Available online at www.sciencedirect.com
ScienceDirect
Optik 121 (2010) 1405–1411
Optik Optics
www.elsevier.de/ijleo

A wavefront aberrometer for dynamic high-order aberration measurement

Xiang Yu[a,b,*], Yun Dai[a,b], Xuejun Rao[a,b], Cheng Wang[a,b], Lixia Xue[a,b], Wenhan Jiang[a,b], Ying Xiong[c,**]

[a]*The Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China*
[b]*The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209,China*
[c]*Tongren Eye Center, Beijing Tongren Hospital, Capital University of Medical Sciences, Beijing 100005, China*

Received 21 November 2008; accepted 6 February 2009

Abstract

This research studied the dynamic aberration of human eyes at near vision. A wavefront aberrometer was developed based on the Hartmann–Shack theory. This aberrometer can achieve dynamical aberration measurement of the human eye. The Aberrometer induces ocular accommodation by a moving target at near vision, and records the vision information of human eyes simultaneously during ocular accommodation process using a Hartmann–Shack sensor. Nineteen eyes of 10 volunteers are tested. Eighty-four percent eyes have induced accommodation amplitude between 3 diopter (D) and 8D. The highest induced accommodation amplitude is 8.6D. The aberrometer produces results with high precision and repeatability, i.e. an accuracy root-mean-square (RMS) of $1/50^{\lambda}$ and a repeatability RMS of $1/500^{\lambda}$.

Keywords: Optical measurement; Hartmann–Shack wavefront sensor; Dynamic aberration; Accommodation; Moving target

1. Introduction

Although cornea contributes most of the eye's focusing power, its focus is fixed. The curvature of the crystalline lens is the one that can be adjusted to shift focus on objects of different distance between the eye's near point and far point. Human eye's dynamic process of focusing is entitled accommodation, which is one of the most important functions that maintain vision.

It has been reported by many researchers that high-order ocular aberrations vary with accommodation [1–3]. For example, in 2002, Ninomiya et al. [4] found that the spherical aberration changed obviously in the positive direction with eye accommodation even though the quality of retinal image was not affected by the eye's accommodation process. However, the relationship between the fluctuation of the high-order aberration and the ocular accommodation is still not clear due to lack of appropriate equipment that can record the change of high-order aberrations in the process of accommodation dynamically. Because of the same reason, currently in laser-assisted in situ keratomileusis (LASIK), a static aberration acquired before the operation, instead of a dynamic aberration, is used as reference for the correction. This inevitably leads to the correction error because the calculation for operation neglects the spacial and contemporary characteristics of a human eye.

Apparently, measuring only the static aberration of the human eye cannot meet the requirements of modern

*Corresponding author at: The Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China. Fax: +86 288 510 0433.
**Also for correspondence.
E-mail address: shannonyx@sina.com (X. Yu).

0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2009.02.023

vision researches. A new apparatus that can actively induce ocular accommodation and can measure the high-order aberration during the eye accommodation process is urgently needed.

Currently, there are three major types of aberrometers to measure ocular aberrations, namely the Hartmann–-Shack (H–S) objective aberrometer, the Tscherning objective aberrometer and the ray-tracing subjective aberrometer. Compared with the other two types of aberrometer, the H–S aberrometer is faster and more accurate. The Institute of Optics and Electronics (IOE) at Chinese Academy of Sciences has a long history of researches on H–S wavefront sensors [5–8]. Researchers have successfully developed an H–S aberrometer for the human eye [9]. Based on the previous model, a more advanced H–S aberrometer was developed, which integrated an active ocular accommodation induction mechanism and can record high-order aberrations dynamically.

2. Principle of a Hartmann–Shack wavefront sensor

A wavefront passes through an array of lenses (called lenslets) of the same focal length and forms an array of focused light spots on the focal plane of the lens. The charge-coupled device (CCD) detector on the focal plane detects the location of focused light spot (Fig. 1).

An ideal plane wave results in an array of focus spots with each spot locating at the intersection the optical axis of the corresponding lens and the focal plane. This pattern of spots is used as the reference pattern in measuring the aberration of a distorted wave.

A distorted wavefront will form spots deviated from that of an ideal plane wave. Assume that an ideal plane wave focuses at (x_o, y_o). The location of a distorted wave will be at position (x_i, y_i) (Fig. 2), and the displacements $(x_i–x_o)$ and $(y_i–y_o)$ are proportional to the slope of the distorted wave in the x and y directions, respectively.

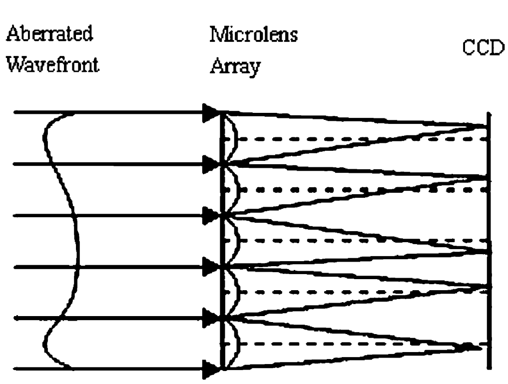

Fig. 1. Principle of an H–S wavefront sensor.

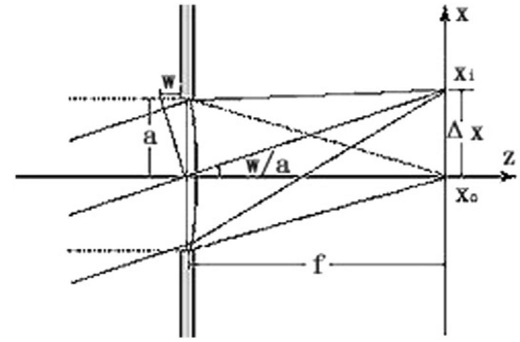

Fig. 2. Tilted wave deviates focus.

The wavefront slope (unit λ) can be expressed as

$$\left\langle g_{x_i} \right\rangle = \frac{x_i - x_o}{\lambda f} = \frac{\iint \frac{\partial \phi(x,y)}{\partial x}\, ds}{2\pi \iint ds}$$
$$\left\langle g_{y_i} \right\rangle = \frac{y_i - y_o}{\lambda f} = \frac{\iint \frac{\partial \phi(x,y)}{\partial y}\, ds}{2\pi \iint ds} \tag{1}$$

where $\phi(x, y)$ is the phase distribution function of the incoming wavefront.

The position of focus spot, (x_i, y_i), is defined as the 1st moment of intensity distribution. $I_{i,j}$ is the intensity of pixel (x_i, y_i). For wave aberration measurement, discrete samples are usually taken. The centroid of focus spot can be computed through the following expression:

$$x_i = \frac{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} x_i I_{i,j}\right)}{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} I_{i,j}\right)}$$
$$y_i = \frac{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} y_i I_{i,j}\right)}{\sum_{i=1}^{m}\left(\sum_{j=1}^{n} I_{i,j}\right)} \tag{2}$$

The phase distribution of wavefront can be obtained from the slope with the reconstruction algorithm [6,7]. Many parameters such as peak to value (PV), root-mean-square (RMS), Zernike coefficients, point spread function (PSF) and modulate transfer function (MTF) can also be calculated from the phase map.

The processor reads signals from CCD continually and calculates the average slope in real time and then recovers the wavefront by wavefront reconstruct algorithm. The result is given by phase map, PV value, RMS value and Zernike coefficients. Additionally the PSF, MTF, encircled energy and Strehl ratio can be calculated based on the anterior result. Accordingly this instrument is a feasible tool to analyze optical aberration in time and space domain.