Large-dynamic-range Shack-Hartmann wavefront sensor for highly aberrated eyes

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Abstract. A conventional Shack-Hartmann wavefront sensor has a limitation that increasing the dynamic range usually requires sacrificing measurement sensitivity. The prototype large-dynamic-range Shack-Hartmann wavefront sensor presented resolves this problem by using a translatable plate with subapertures placed in conjugate with the lenslet array. Each subaperture is the same size as a lenslet and they are arranged so that they overlap every other lenslet position. Three translations of the plate are required to acquire four images to complete one measurement. This method increases the dynamic range by a factor of two with no subsequent change in measurement sensitivity and sampling resolution of the aberration. The feasibility of the sensor was demonstrated by measuring the higher order aberrations of a custom-made phase plate and human eyes with and without the plate. © *2006 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.2197860]

1 Introduction

Our understanding of the optical quality of the eye is becoming more accurate with the ability to precisely measure the lower and higher order wave aberrations using ocular wavefront sensing techniques.[1,2] Reliable measurements of the ocular wave aberration also make it possible to correct these aberrations using advanced methods such as adaptive optics,[3] laser refractive surgery,[4] and customized optics.[5–7] Optical and psychophysical tests have demonstrated that correcting these aberrations significantly improves visual performance, especially when the pupil size is relatively large; however, most of these studies have been done in normal eyes. Logically, even greater visual benefit can be achieved when correcting the aberration in eyes having abnormal corneal conditions such as keratoconus (cone shape cornea).

A Shack-Hartmann type wavefront sensor[2] has been proven as a reliable and objective way to measure the ocular wave aberration and is one of the most practical and robust techniques in a clinical setting. However, it has been difficult for a conventional Shack-Hartmann wavefront sensor to reli-

ably measure these highly aberrated eyes, especially for a large pupil size, due to a limit that constrains the dynamic range of the system. Yoon et al. computed the required specifications (focal length and pitch of a lenslet array) of a conventional wavefront sensor with a given dynamic range requirement.[8] This limitation is caused by a tradeoff between dynamic range and measurement sensitivity. A solution to this problem would not only allow for measurement and characterization of these abnormal eyes, but also provide a more reliable basis for customized correction methods described elsewhere. A few methods[9,10] have been proposed to overcome this dynamic range/sensitivity tradeoff by using software algorithms and hardware modifications. One of the assumptions in these software algorithms is that the wavefront slope varies continuously between adjacent lenslets and spots are separated. Therefore, they are not capable of detecting spots that are crossing over and may be partially overlapped.

In this letter, a robust and simple way of using an optomechanical modification to increase the dynamic range of a Shack-Hartmann type wavefront sensor without sacrificing measurement sensitivity is introduced. The key to expanding dynamic range is the use of a translatable plate blocking adjacent lenslets that increases spacing between wavefront sensing spots.

2 Materials and Methods

One of the fundamental limitations of a Shack-Hartmann wavefront sensor is the requirement that each spot generated by a lenslet array must be within the virtual subaperture on a detector for spot centroiding. The relationship between incoming wavefront slope θ, spot displacement Δd, and focal length of the lenslet f can be described by the following equation:

$$\theta = \frac{\Delta d}{f}. \qquad (1)$$

With a constant lenslet size, which determines the centroiding area, the maximum measurable wavefront slope (dynamic range) is inversely proportional to the focal length of the lenslet. When highly aberrated wavefronts are measured with a long-focal-length lenslet array, multiple spots or crossed-over spots could appear within the same virtual centroiding area due to a larger spot displacement. The simplest way to avoid this problem is to reduce the amount of spot displacement by using a significantly shorter focal length. However, this solution also decreases measurement sensitivity due to the inability to detect small spot displacements when relatively small amounts of aberration are measured. Therefore, an increase in the dynamic range results in a decrease in measurement sensitivity. If abnormal eyes are to be measured accurately with such a system, a solution must include an increase in dynamic range without loss of measurement sensitivity.

The method proposed in this letter is to increase the virtual centroiding area that each spot is allowed to fall within. This can be achieved by blocking adjacent lenslets using a translatable plate that has subapertures every N number of lenslets. The configuration shown here assumes that every other lenslet is blocked by the translatable plate. In this prototype large-
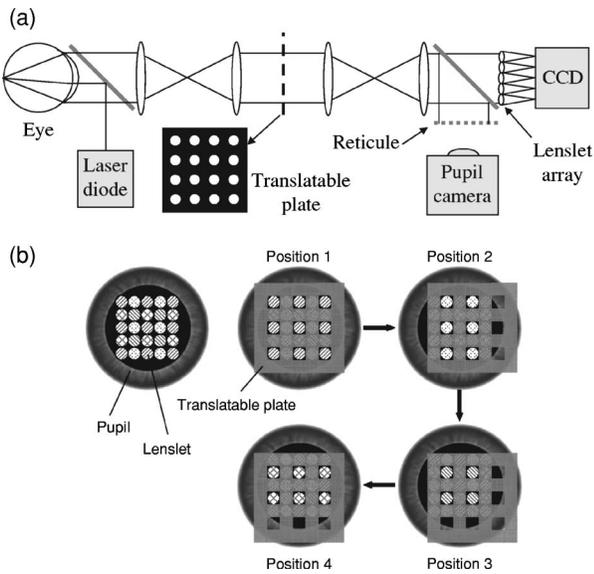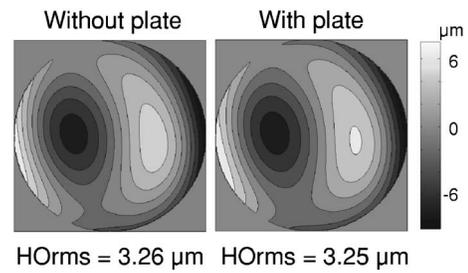
Fig. 1 (a) Optical layout of the prototype large-dynamic-range wavefront sensor having a translatable plate blocking every other lenslet. (b) Schematic diagram of capturing spot pattern at each position of the plate after translations assuming the aberration measured with a 5×5 lenslet array.

Fig. 2 Measured static higher order aberrations of the custom-made phase plate with and without the translatable plate for a 6-mm pupil: wavefront maps from the coefficients. HOrms indicates higher order RMS.

dynamic-range wavefront sensor, the virtual centroiding area is increased by a factor of 2. After the first spot array pattern is captured, the translatable plate is translated by one lenslet spacing to capture the second spot array pattern that includes spots blocked by the plate previously. In 2-D space, each complete measurement consists of four spot-array images after each of three translations of the plate in horizontal and vertical directions. A centroiding algorithm was applied to each spot array image to detect spot displacements of individual spots from reference positions. The spot displacement data from those four images were then combined together in the proper order, which can be determined from the original lenslet array configuration and the direction of the translations. From the combined spot displacement data, Zernike coefficients were computed. The measurement performance of the large-dynamic-range wavefront sensor is compared to a conventional Shack-Hartmann wavefront sensor with a custom-made phase plate and real human eyes that both include various higher order aberrations. The subject's pupils were dilated with 1.0% tropicamide, which also paralyzed accommodation. The effect of aberration changes due to fixation instability, accommodation, and tear surface change during the plate translations on the measured aberration is also evaluated at different total acquisition times. The total acquisition time includes the exposure time of the camera required to acquire each image plus the time to move the plate to each of the four positions.

3 Results

The prototype large-dynamic-range wavefront sensor was developed, and its optical layout and the four positions of the translatable plate are shown in Fig. 1. The translatable plate, lenslet array, and pupil camera were all co-aligned optically onto planes conjugate with the pupil. This was done using two relay optic systems that each consisted of a pair of imaging lenses. All four lenses had equivalent focal lengths, resulting in a one-to-one pupil magnification on the lenslet array. Since the lenslet array was also placed in conjugate with the pupil, the translatable plate and lenslet array are optically superimposed onto the same plane, which allows for blocking of each lenslet accurately. A broadband superluminescent diode having a wavelength of 830 nm was used to generate a laser beacon on the retina, which served as a light source for wavefront sensing. The size and focal length of the lenslets were 400×400 μm and 10.2 mm, respectively. This lenslet array combined with the translatable plate allows us to measure up to ±10D corresponding to a peak-to-valley value of 45 μm for a 6-mm pupil or up to ±8 μm of Zernike coma, $Z(\pm 1, 3)$. The pupil size used for all results was 6 mm in diameter.

We first measured the static aberration induced by a custom-made phase plate that has various kinds of higher order (3rd order and above) aberrations based on the actual aberration of an abnormal eye. This aberration was chosen because it has relatively large amounts of higher order aberrations that can still be measured with and without the translatable plate. Figure 2 shows the measured higher order aberrations with and without the translatable plate. The most dominant higher order aberration was horizontal coma. The difference in all the higher order Zernike coefficients between the measurements with and without the translatable plate was insignificant and the wavefront maps generated from those coefficients were almost identical. The higher order wavefront RMS values with and without the translatable plate were 3.25 and 3.26 μm, respectively. This small difference could be due in part to the difference in an aperture shape between lenslets (square) and clear apertures (circular) on the translatable plate, which induced slightly different averaged wavefront slopes within the apertures.

An experiment was performed to investigate the effect of eye movements that might occur while the translatable plate is translated in horizontal and vertical directions. This is important since the concept of the large-dynamic-range wavefront sensor requires that the pupil position be the same while all four images are captured sequentially. Measurement reliability of the sensor would be decreased if there was significant eye movement causing pupil decentration. One normal eye's aberration was measured with and without the translatable plate at the same CCD exposure time of 50 ms. Since the large-dynamic-range wavefront sensor requires three more additional CCD exposures, total acquisition time including the time required to translate the plate was approximately five
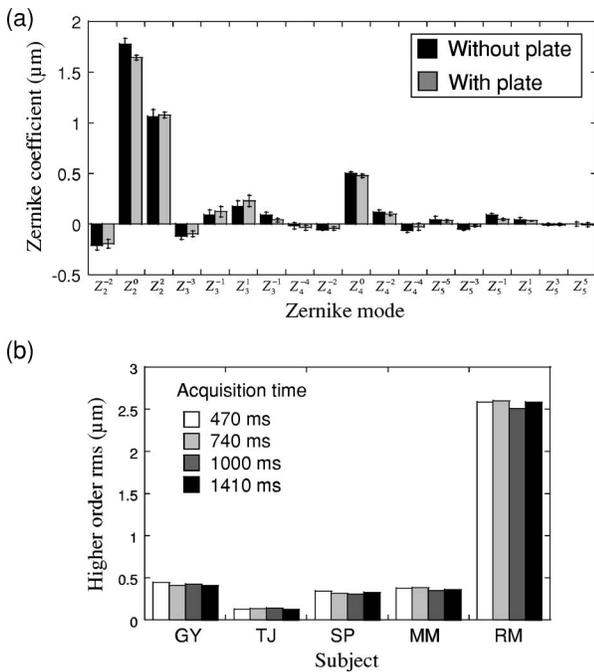
Fig. 3 (a) Measured higher order aberrations of a human eye with and without the translatable plate. (b) Variability of the measured higher order wavefront RMS when using different total acquisition times for four normal eyes and one keratoconic eye (RM). All measurements were over a 6-mm pupil.

times longer (470 ms) than the conventional wavefront sensor. Four measurements were made and averaged for both cases. Figure 3(a) shows a direct comparison of individual higher Zernike coefficients as well as the wavefront maps generated from the Zernike data with and without the translatable plate. A slight but statistically significant difference (0.13 μm) in defocus with and without the plate was found. This discrepancy might be caused by slightly different refractive states because those two measurements were performed on two different dates. The higher order RMS values with and without the plate were 0.59 and 0.58 μm, respectively. The difference between individual coefficients for both cases was within a typical measurement variability observed with a conventional wavefront sensor and was not statistically significant. We intentionally increased the total acquisition time to determine if there is an increased effect of eye movements on the measured aberration of four normal eyes and one keratoconic eye. Figure 3(b) plots the measured higher order RMS when different total acquisition times were used. For all of the acquisition times up to 1410 ms, the higher order RMS values were insignificantly different for all five subjects including one keratoconic eye (RM). A variability of higher order RMS values for the subjects were evaluated by computing the mean of the standard deviation of the higher order RMS for the individual subjects which was 0.028±0.024 μm (mean ±standard deviation). This result indicates that eye movements, at least those occurring up to 1410-ms total acquisition time, do not significantly affect the aberration measurement using the large-dynamic-range wavefront sensor.

4   Discussion and Conclusion

The feasibility of the prototype large-dynamic-range Shack-Hartmann wavefront sensor has been demonstrated by measuring the aberration with and without the translatable plate. This wavefront sensor can increase dynamic range even more without sacrificing measurement sensitivity by blocking more adjacent lenslets. Due to a longer acquisition time, there may be a limitation in combining the large-dynamic-range wavefront sensor with a real-time adaptive-optics closed loop. Poor fixation caused by fast eye movements during the plate translation might also limit the measurement accuracy. The extreme case of this concept would be to have one clear aperture on the translatable plate and to scan the entire pupil sequentially, which allows individual spots to have a centroiding area the same as a detector size resulting in a greatly increased dynamic range. This would be similar in concept to a reversed laser ray tracing wavefront sensor and does not require a lenslet array although rapid pupil scanning with the single clear aperture is necessary. Not only the highly aberrated eyes but also normal eyes can be reliably measured using the large-dynamic-range wavefront sensor; measurement sensitivity remains the same for both cases. The ability to reliably measure the highly aberrated eyes also makes it possible to correct their higher order aberrations to enhance visual performance substantially. The same method can also be used for optical testing of lenses and mirrors with large amounts of higher order aberrations.

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