Optik 125 (2014) 4389–4393

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Study on the reduction of speckle noise in the reconstructed image of digital hologram

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ARTICLE INFO

Article history:
Received 12 August 2013
Accepted 10 March 2014

Keywords:
Digital holography
Speckle noise
Object light
Reconstructed image
Rebuilt hologram

ABSTRACT

As one of the most important 3-D display technique, reduction of speckle noise in the reconstructed image of digital holography should be grounded on the digital hologram itself. Based on the whole process of the recording and reconstruction of digital holography, the optical distributions of recorded object and reconstructed image of digital holography have been studied. It has been proposed that the root formation cause of speckle noise in its reconstructed image is the speckle noise formed on the recorded object surface when illuminated by coherent light because of its optical roughness. A novel approach has been presented to reduce speckle noise in digital holography by changing the interference structure of hologram itself. First, by reducing the speckle noise in the reconstructed image, the distribution of ideal reconstruction light with reduced speckle noise is acquired. Then in turn, taking the ideal reconstruction light with reduced speckle noise as ideal object light, a new hologram can be rebuilt, which can reconstruct the ideal object light. The experimental results are given to confirm the proposed method. Therefore, it offers a brand-new thought and practical way to reduce the speckle noise in the reconstructed image of digital holography.

1. Introduction

As an important technique for information recording and display, holography has been widely applied in many fields, covering measurement of profilometry, deformation and vibration, etc. And with the increasing application on digital holography, how to acquire reconstruction with high image quality has been a very important research topic [1,2]. But for the digital holography, its coherent noise is inevitable, and the coherent noise debases the quality of reconstructed image seriously. Especially speckle noise in the reconstructed image does. Since the existence of speckle noise, the light intensity of reconstructed image changes sharply, namely, some units are very bright and some other units are dark on a surface with even light intensity, which conceals the fine-construction, declines the gray-level and space resolution of the reconstructed image. Additionally, the speckle noise has been one of the most difficult problems in the coherent imaging system because of its badly statistical regularity. Hence, it is of particular importance to seek an effective way to reduce the speckle noise of digital holography. Based on digital signal processing techniques, many approaches were proposed, i.e. classical filtering [3], suppression based on flat fielding with apodized apertures [4],Wiener filtering with an aperture function [5], discrete Fourier filtering [6], and wavelet filtering [7]. However, these processes are based upon speckle noise in the reconstructed image only, rather than the digital hologram itself. As one of the most important 3-D display technique, reduction of speckle noise in the reconstructed image of digital holography should be grounded on the digital hologram itself. That is, to meet the most fundamental requirement as a medium for storage and reconstruction of 3D object light information, the reduction of speckle noise in the reconstructed image can only be accomplished by changing the interference structure of hologram itself.

Focusing on the whole process of the recording and reconstruction of digital holography, we study the formation causes and reduction way of speckle noise in the reconstructed image of digital holography. Firstly, the optical distributions of recorded object and reconstructed image of digital holography have been studied. We gain the conclusion that the root formation cause of speckle noise in its reconstructed image is the speckle noise formed on the recorded object surface when illuminated by coherent light because of its optical roughness. Then the distribution of ideal reconstruction light with reduced speckle noise is gained by reducing the speckle noise in the reconstructed image. And in turn, taking the ideal reconstruction light as ideal recording object light, a new hologram can be rebuilt, which can reconstruct the ideal object light with reduced speckle noise. The experimental results are given

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http://dx.doi.org/10.1016/j.ijleo.2014.03.017
0030-4026/

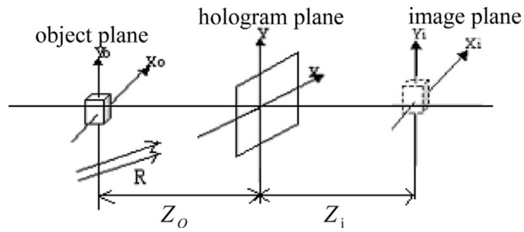

Fig. 1. Schematic for recording and reconstructing of a digital hologram.

to confirm the proposed method. Therefore, the paper offers a brand-new thought and practical way to reduce the speckle noise in digital holography.

2. Formation cause of speckle noise in the reconstructed image of digital holography and its characteristics

Based on interference theory, information including amplitude and phase of object light, can be recorded by hologram in the form of interference fringes. Supposing that the reference light is $R(x,y)$, object light is $O(x,y)$ and reconstruction light is $C(x,y)$, schematic for recording and reconstructing of a digital hologram is shown in Fig. 1.

Since different object have different surface scattering when the coherent light is reflecting on its surface, an object reflectivity can be expressed as Eq. (1).

$$t(r) = f(r)s(r) \tag{1}$$

where $f(r)$ is a determinate function expressing an ideal signal, $s(r)$ is the random phase distribution. In other words, as shown in Fig. 2, a piece of object surface is equivalent to two overlapping plates, in which, one plate is the plate whose reflectivity is $f(r)$, the other is a random phase screen $s(r)$.

So the complex amplitude distribution of light field attaching to the object surface can be expressed as:

$$\begin{aligned} O(x_0, y_o, z_o) &= \sum_n f(x_{on}, y_{on}, z_{on}) s(x_{on}, y_{on}, z_{on}) e^{i(2\pi/\lambda)s(x_{on}, y_{on}, z_{on})} \\ &= O(x_0, y_o, z_o) n(x_0, y_o, z_o) e^{i(2\pi/\lambda)O'(x_0, y_o, z_o)} \end{aligned} \tag{2}$$

where $f(x_{on}, y_{on}, z_{on})$ is complex amplitude reflectivity of an ideal object surface without optical roughness, $s(x_{on}, y_{on}, z_{on})$ and $2\pi/\lambda s(x_{on}, y_{on}, z_{on})$ are random variety of the reflectivity and phase difference resulting from the rough surface respectively, $n(x_0, y_o, z_o)$ and $2\pi/\lambda O'(x_0, y_o, z_o)$ are amplitude distribution of speckle noise and phase distribution of light field attaching to the object surface

$$\begin{aligned} U_{ireal}(x,y) &= \left|R(x,y)^2\right| \iint \sum_n f^*(x_{on}, y_{on}, z_{on}) s^*(x_{on}, y_{on}, z_{on}) e^{-i\frac{2\pi}{\lambda} s(x_{on}, y_{on}, z_{on})} e^{-i\frac{2\pi}{\lambda}\left(\frac{x_{on}^2 + y_{on}^2}{2z_{on}} - \frac{x x_{on} + y y_{on}}{z_{on}}\right)} \times e^{i\frac{2\pi}{\lambda}\left(\frac{x_i^2 + y_i^2}{2z_i} - \frac{x x_i + y y_i}{z_i}\right)} dxdy \\ &= \left|R(x,y)^2\right| \sum_n f^*(x_{on}, y_{on}, z_{on}) s^*(x_{on}, y_{on}, z_{on}) e^{-i\frac{2\pi}{\lambda} s(x_{on}, y_{on}, z_{on})} e^{-i\frac{2\pi}{\lambda}\left(\frac{x_{on}^2 + y_{on}^2}{2z_{on}}\right)} \times e^{i\frac{2\pi}{\lambda}\left(\frac{x_i^2 + y_i^2}{2z_i}\right)} \iint_{\Sigma} e^{-i\frac{2\pi}{\lambda}\left(\frac{x_i - x_{on}}{z_{on}} x + \frac{y_i - y_{on}}{z_{on}} y\right)} dxdy \\ &= C_{ireal} \sum_n f^*(x_{on}, y_{on}, z_{on}) s^*(x_{on}, y_{on}, z_{on}) e^{-i\frac{2\pi}{\lambda} s(x_{on}, y_{on}, z_{on})} e^{-i\frac{2\pi}{\lambda}\left(\frac{x_{on}^2 + y_{on}^2}{2z_{on}}\right)} \times e^{i\frac{2\pi}{\lambda}\left(\frac{x_i^2 + y_i^2}{2z_i}\right)} \delta(x_i - x_{on}, y_i - y_{on}) \\ &= C_{ireal} \sum_n f^*(x_{on}, y_{on}, z_{on}) s^*(x_{on}, y_{on}, z_{on}) e^{-i\frac{2\pi}{\lambda} s(x_{on}, y_{on}, z_{on})} \\ &= C_{ireal} O(x_o, y_o, z_o) n(x_o, y_o, z_o) e^{-i\frac{2\pi}{\lambda} o''(x_o, y_o, z_o)} \end{aligned} \tag{9}$$

respectively resulting from addition of random complex amplitude when the object is in the laser illumination. And the according light intensity is

$$I = \left|O(x_o y_o, z_o)\right|^2 \left|n(x_o, y_o, z_o)\right|^2 = I_o I_n \tag{3}$$

where I_o is light intensity distribution of an ideal object surface without optical roughness, and I_n is light intensity distribution of speckle noise. It is evident that there is speckle noise on the object surface in the laser illumination. On the recording plane of hologram, the distribution of object light can be expressed as:

$$O(x,y) = \sum_n f(x_{on}, y_{on}, z_{on}) \times s(x_{on}, y_{on}, z_{on}) e^{i(2\pi/\lambda)s(x_{on}, y_{on}, z_{on})} e^{i(2\pi/\lambda)d(x_{on}, y_{on}, z_{on}, x, y)} \tag{4}$$

where $d(x_{on}, y_{on}, z_{on}, x, y) \approx (x^2 + y^2/2z_{on}) + (x_{on}^2 + y_{on}^2/2z_{on}) - (x x_{on} + y y_{on}/z_{on})$, which is additional optical path expressed with Fresnel approximation when the object light reaches the recording plane of hologram. So the total light intensity recorded by CCD is

$$\begin{aligned} I(x,y) = \left|O(x,y) + R(x,y)\right|^2 &= O(x,y)O^*(x,y) + R(x,y)R^*(x,y) \\ &+ O(x,y)R^*(x,y) + O^*(x,y)R(x,y) \end{aligned} \tag{5}$$

And the holographic transmission is

$$\begin{aligned} \tau \propto \left|O(x,y) + R(x,y)\right|^2 &= O(x,y)O^*(x,y) + R(x,y)R^*(x,y) \\ &+ O(x,y)R^*(x,y) + O^*(x,y)R(x,y) \end{aligned} \tag{6}$$

Using the conjugate wave of the reference light as reconstruction illumination, the outgoing light from hologram is

$$\begin{aligned} U_c(x,y) = R^*(x,y)I(x,y) &= R^*(x,y)O(x,y)O^*(x,y) \\ &+ R^*(x,y)R(x,y)R^*(x,y) + R^*(x,y)O(x,y)R^*(x,y) \\ &+ R^*(x,y)O^*(x,y)R(x,y) \end{aligned} \tag{7}$$

So the diffraction light on the reconstruction plane is

$$U_i(x,y) = \iint_{\Sigma} U_c(x,y) e^{i(2\pi/\lambda)d'(x_i, y_i, z_i, x, y)} \tag{8}$$

where $d'(x_i, y_i, z_i, x, y) \approx (x^2 + y^2/2z_i) + (x_i^2 + y_i^2/2z_i) - (x x_i + y y_i/z_i)$, which is optical path expressed with Fresnel approximation when outgoing light from hologram reaches the reconstruction plane, and the integral range Σ is holographic aperture.

When image distance z_i is equal to the object distance z_{on}, the diffraction wave of real image $U_{ireal}(x,y)$ is:

where $O(x_o, y_o, z_o) \times n(x_o, y_o, z_o)$ is amplitude distribution of object light with speckle noise. And its according intensity is

$$\begin{aligned} I = U_{ireal}(x,y)U^*_{ireal}(x,y) &= \left|C_{ireal}\right|^2 \left|O(x_o y_o, z_o)\right|^2 \left|n(x_o, y_o, z_o)\right|^2 \\ &= \beta I_o I_n \end{aligned} \tag{10}$$