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Impact of aberrations on speckle suppression efficiency on moving a DOE inside the optical system ☆

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ABSTRACT

The impact of aberration on the speckle suppression efficiency is investigated in a laser projector system containing a moving diffractive optical element (DOE). The results of a qualitative analysis based on the number of diffraction orders passed through the optical system are presented, along with a quantitative analysis built upon the Fresnel approximation and the thin lens model. It is shown that the speckle contrast in the paraxial area of the screen is practically insensitive to aberrations — limited to a few percent at most, due to the change in angle between diffraction orders. However, the speckle contrast in peripheral areas changes stepwise if aberrations change the number of diffraction orders that illuminate the area.

1. Introduction

Lasers have high optical efficiency and emit high-quality beams, and enable the production of low-cost, compact optical projectors and illumination systems [1]. However, an image created by a coherent source is modulated by the coherent noise (subjective speckle) [2]. Therefore speckle reduction is a pressing issue in the design of laser projectors [2–5] and coherent light systems [6,7]. The speckle contrast (SC) is used to characterize the intensity of the speckle noise and it is calculated as follows:

$$SC = \sigma/\bar{I}, \tag{1}$$

where $\bar{I}$ is the mean light intensity and σ is the standard deviation of the light intensity. Hardware noise reduction methods are based on the noise averaging [2]. In turn, speckle noise averaging is based upon the reduction of the coherence of the laser beam. There exist three possibilities to reduce the coherence of the laser source: lowering the polarization coherence (polarization averaging) [8,9], decreasing the temporal coherence (averaging over wavelengths) [2,10,11], and reducing the spatial coherence (averaging over incidence angles) [2,12–25].

One of the simplest ways to reduce the spatial coherence is by using decorrelated beams, coming from different angles (decorrelation angles). This can be achieved by dividing a single laser beam with the help of a diffractive optical element and then applying different beam delays [14]. It is also possible to use sufficiently long multimode optical fibers [15,16] or light tubes [12] in this decorrelation regime.

One of the most promising methods of speckle reduction is based on the use of a moving diffuser [17] or DOE [18–26], placed inside the optical system. Application of a DOE allows accurate control over the parameters of the optical system, which facilitates the development of optical systems with the required characteristics.

One method is to use a 2D DOE based on pseudorandom binary sequences (Barker or *M*-sequences code), allowing manipulation of the angular diversity in two planes simultaneously by a simple rectilinear DOE shift [22–26]. A shift of *N* DOE periods is sufficient to obtain the maximum achievable speckle suppression efficiency of this method, where *N* is the code length. Using such an approach, large speckle suppression efficiencies have been experimentally demonstrated [26].

It is well known that fully developed speckle is not sensitive to aberrations in the imaging system [2,27–29] (human eye). The topic of this research is the dependence of speckle suppression efficiency on aberrations in the optical system of a projector

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(not aberrations of the imaging system, and not for fully developed speckle). It is shown that the problem of speckle can be reduced to the width of the module autocorrelation function of the laser beam passed through the DOE. Therefore the problem can be reduced to the distortion of the autocorrelation function of the laser beam that is incident on screen by the aberrations in the projector. In order to obtain a large speckle suppression efficiency the autocorrelation function of light passed through the moving DOE should be narrow relative to the resolution of image system (both measured at the screen plane). The objective lens of the projector should collect the majority of the light diffracted by DOE to have large optical efficiency. Therefore, the DOE element width should be within the resolution of the projector. It is well known that the autocorrelation function width of scattered-by-screen light should be significantly smaller than the resolution of the objective lens of the imaging system (human eye) to obtain a fully developed speckle pattern (contrary to conditions to get large speckle suppression efficiency with high optical efficiency in the projector). This condition is directly used to prove the independence of fully developed speckle statistics on aberrations in the imaging system (human eye) [2]. Consequently, the dependence of speckle suppression efficiency on aberrations in the projector cannot be derived from the fully developed, aberration-independent, speckle in the imaging system.

The influence of aberrations on speckle suppression for the case of a 1D scanning laser projector was analyzed in [19]. The lens in this projector was placed in the far zone of the optical modulator because of small pixel widths. In this case, aberrations only distort the phase of the light spatial frequencies. However, the situation is different for a laser projector with a 2D optical modulator, the length and width of which can be comparable to the diameter of the lens diameter. Note that in [19] it was assumed that the objective had an infinite aperture, an assumption which is not valid in our case.

The influence of aberrations and defocusing of the optical system on the efficiency of speckle reduction is analyzed below for two different locations of the DOE inside the optical system. A model based on the thin lens and Fresnel approximations is applied, in which the quadratic phase factor in the object plane [30] — an important parameter in the study of coherent optical systems — is taken into account.

2. Optical scheme of laser projector with movable DOE

Fig. 1 shows two possible optical schemes with different DOE locations. In the optical scheme shown in Fig. 1a, the optical modulator (2) is positioned in the image plane of the moving Barker code type DOE (4) of the first lens (3). DOE movement changes the phase of the diffraction orders and decreases the spatial coherence of the laser beam, which results in the speckle suppression effect. The wave front of the collimated laser beam is modulated by the DOE and then projected onto the optical modulator. The image created by the optical modulator (free of speckle) is projected on the screen (6) by the second lens (5). The lens of the optical image system (7) (human eye or camera) collects the light scattered by the rough screen and creates an image modulated by the speckle (which arises due to the scattering of light by the screen). In order to implement this scheme it is important to know how sensitive the speckle suppression efficiency is to aberrations in the projector optical system and to a shift of the optical modulator relative to the image plane of the DOE. This analysis was performed only for the aberrations of the first lens (3), but it can easily be generalized to the entire optical system of the laser projector.

In the second scheme (Fig. 1b), the moving DOE (4) is placed just before the optical modulator (2). In this case, the distance between the DOE and optical modulator can vary within a large range. The image created by the optical modulator is projected on the screen (6) by the lens (3). Then, the lens of the optical image system (7) collects the scattered light and creates an image modulated by the speckle. Prior to implementation of this scheme, more research is necessary to determine how the distance between the DOE and an optical modulator influences the efficiency of speckle suppression.

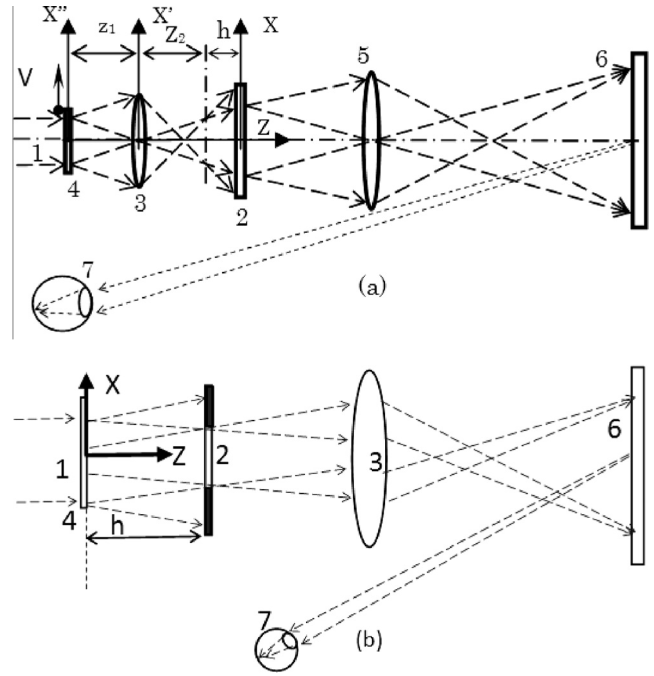

Fig. 1. Two optical schemes of the laser projector with moving DOE: collimated laser beam 1; - optical modulator 2; first lens 3; DOE 4; second lens 5; screen 6, eye 7.

Since we are only interested in the SC, we can assume that all pixels of the optical modulator are switched on and do not modulate the beam intensity. We also assumed that without moving the DOE, the viewer would see a fully developed speckle pattern on the screen (this assumption is made to extract information on the independent effect of DOE movement on speckle suppression).

The dependence of SC on the aberrations of the illumination part of the projector (with the DOE placed inside the illumination part) is investigated below. Similar results can be obtained for the objective lens of the projector; therefore, the results obtained below are valid for the whole optical system of the projector. The results obtained are also valid when the DOE is situated in any plane conjugated to the screen.

3. Mathematical model of speckle reduction mechanism

The SC in the image of the screen was calculated by [20] (for 2D geometry):

$$SC = 2\sqrt{\int_{-\infty}^{\infty} |A_0(Du)/A_0(0)|^2 Q(u)du} \qquad (2)$$

where $Q(u) = \int_{-\infty}^{\infty} \sin c^2(2\pi v) \sin c^2(2\pi(v+u))dv = [1 - \sin c^2(4\pi u)]/8\pi^2u^2$; D is the spatial resolution of the eye at the screen, $D = \lambda/NA_{2in}$; NA_{2in} is the input numerical aperture of the human eye; $A(x)$ is the autocorrelation function of the light field on the screen which was obtained by taking an average over the time resolution of the human eye t_0