Wave front sensor based on holographic optical elements

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Abstract. A wavefront sensor (WFS) based on holographic optical elements, namely computer generated Fourier holograms is proposed as a perspective alternative to the Shack-Hartmann sensor. A possibility of single and multimode sensor and the dependence of their characteristics were investigated.

1. Introduction

Creating reference wavefronts (WF) with an error of less than 0.01λ is an actual task for many fields of optics [1, 2]. Typically, WF distortion occurs during the passage of radiation and optical components and is a consequence of the refractive index distribution inhomogeneity and the presence of streaks. The technology of obtaining elements with high requirements on the deviation values of the refractive index of the calculation and the absence of streaks is very time-consuming, long and expensive. Therefore, the development of optical systems with high beam quality using different ways to measure and correct aberrations of the wave function. This correction is usually performed by the adaptive optics [3, 4], which gives the possibility of dynamic correction.

Wavefront control by Hartmann method and its kind - by Shack-Hartmann method - is currently one of the most simple, yet accurate and effective way. The difference between the methods is to use a variety of masks, mounted in front of the radiation detector: in Hartmann sensors mask may be a raster small holes in an opaque screen [5] or multi-element amplitude mask with apodized apertures [6], and in Shack-Hartmann sensors masks are performed as matrices of microlenses of square or circular aperture [7].

Shack-Hartmann sensor application is effective when wavefront distortions are static or slowly change - for example, in ophthalmology, in a number of applications in laser technology, etc. However Shack-Hartmann sensor has limitations, firstly, when the distortion changes at high speed (for example, in the case of atmospheric turbulence, which varies at a rate above a few KHz structure), the method encounters serious problems even when using modern high-speed computer systems [8]. Secondly, it is not possible to register a phase change, when the spatial scale is less than the distance between the holes or matrices of microlenses.

Perspective alternative is using computer-generated holograms (CGH) in the problem of WFS. In this case, CGH can replace more expensive and complex in terms of technology of obtaining and control, lens and raster components. In [9] a method of measuring the WF based on the principle of the mode holographic sensor provided by the author shows a linear response to the amplitude of the wave function contained in the Zernike directly measures the numerical value of Zernike modes, which can reduce the processing time. Another version of WFS has been proposed in [10] based on the
holographic filtering the input wavefront. However, such devices have been demonstrated only in laboratory performance, their practical application was restrained by imperfection of the technology used.

The present work is devoted to the development of principles of construction of specialized WFS based on Fourier CGH. The physical implementation of such holograms is based on using liquid crystal spatial light modulators (SLM) and is described in detail in [11, 12].

2. Analysis of WF phase distortion

There are many approaches to the description of the distorted wavefront [13,14], the most common expansion in Zernike polynomials orthogonal basis. Every polynomial is a smooth function is uniquely described by the expression, responsible for its own type of aberrations. Then the representation of the input radiation in the form of a linear combination of Zernike modes is:

\[ W(x, y) = \sum_n a_n \cdot Z_n(x, y) . \]

Distorted wavefront:

\[ B(x, y) = B_{\text{plane}}(x, y) \cdot \exp \left( i \cdot \frac{2\pi}{\lambda} \cdot W \right) = B_{\text{plane}}(x, y) \cdot \exp \left( i \cdot \frac{2\pi}{\lambda} \cdot a_n \cdot Z_n \right) . \]

The orthogonality of Zernike polynomials gives them great advantages in the analysis of aberrations comparing with the power basis. The main advantage is that each factor contributes to a number of aberrations given type and order in the overall wave aberration from a position of balance of all types of aberrations. This means that certain types of aberration represented by Zernike polynomial expansion, affect the image quality quite independently from each other.

25-30 first polynomials are quite enough for a complete description of the WF.

Table 1. An example of the WF in the representation of Zernike polynomials. \( \rho \) – normalized pupil size \( \Theta=\tan^{-1}(y/x) \) – angle coordinate.

| Defocus \( Z_3 = 2 \cdot \rho^2 - 1 \) | Coma \( Z_6 = (2 \cdot \rho^3 - 2 \cdot \rho) \cdot \cos 2\Theta \) | Spherical \( Z_8 = 6 \cdot \rho^4 - 6 \cdot \rho^2 + 1 \) |
|----------------------------------------|-------------------------------------------------|-----------------------------------------------|
| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |

3. The principle of constructing a computer-synthesized Fourier hologram

As known, there are two types of computer-generated holograms - Fourier and Fresnel hologram. In both cases, the synthesis is the calculation of one or more fast Fourier transform operations. The disadvantage of Fresnel holograms is the presence of spatial noise due to zero order, which could have a critical impact on the accuracy of measurements of aberrations, the size of which is not more than four pixels.
Therefore, the author considers the principles of the sensors only based on computer-synthesized Fourier holograms, implemented in accordance with the diagram shown in Figure 1a. In the synthesis method of such holograms uses zero order suppression.

In this case the synthesized hologram is an intensity distribution of the two waves - the reference (distorted $- B(x, y)$) and the object ($O(x, y)$):

$$I(x, y) = |O(x, y) + B(x, y)|^2 = |B(x, y)|^2 + |O(x, y)|^2 + O(x, y) \cdot B^*(x, y) + O^*(x, y) \cdot B(x, y).$$

The reference wave we assume WF, object wave is a radiation of a point source, the position of the source is given by encoding. Thus, illuminated hologram with distorted WF restores image of the object - the point. In his position can judge the presence of aberrations in the sensor.

![Diagram](image)

Fig. 1. Principles of recording (a) and reconstruction (b) CGH for WFS

4. **Mathematical modeling of the sensor**

Simulation of the sensor was produced in Mathlab, using an FFT algorithm. Fig. 2-4 shows the synthesized binary hologram, which demonstrates the ability to create CGH containing various combinations of aberrations. Type of the hologram image (binary or 8bit grayscale) determine by the characteristics of the LCD SLM used in the projection recording scheme. The quality of the recorded hologram to determine the parameters of the optical components of the circuit, but not the calculated structure.
The total hologram at coordinates (100,200) has been encoded defocus aberration, the wave aberration with a value of 2λ, and at the point with coordinates (400, 200) the same type of aberration with a value of 1λ.

Fig. 5,6 shows the results of research. The ordinate shows normalized intensity, the abscissa shows coordinate on the light receiver. When additional illumination hologram different distorted waves diffraction patterns were obtained, the position of different points.
Fig. 5. Reconstruction of the hologram on computer (perfect case)

Fig. 6. Reconstruction of the hologram using distorted wave (real case)

Centre position of the reconstructed spot corresponds to encoded. Blur and noticeable distortions arising from the use of the arithmetic addition of a hologram, further work will focus on the study of methods for creating multiplex and composite holograms.

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