Wavefront Sensors and Aberration Sensors in Ophthalmology

Subjects: Ophthalmology | Optics

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The wavefront sensor is one of the main elements of the adaptive vision correction system. Its task is to measure the aberrations of the wavefront and transmit the results of these measurements to the processing device. The main causes of wavefront aberrations in the eye are the shape and optical properties of the cornea, pupil and lens. In modern diagnostic devices, wave aberrations are described in terms of Zernike polynomials (OSA and ANSI standards). Nowadays, there are a wide variety of wavefront sensors.

Keywords: wavefront aberration ; Zernike polynomials ; myopic eye cornea ; numerical simulation

1. Introduction

Detection, identification and compensation of wavefront aberrations are in demand in various applications, including vision correction. Not being able to directly measure the wavefront of the light field on the retina of the eye, it is necessary to determine it indirectly, including by measuring the intensity of the light field in a certain plane.

2. Wavefront Sensors

For example, the wavefront of a light field can be reconstructed from an interferogram. This method was proposed as early as 1800 (Fizo, Jamin, Michelson, Jung) [1][2]. It still has unsurpassed accuracy and makes it possible to directly obtain a map of wavefront deviations at very large aperture sizes. The accuracy of interferometers, especially heterodyne ones, exceeds λ/100. In addition, taking into account the use of data mining and neural networks [3][4], the wavefront of a light field can be reconstructed from an interferogram with a reference beam of a given shape using both a diffractive and refractive optical element (in particular, **a diffraction grating** for forming a linear interferogram, **a lens** for spherical, **axicon** for conical) [5][6]. Disadvantages of interferometry are well known-they include the sensitivity of the measuring equipment to vibrations, as well as the need for the physical presence of a reference wavefront. In addition, interferometers are able to determine the phase with an uncertainty of 2π, which imposes additional restrictions on the magnitude of detected aberrations.

Hartmann's method [7], which appeared 100 years later, differs in that wavefront deviations are calculated from a set of **sub-apertures.** It covers the full size of the area to be studied with a certain step. It was first described in 1900 by Johann Hartmann. Later it was modified in 1971 by Ronald Shack, and it is used in astronomy to compensate for aberrations in telescopes. The idea of using wavefront technology belongs to J. Bill (1982). A little later, a technology was developed to use aberrometric analysis for **vision** diagnostics. This year, an algorithm for wavefront reconstruction was developed. The Shack-Hartmann wavefront sensor is a device in which the wavefront is divided into separate beams by a matrix of focusing microlenses (**lens raster**) [8][9][10]. The finite dimensions of each of the sub-apertures lead to restrictions on the magnitude of the detected aberration. Local slopes can only be measured within the area assigned to the microlens. When a focused beam leaves this region, errors in the measurement of slopes occur, leading to phase reconstruction errors [11]. Among the advantages of the Shack-Hartmann sensor, one can distinguish an accuracy comparable to the interference method and achromaticity.

In the 1950s, Fritz Zernike developed a method to visualize the phase of the light field in a direct way. The Zernike phase contrast method [12] is a powerful tool for converting the spatial phase information of an optical beam into a spatial intensity distribution without light absorption. The basic principle is separate a light beam into its Fourier components using a lens and a **phase plate**. The introduced phase shift creates an intensity distribution according to the phase information carried by the higher spatial frequencies. This method has been successfully applied to analyze aberrations and improve resolution in telescopes, in the decoding of phase-coded information, and in the microscopy of biological tissues [13][14][15]. However, the phase reconstruction is carried out incorrectly, with an increase in the level of aberration due to the limitation of the linear approximation of the expansion of the wavefront in a Taylor series.

Adaptive methods are the most versatile tool for wavefront control and correction of optical aberrations over a wide range. The idea of using adaptive optics to compensate for distortions caused by low visibility was first proposed in 1953 by Horace Babcock, and the method of wavefront correction by a compound mirror was proposed and described by V.P. Linnik in 1957 [16][17]. However, the technological level for the development of adaptive optics systems in the 1950s was not yet high enough. The possibility of creating such a system has appeared since the 1980s due to the development of technology and the possibility of computer control and monitoring with high accuracy. Wavefront sensors based on adaptive methods continue to develop and have found their application in such fields as improving the imaging systems of optical microscopes and telescopes, remote sensing of the Earth, clinical research, etc. [18][19][20][21]. This approach uses adaptive optics to compensate for distortion, such as a composite or **adaptive mirror**. Among the shortcomings of this method, one can single out the need to use long-converging iterative or optimization algorithms to fully or partially compensate for wavefront aberrations by selecting a complex phase.

In addition, in the 1990s scientific school of Academician V.A. Soifer (V.V. Kotlyar, S.V. Karpeev, S.N. Khonina), a method for detecting wavefront aberrations was proposed. It is based on multichannel diffractive optical elements (DOE) [22][23][24] that perform in various diffraction orders consistent filtering of phase distributions corresponding to different basis functions. For direct optical measurement of wavefront decomposition coefficients, **multi-order diffractive optical elements** (DOEs) matched to the Zernike function set, which has been successfully applied to wavefront analysis with small aberrations, can be used. Sensors based on multi-order DOEs provide sensitivity to wavefront deviations no worse than λ/20, are resistant to vibrations and do not require the use of optical reference elements [24].

Another solution and extension of the adaptive method can be a **multichannel diffractive optical element** matched to phase distributions in the form of Zernike functions. In contrast to the expansion in terms of the Zernike function basis, which provides correct detection of only small aberrations (up to 0.4 wavelength λ), the proposed approach removes the limitation on the aberration value. The correct detection up to the wavelength λ has been confirmed numerically and experimentally) [25][26].

Since the 2000s, continuously developed modifications of methods [27][28][29] based on the analysis of Zernike polynomials, as well as using digital information processing and data mining. Alternative methods for measuring and reconstructing wavefront aberrations in optical systems, including the human eye, are considered [30][31][32][33].

When a significant blurring **of the focal spot** occurs, it makes sense to apply methods focused on the analysis of the intensity distribution pattern formed by an aberrated optical system in one or several planes. In this case, iterative and optimization algorithms are used to reconstruct the phase, as well as machine learning and neural networks [34][35]. The use of neural networks in the problem of recognition of wavefront aberrations is a new, developing approach. However, this approach is problematic at low levels of aberrations, when the pattern is almost indistinguishable from a diffraction-limited focal spot. Therefore, intensity patterns outside the focal plane are often used for analysis, which, in turn, introduces ambiguity into the analysis of aberrations since defocusing is also one of the types of aberrations.

One of the applications **of diffraction axicons** can be used as a sensor of singular beam states and wavefront characteristics. It is possible to improve the detection of spatial anisotropy and the visualization of wave aberrations by supplementing the lens with a diffractive axicon [36]. When the lens is supplemented with an axicon in the plane corresponding to the focal plane of the lens, an out-of-focus picture is formed instead of the focal picture. This allows researchers to measure out-of-focus patterns and increase the depth of field and its transverse scale without moving the detector device. However, it is necessary to keep a balance between high visualization efficiency and preservation of the characteristic structure of the original scattering function of the aberrated wavefront (the longer the period of the axicon, the higher its efficiency for visualizing aberrations) [37]. Supporting technologies are being developed to provide new types of wavefront sensors based on multilevel diffractive axicons. That brings the advantage of compact optical systems; moreover, multilevel axicons have a higher conversion efficiency compared to binary ones [38].

Another way to detect aberrations is a holographic wavefront sensor, which is based on a **holographic optical element** (HOE). The main difference between a HOE and a DOE lies in their formation. For the HOE, a reference beam is needed, and the DOE is implemented as an amplitude or phase element corresponding to the complex transmission function. The HOE, on which some aberrated wavefront is recorded, can be immediately used for compensation. To use the HOE in this way requires a recording medium. Among the advantages is the need to process information about the value of the radiation intensity only at two points for one aberration. Among the disadvantages-the use of a holographic multiplex (set of HOE) leads to strong and unavoidable crosstalk (intermodal) noise, preventing real use [39].

As an extension of the HOE-based method, Andersen's compromise between the new **holographic sensor** and the traditional Shack–Hartman approach is considered. The resulting device provides information not about the minimum required 10–15 aberrations but about several hundred local deformations of the wavefront, which makes it difficult to process the information received. In addition, in the approach under consideration, the depth of distortion is measured in each "zone" of the wavefront and not at 2 points [40][41].

3. Aberration Sensors in Ophthalmology

Wavefront sensors (WFS) are the main components in the field of determining the aberrations of the optical system of the human eye for their subsequent compensation. However, none of the designs used and proposed so far provides the simultaneous achievement of high spatial resolution in the pupil of the tested optics and absolute measurement accuracy comparable to that achieved by laser interferometers. The principles of operation of aberrometers can be divided into the Hartmann-Shack method, the ray tracing method, the Cherning principle, etc.

Among the new research over the past 5 years, the following works on the analysis of various types of aberrometers can be distinguished: at the *Moorfields Eye Hospital eye Hospital* (London, UK) analyzed the results of studies of eyes treated under wavefront control using a Peramis pyramidal aberrometer (SCHWIND eye-tech-solutions GmbH) [42]; in the eye clinic *Maja Clinic* (Nis, Serbia) studies were carried out using the WaveLight Allegro Oculyzer, WaveLight Allergo Biograph instruments, DGH Pachette 3 ultrasonic pachymeter [43]; at the *Al-Watani Eye Clinic* (Cairo, Egypt), a study was conducted to detect keratoconus (KC) with higher sensitivity and specificity using Scheimpflug sensors–Oculyzer [44]; at the *Beijing Tongren Eye Center* (Beijing, China), a consistent comparison of Oculyzer and Topolyzer Vario aberrometers was carried out before and during corneal refractive surgery [45]; and at the *Branchevsky Eye Clinic* (Samara, Russia), a comparative analysis of devices based on Plasido, Scheimpflug and OCT for measuring keratometry in patients after laser vision correction was carried out [46].

Среди множества офтальмологических измерительных приборов есть несколько, наиболее часто используемых в клинических условиях и встречающихся в специализированной литературе. Кроме того, представленное количество датчиков рассматривается в статьях высокорейтинговых журналов, анализируется в диссертациях, и на основании данных, полученных с этих датчиков, принимаются решения о диагнозе, а также хирургическом вмешательстве.

In practice, new technologies of ocular **pyramidal aberrometers can be used in ophthalmological clinics**. Osiris pyramidal aberrometers provide repeatable and consistent measurements of ocular aberrometry in normal eyes [47]. A wavefront sensor with an expanded source pyramid-shaped optical element has been successfully used to measure aberrations in the human eye. An important advantage of this sensor for the eye is the easy adaptation to variations in the range of aberrations that can be expected in the optics of the human eye: from very slightly aberrated normal eyes to extremely aberrated eyes in patients with pathological corneas. The disadvantage is that the sensor collects light from false reflections from the surfaces of the eye.
One of the classic technologies for analyzing aberrations in the human eye is the **Hartmann-Shack type aberrometer**. For example, using a tracer aberrometer (iTrace) and a Hartmann-Shack aberrometer (Topcon KR-1 W) provide excellent repeatability but less reliable reproducibility when measuring high-order aberrations [48]. Portable wavefront aberrometer (*hand-held wavefront aberrometers*) with postcycloplegic autorefraction (*postcycloplegic autorefraction-AR*) and cycloplegic refraction (*cycloplegic refraction–CR*) showed good agreement between measurements with postcycloplegic AR and CR in spherical equivalents but tended to give results with falsely detected myopia [49].

Another well-known solution to the phase problem in ophthalmology is the **Scheimpflug sensor**. For example, the DRS Analyzer (Galilei; Ziemer Ophthalmology) uses two rotating Scheimpflug cameras in combination with Placido's topographic system. It uses the Placido disk to provide more accurate anterior curvature topographic data, in addition to the data obtained from the Scheimpflug cameras. Overall, the DRS analyzer provides anterior segment measurements with good repeatability and reproducibility for both normal and refractive corneas [50]. For the detection of keratoconus (KC) with higher sensitivity and specificity in ophthalmological offices, aberrometers such as Scheimpflug tomography, for example, Oculyzer (Alcon), are used. The device is intended for performing computed tomography of the cornea and examination of the anterior part of the eyeball.

Existing and other technologies, on the basis of which clinical aberrometers are built, provide fairly accurate measurements of the deflection of the wavefront of the eye. At the same time, high-order aberrations are measured, which makes it possible to evaluate individual deviations of the wavefront, including those associated with professional activity or age-related changes, in order to optimize the optical (contact or intraocular lenses) or surgical correction of the human eye.

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