[5] Design of a holographic combiner for a virtual display

G.I. Greisukh[I], E.G. Ezhov[I], S.V. Kazin[I], S.A. Stepanov[I]
[I] Penza State University of Architecture and Construction

Abstract

Ways and methods of modeling and calculating a holographic combiner for a virtual display are presented. On the one hand, they allow Denisyuk holograms with high diffraction efficiency independent of the field angle to be generated. On the other hand, they allow the advantages of the holographic combiner when compared with a multilayer dielectric mirror to be maximally realized.

Optimization and search of the design parameters of elements of an optical setup for generating an aspherical wavefront for recording a Denisyuk hologram are based on ray tracing.

These processes are greatly facilitated by the use of an intermediate model in the form of a thin transparency for phase delay.

The phase delay of this transparency, the mirror geometry of the optical setup that forms the aspherical wavefront for recording the hologram, and the actual model of Denisyuk hologram in this article are described in the form adopted in the Zemax environment for surfaces such as Binary1, Extended polynomial and Optically Fabricated Hologram, respectively.

Keywords: *virtual display, holographic combiner, diffraction efficiency, monochromatic aberrations, freeform surface.*

Citation: *Greisukh GI, Ezhov EG, Kazin SV, Stepanov SA. Design of a holographic combiner for a virtual display. Computer Optics 2016; 40(2): 188-193. DOI: 10.18287/2412-6179-2016-40-2- 188-193.*

Introduction

A device called "virtual display" superimposes artificially generated images on real patterns of the selected volume of the external environment. The device contains a small-size matrix image generator (a micro display) and an optical system which acts, according to its main functional feature, as oculars, since it displays an infinity information-carrying image, which is superimposed on the pattern traced directly by an observer [1].

Works on development and improvement of virtual displays of different functional purposes, from in-cabin and helmet-mounted displays to the smallest eyeglass ones, have been widely performed from the 1970s both in our country and abroad. The most well-known works on this subject have been performed in our country at Vavilov State Optical Institute [2-4] and Bauman Moscow State Technical University [5-8]. An adequately complete overview of similar works carried out abroad is given in papers [9, 10].

An optical system of the virtual display contains a projection lens and a combiner. The combiner places a micro-display screen image formed by the projection lens within the field of view not overlapping it and providing an opportunity to watch the environment (see Fig. 1).

As far as the combiner's design is concerned, various options have been currently proposed for its implementation, and one of the most prominent options thereof is the combiner based on 3D holograms recorded in colliding beams by the Denisyuk method. These holograms have a high index of selective ray reflection of the same wavelength and sufficient optical transmission of all other wavelengths at the same time. This particularly allows a monochromic information pattern to be superimposed onto a color pattern of the external environment. Thus, in contrast to the combiner based on a multilayer dielectric mirror, a holographic combiner (HC) can be placed almost at any angle, as well as normally, to an observation line.

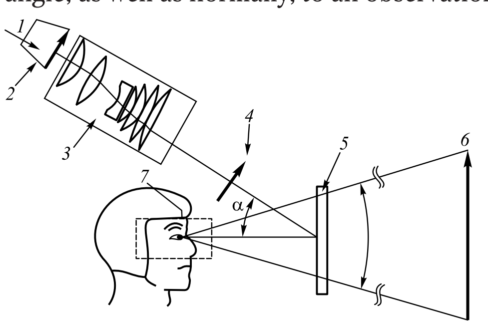

Fig. 1. A diagram of the virtual display: 1 and 2 – the micro display and its display image; 3 – the projection lens; 4 – an intermediate real image; 5 – the combiner; 6 – a false image of the micro display screen; 7 – an exit pupil of the optical system

1. Requirements on wavefronts for recording the holographic combiner

Regarding the operation of the optical system of the virtual display on its beam return (Fig. 2), it can be easily seen that parallel beams will fall on the holographic combiner from the pupil of the observer's eye within the angle range of $-\omega_{max} \leq \omega \leq \omega_{max}$ dependent on the choice of the visible optical magnification. Diffraction efficiency (DE) of the holographic combiner depends on the degree of deviation from the Wolf-Bragg equation. In the absence of shrinkage of a hologram regulating layer and in case of equal wavelengths for recording and reconstruction, the equation is determined by the difference of HC incidence angles during recording and reconstruction [11, 12].

From Figure 2, it can be easily seen that when HC is placed normally towards the observation line, the above angular difference can be described as follows:

$$\Delta i = \omega - \mathrm{arctg}\left[\frac{R + s \cdot \mathrm{tg}(\omega)}{c}\right], \qquad (1)$$

where $\boldsymbol{R}$ is the radius of the exit pupil of the optical system (on beam return – an entrance pupil), larger or equal to the radius of the eye pupil, $\boldsymbol{s}$ is the distance between HC and the pupil in line of observation, and $\boldsymbol{c}$ is the distance from HC to a point source of recording (the radius of curvature of a wavefront for recording a hologram).

Figure 3 shows one of the options for the helmet-mounted virtual display, whereas Table 1 gives the values of the angular difference $\Delta\boldsymbol{I}$ calculated by the values of parameters corresponding to this display ($\boldsymbol{R}$=5 mm, $\boldsymbol{s}$=50 mm). The table illustrates that when the centre of a spherical wavefront for recording the hologram is combined with the pupil center ($\boldsymbol{c}$=$\boldsymbol{s}$), the angular difference $\Delta\boldsymbol{i}$ remains almost the same while changing the field angle. Therefore, diffraction efficiency of the hologram will be the same over the total field of view.

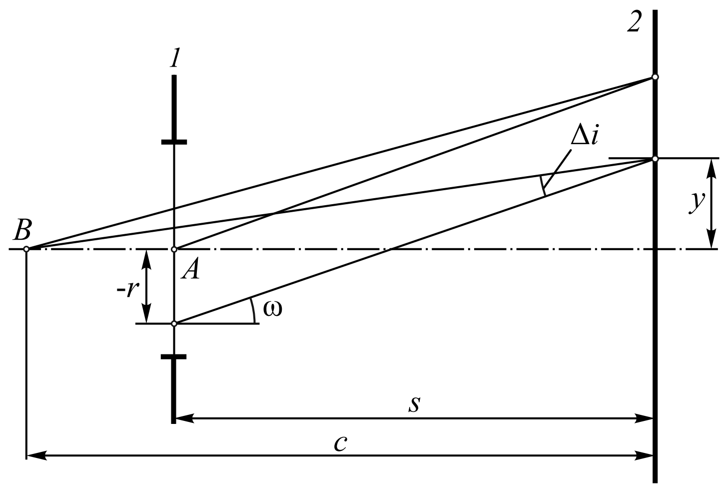

Fig. 2. To determination of the difference of HC incidence angles: 1 – the pupil of the observer's eye; 2 – the hologram; A – the pupil centre; B – the center of the spherical wavefront for recording; w – the field angle (the angle of incidence of a parallel beam); Di – the difference of HC incidence angles for beams pertaining to divergent recording beams and the parallel beams

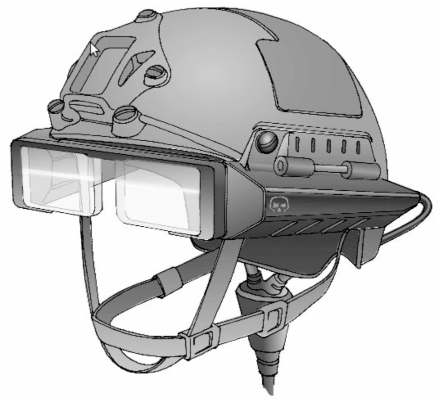

Fig. 3. The helmet-mounted virtual display by Sarnoff Corporation [13]

Moreover, due to the fact that the angular difference $\Delta \boldsymbol{i}$ (in this case depending only on the ratio R/s) is less than the maximum field angle ω_{max} at least 3.5 times ($\Delta \boldsymbol{i}_{max}<6°$), diffraction efficiency is expected to be quite acceptable.

As far as the second wavefront for recording the hologram is concerned, it should be tilted to angle of $\alpha \geq 45°$ to a hologram plane for reasons of design and, in the first approximation, it must be flat. In fact, only in this case and upon arrangement of regenerating point sources in the HC focal plane, the plane waves will be reconstructed, and the beams corresponding thereto will be parallel.

This automatically leads to HC diffraction efficiency to be independent from the field angle that results in building the optical system of the virtual display based on a setup with an intermediate real image lying in the HC focal plane (see Fig. 1).

Table 1. The values of the angular difference Di and their relevant amplitudes in the pupil plane r versus the field angle w and the distance from HC to the recording point source c

c	ω	–R≤r≤R			
		$\Delta \boldsymbol{i}_{max}$	$\boldsymbol{r}(\Delta \boldsymbol{i}_{max})$	$\Delta \boldsymbol{i}_{min}$	$\boldsymbol{r}(\Delta \boldsymbol{i}_{min})$
∞	0	0	–5 mm	0	0
	10°	10°	–5 mm	10°	5
	20°	20°	–5 mm	20°	5
50 mm	0	5.71	–5 mm	0	0
	10°	5.64°	–5 mm	0	0
	20°	5.21°	–5 mm	0	0
75 mm	0	3.81°	–5 mm	0	0
	10°	7.09°	–5 mm	0.07°	4.5 mm
	20°	10.0°	–5 mm	2.81°	5 mm

Unfortunately, due to discrepancy between a reconstruction setup and the HC recording geometry (recording is made by tilted flat wavefronts and reconstruction is made by tilted spherical wavefronts), some monochromatic aberrations and, in particular, rather heavy astigmatism occur [14]. In fact, it is easy to show that the relative astigmatic difference between the sagittal $\boldsymbol{f_S}$ and meridian $\boldsymbol{f_T}$ focal distances is as follows:

$$\frac{f_S - f_T}{f_S} = \sin^2 \alpha \,. \qquad (2)$$

Wherein the sagittal focal distance equals to the distance between HC and the eye pupil in line of observation, i.e. $\boldsymbol{f_S}=\boldsymbol{s}$ (see Fig. 2).

Such heavy astigmatism, unusual for rotary-and-symmetrical optical systems [15], in combination with the axial coma proportional to sinα, considerably complicates the correction of aberrations of the optical system of the virtual display in whole. Hence, to achieve acceptable quality of generated images, it is necessary to use one or more efficient measures from those ones proposed below:

- the aspherization of one of the wavefronts for recording HC, e.g., the substitution of a flat wavefront for a freeform wavefront;
- the integration of a freeform rotating mirror into the optical system setup;
- tilts and displacements of centered aspherical lenses of the projection lens about the optical axis;
- tilting of the micro display about the optical axis.

2. Modeling and calculating the setup for recording the holographic combiner

At the first stage, based on design solutions known from literature and patent sources, and taking into consideration the micro display geometry, its resolution, and required visible optical magnification, the optical system of the virtual display should be totally set up and its dimension should be calculated. Then, following on from calculating the beam return, the optical design parameters should be measured and optimized. In this regard, one of the well-known optical design programs (Zemax, CodeV, etc.) can be used.

At the stage of optimization, it is reasonable to simulate the holographic combiner by a surface inducing phase delay to the incident wavefront described by a polynomial of two variables. In particular, in the Zemax environment [16], the Binary1 surface may be successfully used as such a surface. The phase delay induced thereby is described by the following polynomial:

$$\psi(x,y) = \sum_{j=1} A_j E_j(x,y) \,, \qquad (3)$$

where $\boldsymbol{A_j}$ are the dimension factors, and $\boldsymbol{E_j}(\boldsymbol{x},\boldsymbol{y})$ are the coordinate cofactors:

$$E_1 = x,\ E_2 = y,\ E_3 = x^2, E_4 = xy\ ,\ E_5 = y^2\ ,$$

$$E_6 = x^3,\ E_7 = x^2 y,\ E_8 = xy^2 \ldots \qquad (4)$$

The factor $\boldsymbol{A_1}$ should be put equal to zero, and the factor $\boldsymbol{A_2}$ should be calculated as follows:

$$A_2 = \frac{2\pi}{\lambda} \sin\alpha \,, \qquad (5)$$

where the operating wavelength of the virtual display λ should be set in millimeters. Other factors $\boldsymbol{A_j}$, provided $\boldsymbol{j} \geq 3$, may be used as the optimization parameters.

Upon completing optimization, the Binary1 surface, having simulated the holographic combiner, should be replaced by a surface such as Optically Fabricated Hologram whose infinitely thin diffraction microstructure, as also provided for the real hologram, is generated as a result of the interference of two coherent recording waves. Simulation of recording wavefronts is carried out by optical setups in two special files. In our case, the first recording wavefront requires no optical setup for its generating, since it is represented by the spherical wavefront being propagated normally over the plane of the holographic combiner and radiating from the pupil centre (point ***A*** in Fig. 2).

Regarding the optical setup for generating the second recording wavefront, an additional Zemax-file should be set up to search it. The Binary1 surface found therein as a result of optimization must be lighted by the first recording wavefront. Besides, the aspherical wavefront generated by this surface and being propagated at the angle α to the optical axis with the help of additional optical elements must turn into an ideally spherical wavefront. It can be generally achieved by radial optimization of the design parameters of one or two freeform mirrors. In the Zemax environment, this is the Extended polynomial surface described by a polynomial as follows:

$$z(x,y)=\frac{c(x^2+y^2)}{1+\sqrt{1-(1+\kappa)c^2(x^2+y^2)}}+\sum_{j=1} B_j E_j(x,y), \quad (6)$$

where $\boldsymbol{z(x,y)}$ is the coordinate of a surface point in the coordinate system where the ***XOY*** plane contacts with the top of this surface; $\boldsymbol{c}$ is the surface curvature on its top; κ is the conic constant; $\boldsymbol{B_j}$ are the asphericity factors, and $\boldsymbol{E_j(x,y)}$ are the coordinate co-factors determined by equations (4).

Figure 4 shows the two-mirror optical setup for searching the design parameters of elements of the setup for generating the second wavefront for recording the holographic combiner. The parameters for mirrors 2 and 3 found during steps of optimization, and the beam return radiated from the point ***C*** are filed in a special file assigned for the optical setup for generating the second recording wavefront. Finally, the Optically Fabricated Hologram surface shall simulate the setup for recording the holographic combiner represented in Fig. 5.

The final optimization of the whole optical system of the virtual display in the Zemax environment may be performed for all design parameters, including the setup parameters for generating the second wavefront for recording the holographic combiner.

Conclusion

Ways and methods of modeling and calculating the holographic combiner for the virtual display are presented in this paper. On the one hand, they allow high diffraction efficiency independent of the field angle to be generated. On the other hand, they allow the advantages of the holographic combiner when compared with a multilayer dielectric mirror to be maximally realized.

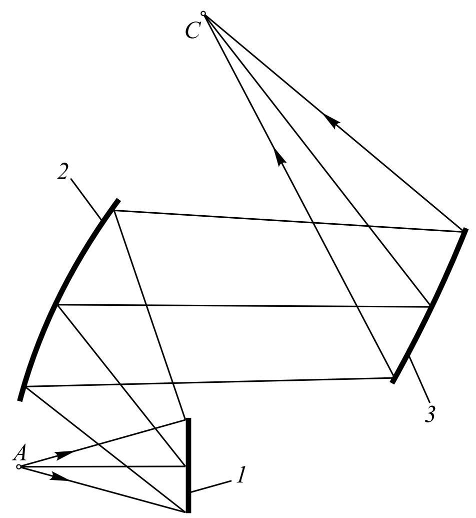

Fig. 4. The optical setup for searching the design parameters of elements of the setup for generating the second wavefront for recording the holographic combiner: A is the centre of the spherical wavefront normally lighting the Binary1 surface (1); 2 and 3 are the freeform mirrors; C is the real image of the point source A

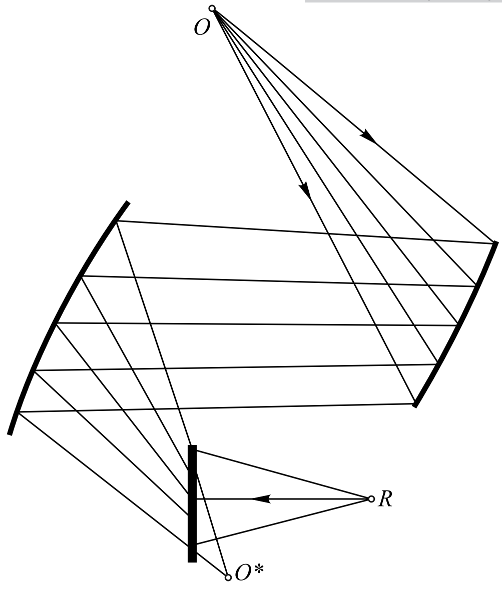

*Fig. 5. The optical setup for recording a Denisyuk hologram simulated by the Optically Fabricated Hologram surface in the Zemax environment: R and O are the centers of radiated spherical wavefronts; O*is a conditional centre of the distorted wavefront generated by a system consisting of two freeform mirrors*

Optimization and search of the design parameters of elements of the optical setup for generating the aspherical wavefront for recording the Denisyuk hologram are based on ray tracing. These processes are greatly facilitated by the use of the intermediate model in the form of a thin transparency for phase delay. The phase delay of this transparency, the mirror geometry of the optical setup that forms the aspherical wavefront for recording the hologram, and the actual model of the Denisyuk hologram in this article are described in the form adopted in the Zemax environment for surfaces such as Binary1, Extended polynomial and Optically Fabricated Hologram, respectively.

Acknowledgements

The work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the State Contract for Higher Educational Institutions in the Area of Scientific Activity.

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