Optics Communications 312 (2014) 245–251

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Color digital holography using speckle illumination by means of a multi-mode fiber

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ARTICLE INFO

Article history:
Received 19 July 2013
Received in revised form
10 September 2013
Accepted 15 September 2013
Available online 27 September 2013

Keywords:
Digital holography
Multi-mode fiber
In-line holography
Color

ABSTRACT

We present color digital holography using speckle illumination by means of a multi-mode fiber. In this technique, speckle fields emitted from the fiber are used as both a reference wave and a wavefront illuminating an object. For three wavelengths, the interference patterns of two coherent waves are recorded as digital holograms on a CCD camera. A speckle method is used for suppressing DC terms and reducing a twin image in an in-line color digital holography. The speckle fields are changed by vibrating the multi-mode fiber using a vibrator, and a number of holograms are acquired to average reconstructed images. The dependence of the averaged number of holograms on color quality of reconstructed images is evaluated by chromaticity coordinates and color differences in colorimetry.

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1. Introduction

It is known that digital holography is a technique for the recording and reconstruction of complex amplitudes of an optical field [1–4]. In this technique, an interference pattern of two coherent wavefronts is detected and digitized by an image sensor such as a CCD or CMOS camera, and digital holograms are saved into a computer. The wavefront is reconstructed from the digital holograms numerically. In a reconstruction process of the wavefront, DC terms, real and twin images are produced simultaneously. In an in-line setup, DC terms and a twin image are superimposed on a real image, which causes a degradation of image quality [5–8]. In off-axis [9–14] and phase-shifting digital holography [15–23], a real image is free from the degradation due to these cumbersome terms while these methods make a sacrifice of either temporal or spatial resolutions.

As an alternative method for reducing DC terms and a twin image in an in-line digital holography, a technique using a speckle illumination, which is called a speckle method, has been proposed [4,24,25]. In this technique, an object is illuminated with speckle fields generated from a diffuser. After acquiring a number of holograms using statistically independent speckle fields, DC terms are suppressed by applying a high-pass filter to each digital hologram [26]. Real and twin images reconstructed from multiple holograms are averaged for reducing the intensity fluctuation of real images due to speckle illuminations and eliminating a twin image. After the averaging process, intensity distributions of a twin image become a constant since it is regarded as a speckle field by the use of speckle illumination. Therefore, a twin image is eliminated by subtracting the constant from the reconstructed image. In comparison with the other methods, the speckle method has several advantages in that spatial resolution in the three-dimensional space and image quality are improved by the averaging process since speckle noises are reduced in reconstructed images and phase-shifting devices with high cost are not necessary. Meanwhile, it has disadvantages in that temporal resolution becomes lower due to the acquisition of a number of holograms and phase information of reconstructed images is not directly obtained since it is randomly modulated by the complex amplitude of speckle illuminations.

Recently, we proposed the speckle method by means of a multi-mode fiber in an in-line digital holography [27]. In this method, we use speckle fields emitted from a multi-mode fiber as both a reference wave and a wavefront illuminating an object. To capture multiple holograms in the speckle method, speckle fields are changed by vibrating the multi-mode fiber using a vibrator, which is composed of the DC motor with a speed controller. This method has several advantages in that (i) a simple optical system is realized by means of an optical fiber, (ii) it becomes easy to couple a coherent light into the optical fiber since multi-mode fibers have the larger core diameter in comparison with single-mode fibers and (iii) the speckle method can be readily performed by using speckle fields emitted from the fiber with a vibrator.

In the present paper, we report the application of this method to color digital holography, which is actively researched in 3D color imaging [28–38], recognition of a 3D color object [39], deformation

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http://dx.doi.org/10.1016/j.optcom.2013.09.032

measurement [40,41] and microscopy [42,43]. Although this technique can acquire the three-dimensional color information of an object, it has a disadvantage in that an optical system becomes quite complex due to the use of three lasers operating at different wavelengths. While an introduction of a fiber optic system is one of the methods for overcoming this disadvantage, it causes a reduction of optical powers in coupling laser lights with different wavelengths into an optical fiber, in particular, in the case of a single-mode fiber. This problem is mostly solved by means of a multi-mode fiber because of the larger core diameter. The proposed method has an another advantage in that color quality of reconstructed images can be readily improved by averaging multiple holograms since color reconstructed images have low quality due to speckle noise. In addition, to the best of our knowledge, color digital holography using speckle illuminations has not been reported elsewhere.

In Section 2, we introduce the theoretical background of the recording digital holograms and reconstruction of wavefronts. Section 3 describes the suppression of DC terms and reduction of a twin image using the speckle method. In Section 4, we explain the color analysis of reconstructed images. The experimental results are shown in Section 5.

2. Recording digital holograms and reconstruction of wavefront

Fig. 1 shows the schematic diagram of an optical geometry for recording digital holograms. It is based on an in-line digital holography. In this geometry, an image sensor is placed in the (x_h, y_h) plane, which is called the hologram plane. A three-dimensional object and a light source are placed in the (x_o, y_o) and (x_s, y_s) plane, which is called the object and source planes. The object and source planes are located at distances d and d_s from the hologram plane.

A speckle field emitted from a multi-mode fiber is used as a reference wave, while an object wave is generated by illuminating the object with the speckle field. These waves interfere with each other and are detected on the image sensor. It digitizes holograms and digital holograms are acquired in a computer.

Complex amplitudes of object and reference waves on the image sensor are derived from the Fresnel diffraction integral [44]. For simplicity, we carry out 1-D analysis, and constant terms and the integral regions which span from $-\infty$ to ∞ are omitted. The complex amplitude $U_r(x_h)$ of the reference wave in the hologram plane is expressed as

$$\begin{aligned} U_r(x_h) &= \int u_{s1}(x_s)\exp\left[\frac{j\pi}{\lambda d_s}(x_h - x_s)^2\right] dx_s \\ &= U_{s1}(x_h)\exp\left(\frac{j\pi}{\lambda d_s}x_h^2\right), \end{aligned} \tag{1}$$

where $u_{s1}(x_s)$ is a speckle field emitted from a multi-mode fiber in the source plane, λ is the wavelength of an optical source

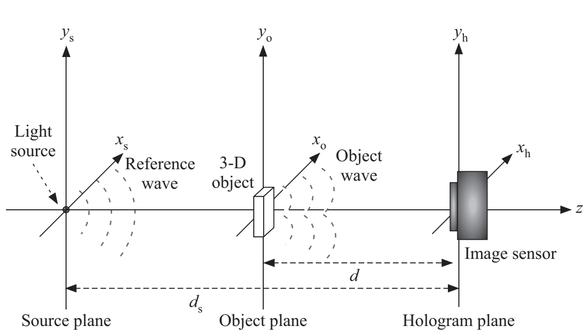

Fig. 1. Schematic diagram of an optical geometry for recording an in-line digital hologram.

and $U_{s1}(x_h)$ is

$$U_{s1}(x_h) = \int u_{s1}(x_s)\exp\left(\frac{j\pi}{\lambda d_s}x_s^2\right)\exp\left(-\frac{j2\pi}{\lambda d_s}x_h x_s\right) dx_s. \tag{2}$$

In a similar fashion, we obtain the complex amplitude $U_o(x_h)$ of an object wave in the hologram plane

$$\begin{aligned} U_o(x_h) &= \exp\left(\frac{j\pi}{\lambda d}x_h^2\right)\mathcal{F}_{\lambda d}\left[u_{s2}(x_o)u_o(x_o)\exp\left(\frac{j\pi}{\lambda d}x_o^2\right)\right] \\ &= \exp\left(\frac{j\pi}{\lambda d}x_h^2\right)\mathcal{F}_{\lambda d}[u'_{s2}(x_o)], \end{aligned} \tag{3}$$

where $u_{s2}(x_o)$ is the complex amplitude of a speckle field generated by the multi-mode fiber in the object plane, $u_o(x_o)$ is the complex amplitude of an object, $\mathcal{F}_{\lambda d}[\cdot]$ stands for the Fourier transform modified by a factor of $1/(\lambda d)$ and $u'_{s2}(x_o)$ is

$$u'_{s2}(x_o) = u_{s2}(x_o)u_o(x_o)\exp\left(\frac{j\pi}{\lambda d}x_o^2\right). \tag{4}$$

The intensity distribution $I_H(x_h)$ of the interference pattern of object and reference waves can be written as

$$I_H(x_h) = |U_r(x_h) + U_o(x_h)|^2 = |U_r(x_h)|^2 + |U_o(x_h)|^2 + U'_o(x_h) + U'^{*}_o(x_h), \tag{5}$$

where $*$ stands for the complex conjugate and $U'_o(x_h) = U_o(x_h)U^*_r(x_h)$. In Eq. (5), the third term is a real image

$$U'_o(x_h) = U^*_{s1}(x_h)\exp\left(\frac{j\pi}{\lambda d_f}x_h^2\right)\mathcal{F}_{\lambda d}[u'_{s2}(x_o)], \tag{6}$$

where d_f is a reconstruction distance of a real image given by

$$d_f = \left(\frac{1}{d} - \frac{1}{d_s}\right)^{-1}. \tag{7}$$

In the reconstruction process, the inverse propagation of optical fields is simulated by using the Fresnel transform method, which is called the single-FFT method [3,4]

$$\begin{aligned} u_{rec}(x_r) &= \mathcal{F}^{-1}_{\lambda d}[S_F(x_h)I_H(x_h)] \\ &= \int I_H(x_h)\exp\left(-\frac{j\pi}{\lambda d_f}x_h^2\right)\exp\left(\frac{j2\pi}{\lambda d}x_r x_h\right) dx_h \end{aligned} \tag{8}$$

$$u_{rec}(x_r) = \mathcal{D}_{d_f}[|U_r(x_h)|^2 + |U_o(x_h)|^2] + \mathcal{D}_{d_f}[U'_o(x_h)] + \mathcal{D}_{d_f}[U'^{*}_o(x_h)], \tag{9}$$

where x_r is the coordinate in the reconstruction plane, $\mathcal{D}_{d_f}[\cdot]$ stands for the optical propagation from the hologram plane to the reconstruction plane and $S_F(x_h)$ is the quadratic phase factor for focusing a real image expressed as

$$S_F(x_h) = \exp\left(-\frac{j\pi}{\lambda d_f}x_h^2\right). \tag{10}$$

In Eq. (9), the first, second and third terms are DC terms, real and twin images, respectively.

In digital holography, an intensity distribution in Eq. (5) is sampled by an image sensor and saved into a computer. A numerical reconstruction of the object wave is performed by the fast Fourier transform of digital holograms. The discrete form of Eq. (8) is expressed for integers p and q as

$$\begin{aligned} u_{rec}(q\Delta') = &\sum_{p=-N/2}^{N/2-1} I_H(p\Delta)\exp\left[-\frac{j\pi}{\lambda d_f}(p\Delta)^2\right] \\ &\times\exp\left(\frac{j2\pi}{\lambda d}q\Delta' p\Delta\right) \end{aligned} \tag{11}$$

for $q = -N/2, -N/2+1, \ldots, N/2-1$, where N is the data size of digital holograms, and Δ and Δ' are the pixel sizes of an image sensor and the reconstruction plane, respectively. The coordinates x_h and x_r are converted into $p\Delta$ and $q\Delta'$. The pixel size Δ' and the field

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