrieval using double pass measurements of human eye PSF [7, 8] and laser ray tracing [9] also can be successfully applied for eye aberration measurements. However, such methods are respectively slow, and can be considered only for the measurements of steady eye aberrations.

The wavefront sensors based on Shack–Hartman technique are sensitive to the speckle modulation of the intensity distribution on the pupil plane. In the case of human eye and illumination and the coherent reference source the amplitude of modulation in the pupil plane is rather high and accurate measurement of the aberrations is possible only when temporal integration of Shack–Hartman picture is performed. This limits the temporal performance of the wavefront measurement. The application of the low temporal coherence reference source (like super-luminescent diodes) only partially improves the situation. The technical opportunity studying the temporal properties of the eye aberrations is appeared only recently [5, 10]. It has been shown that fluctuation in high-order aberrations have similar spectra dropping at a rate of approximately 4 dB per octave in temporal frequency. However, the origin of this fluctuations and dependence of the temporal properties on the action of cycloplegics are not known. That is why the further investigations of eye aberration properties are required.

It is known that the amplitude of eye aberrations decays sharply with the increase of their order number [11]. Low-order aberrations such as the defocusing, astigmatism, coma and spherical aberration have the maximum amplitude. Monolithic and membrane mirrors allow one to correct only for aberrations with relatively low amplitudes. In this connection, in experiments [6, 12, 13] the defocusing and astigmatism were compensated before the feedback closure by means of the additional lens optics. In paper [14], the possibility to use a 69-segment liquid crystal corrector for this purpose was examined. However, the authors failed to achieve a desirable effect and came to a conclusion that the dynamic range and the number of segments of a corrector should be significantly increased to compensate for real eye aberrations. Thus, the issue of optimal choice of a wavefront corrector for compensation of eye aberrations remains open.

There is another type of wavefront correctors yet not been used in adaptive compensation of human eye aberrations – modal deformable mirrors [15, 16]. Using a small number of control channels, such correctors allow a high-precision modelling of low-order aberrations with relatively high amplitudes. This property of such correctors corresponds to the statistical properties of phase distortions of the eye.

The response functions of modal correctors are non-localised: when applying the control voltage at any chosen electrode, the entire mirror changes its form. This fact substantially impedes the control of such a mirror.

In this paper, we introduce an adaptive system for compensation of human eye aberrations during measurements of the eye refraction and acuity. A human subject can look at the reference target through compensator and