Adaptive optics system to accurately measure wavefronts with a complex shape

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Summary

The continuous improvements in optical design and manufacturing capabilities are allowing new lenses with complex shapes to become real-world options in many recent commercial products. The introduction of wild aspheric lenses to enhance the optical performance and weight in complex optical systems, the new generation of more comfortable ophthalmic progressive lenses following the market trend of a lens design personalized to the user [1], and the novel imaging systems based on folded lenses which extremely reduce the volume and weight of traditional telescope imagers [2], are just some examples that involved new complex-shaped lenses. In the lens fabrication process, iterative steps of testing and repolishing are typically needed to ensure a high quality product. Therefore, the fabrication of accurate free-form lenses depends strongly on the possibility and accuracy of its measurement. Regarding this purpose, we propose an adaptive optics (AO) system within an open-loop configuration to measure in a single shot lenses that have a complex shape and demand a large dynamic range of measurement.

Fig. 1 shows the AO system that we have constructed. A 635 nm point light source obtained from a laser diode coupled with a monomode optical fiber is collimated using a diffraction limited achromat. The resulting plane wavefront passes through a linear polarizer, crosses the optic of interest (an ophthalmic lens), and is directed towards a liquid crystal phase modulator (PPM) [3] by means of a pellicle beam-splitter (BS1) which does not alter the optical path length. The aberrated wavefront is compensated and reflected by the PPM, which is conjugated with a proprietary cylindrical Shack-Hartmann sensor (CSHWS) through a 4:1 telescope system [4]. The sensor, formed by two identical arrays of microcylinders (NA=0.02) oriented along the vertical and horizontal directions, samples the wavefront (previously divided by a second pellicle beam-splitter BS2) in the form of a vertical and horizontal focal line patterns simultaneously recorded by two identical CCDs. By processing the patterns, the wavefront slopes are computed following the usual Shack-Hartmann principle, and, from these data, the wavefront is finally reconstructed in terms of the circular Zernike polynomial decomposition.

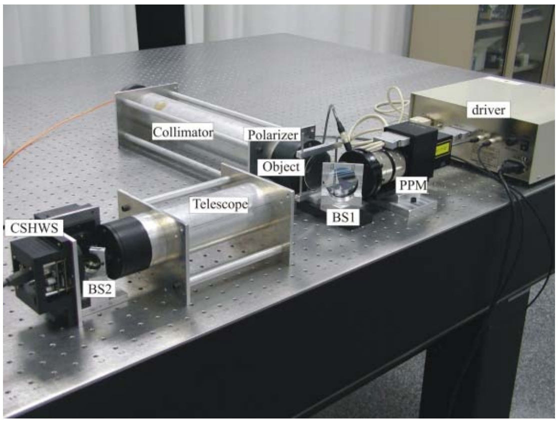

Fig. 1. AO system constructed to test commercial lenses with complex shapes.

To validate the compensation capabilities of the system in open-loop, the wavefront generation performance of the PPM was analyzed in terms of the amount of aberration considered. Spherical wavefronts of different curvatures (0.25 D, 0.5 D, 1 D and 1.5 D) were introduced in the PPM in a wrapped phase map representation over the whole 20 x 20 mm liquid crystal active area, and measured by the CSHWS. In all the cases, a very good correlation between the desired and real wavefronts has been found (relative rms error below the 0.15%), demonstrating the linear response of the PPM and its suitability for active compensation in open-loop.

To show the capabilities of the AO system, we tested a commercial progressive addition lens (PAL) which had a nominal null distance power and +2.5 D power addition. A 20 mm diameter area was scanned in a single shot, covering the whole power progression corridor of the lens. The intersection of the vertical and horizontal line patterns detected by the CSHWS and the reconstructed wavefront are shown in Fig. 2a and 2b., respectively. Subsequently, in order to improve the measurement accuracy, the conjugate of the measured wavefront was placed in the active device for compensation. As a result, shown in Fig. 2c, several additional points (within the circles) appear now to compute for wavefront reconstruction (Fig. 2d), and the width of the focal lines reduces close to the diffraction-limited size. The line pattern also clearly shows the diffractive behaviour of the PPM device. When a large aberration is written on it, the period of the wrapped optical path function is shortened, and the diffraction efficiency noticeably decreases; i.e. the intensity of the first diffraction order (which is the phase-modulated) becomes highly reduced relative to the zeroth order (which is the non-modulated original wavefront). This undesired zeroth order light is superimposed to the compensated pattern, making the image processing task more difficult and time-consuming. At present, two alternatives are under study to overcome it: either the introduction in the system of a filter element to block the zero order light, or to tilt the PPM while adding to the desired wrapped phase map the opposite tilt.

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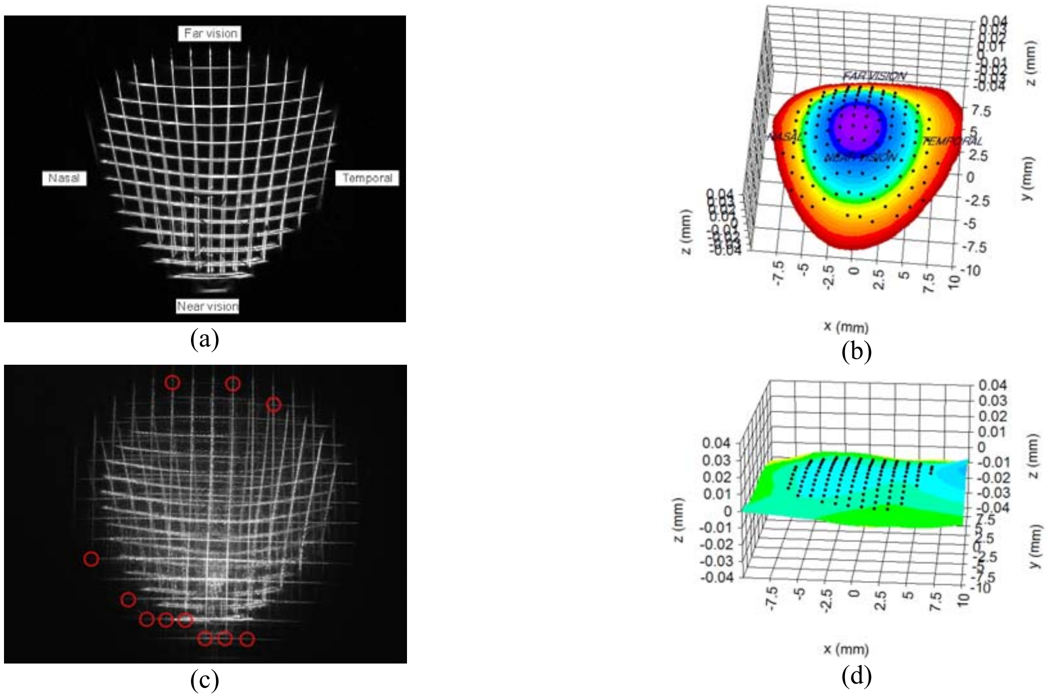

Fig. 2. PAL tested with the AO system: line patterns detected before (a) and after (c) the AO compensation from which the original complex wavefront of more than 94λ peak to valley (b) becomes almost flat with a rms error of 2.77λ (d).

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