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# Reduction of speckle noise in digital holography by combination of averaging several reconstructed images and modified nonlocal means filtering

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A B S T R A C T

Although the speckle noise in hologram reconstructed image can be effectively suppressed by averaging multiple reconstructions with different speckle patterns, the approach usually needs a lot of the reconstructions and encounters an improvement limit. In this paper, we propose a speckle noise suppression method that combines averaging several reconstructed images and a modified non-local means (MNLM) filtering method. First, the probability density function (PDF) of the averaged speckle field after averaging multiple hologram reconstructions is deduced, then the number of hologram reconstructions for the averaging process is inferred for making the speckle noise distribution approaches Gaussian distribution. Second, considering the statistical model of the multiplicative Gaussian noise, we modify the NLM filtering for effectively removing the residual noise in the averaged image. The experimental results show that the proposed method can reduce the speckle noise more than 90% and achieve nearly speckle-free. Compared with another similar method, the presented method is more effective and feasible to suppress speckle noise and preserve image contrast based on a small number of reconstructions.

## 1. Introduction

Digital holography (DH) is a powerful imaging technique with the ability to provide both the amplitude and phase of a light wave field at the microscopic or macroscopic scale [1]. DH as a means for nondestructive testing, as well as metrological tools has led to the development of a huge set of applications in many fields, including examination of biological specimens [2], shape measurement and deformation analysis [3], vibration measurement [4], particle tracking [5], information encryption, and homeland security [6]. However, owing to the coherent nature of the light source, digital holograms are corrupted by the speckle when the coherent light passes through a randomly fluctuating media, or is reflected from a rough surface [7]. Besides, such speckle noise is also propagated in the numerical reconstruction process, which can severely impair the quality of the reconstructed images.

Several attempts have been made to reduce the degradation effect of speckle noise in DH. Based on digital signal processing techniques, many methods were proposed, e.g., classical filtering [8], Wiener filtering [9], discrete Fourier filtering [10], wavelet filtering [11], non-local means filtering [12], and multilevel two-dimensional empirical decomposition mode [13]. However, there is a trade-off for using the method and lateral resolution is diminished. Considering the fact that speckle noise is generated owing to the coherent nature of the light sources, some methods based on reducing the coherence of light are presented, such as engineering the laser source [14] or using a light source with lower coherence [15]. However, by using these methods, the depth that can be recorded is limited and the system impulse response is broadened [16]. Averaging several hologram reconstructions with different speckle patterns has also been proposed to reduce the speckle. The uncorrelated speckle patterns can be provided by various approaches, such as wavelength [17] polarization state [18], illumination angle diversity [19,20], slightly shifting the sample or camera [21,22], adopting a moving rough diffuser [23], slightly rotating the sample [24], or using a multimode laser [25]. Moreover, the uncorrelated speckle patterns can be also acquired by operating on a single hologram [26–28]. As a related approach, the synthetic aperture imaging technique was also used to reduce coherent noises in digital holography microscopy [29]. For this strategy, the de-noising performance depends on the noise decorrelation extent between the different holograms. Among these aforementioned approaches, averaging multiple hologram reconstructions has been demonstrated to be very powerful and practical for

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the reduction of speckle noise in DH. However, the residual noise still cannot be ignored when using this method, because its performance is bounded. To remove the residual noise and surpass the improvement limit, Bianco et al. proposed the MLDH-BM3D method, in which 3D block matching filtering was utilized to remove the residual noise after averaging multiple hologram reconstructions [30]. The 3D block matching filtering strictly relies on the preliminary grouping, whose performance is in turn dependent on the signal-to-noise ratio (SNR) of the reconstructed images. In other words, a low SNR can lead to incorrect grouping and can severely affect the reconstruction quality. Thus, it is vital to obtain large number of uncorrelated speckle patterns to provide an averaged reconstructed image with a high SNR in the MLDH-BM3D.

In this paper, we deduce the PDF of the averaged speckle field after averaging multiple hologram reconstructions. Based on the result, a speckle suppression method that combines averaging multiple reconstructed images and MNLM filtering is proposed. First, multiple holograms with uncorrelated speckle patterns are obtained by rotating the polarization state. Then, every hologram is reconstructed individually and an averaging procedure is conducted. Finally, the MNLM filtering designed for multiplicative Gaussian noise is utilized to remove the residual noise within the averaged image.

## 2. Principle and method

In configuration of DH, speckle noise forms inevitably when the rough surface is illuminated by coherent light. In this case, the light wave field on the object plane $(\xi, \eta)$ can be regarded as the complex amplitude of the object modulated by the random complex amplitude and expressed as [9]

$$U_{op}(\xi,\eta) = B(\xi,\eta)\cdot S(\xi,\eta) \tag{1}$$

where $B(\xi,\eta) = A_b(\xi,\eta)\exp(i\varphi_b)$ is the complex amplitude of the object light wave, and $S(\xi,\eta) = A_s(\xi,\eta)\exp(i\varphi_s)$ is the random complex amplitude due to random scattering, $A$ and $\varphi$ represent the amplitude and phase, respectively. After that, the reflected light wave propagates from the object plane to the recording plane and superposes with a plane reference light wave, so a hologram is formed and recorded by the charge-coupled device (CCD) camera. Subsequently, the complex amplitude is reconstructed by using the Fresnel algorithm on the image plane $(x, y)$, which is written as [31]

$$U_{ip}(x,y) = D\cdot\{b(\xi,\eta)\cdot s(\xi,\eta)\}\otimes \operatorname{sinc}\left(ax-\frac{ak\xi}{d}, \text{by}-\frac{bk\eta}{d}\right) \tag{2}$$

where constant intensity and phase factors are contained in $D$, $\lambda$ denotes the wavelength, $k = 2\pi/\lambda$ is the wave number, $d$ denotes the distance between the object plane and recording plane, $a$ and $b$ are the length and width of the sensor array, and $\otimes$ denotes the convolution operation. Therefore, DH equals to an optical system imaging a light field in the object plane to a reconstructed light field in the image plane. Moreover, the reconstructed light field is the convolution of the light field of object and the shifted Fraunhofer diffraction pattern of the aperture defined by the CCD dimensions. So the reconstructed complex amplitude can be actually obtained by numerically de-convolved, and be rewritten as:

$$U_d(i,j) = B(i,j)\cdot S(i,j) \tag{3}$$

Obviously, the complex amplitude in Eq. (3) has the same distribution as that in Eq. (1). The intensity image can be expressed as

$$I(i,j) = U_d\cdot U_d^* = I_B(i,j)\, I_S(i,j) \tag{4}$$

where $I_B$ and $I_S$ are the intensity of the ideal light field of object and speckle respectively.

When the surface roughness exceeds the wavelength of laser and the surface correlation extent is much smaller than the illuminated area, a fully developed speckle pattern is formed on the object plane in which the probability of the speckle intensity at a given point is described by the negative-exponential density function [32]. In particularly, the reconstructed speckle intensity is discretized and area integrated owing to the finite-sized pixel of the CCD image sensor. Moreover, a pixel on the image plane actually corresponds to a rectangle region on the object plane, whose width is $\Delta\xi = d\lambda/a$ and length is $\Delta\eta = d\lambda/b$. According to boxcar approximation theory, the PDF of integrated speckle intensity can be calculated, where an integrated area is divided into $m$ equal and identically shaped subareas [33]. And the speckle intensity within a subarea is a constant and statistically independent with all other subareas. The PDF of speckle intensity in any one subarea is taken to be the same negative exponential density. Therefore, the reconstructed speckle intensity $I_S(i, j)$ at a given pixel is described as

$$I_S(i,j) \approx \frac{1}{A_D}\sum_{q=1}^{m} A_0 I_q \tag{5}$$

where $A_D = \Delta\xi\cdot\Delta\eta$ is the speckle integrated area, $A_0$ is the area of subarea and $I_q$ is the speckle intensity of $q$th subarea.

In order to suppress the speckle noise in the reconstructed image, a series of digital holograms with different speckle patterns is recorded by using various strategies, as described above. Thus, the reconstructed images possess different speckle patterns. Let $Im_1, Im_2, \ldots, Im_T$ represent a series of reconstructed images with different speckle patterns ($T$ is the number of reconstructed image) and $Ir_1, Ir_2, \ldots, Ir_T$ are corresponding reconstructed speckle patterns. After subjecting these reconstructed images to an averaging process, the corresponding speckle pattern is obtained as

$$I_a = \frac{1}{T}\sum_{t=1}^{T} I_{rt} \tag{6}$$

Therefore, the averaged speckle intensity at a given pixel can be expressed as

$$I_a(i,j) = \frac{1}{T}\left[Ir_1(i,j) + Ir_2(i,j) + \cdots + Ir_T(i,j)\right] \tag{7}$$

Since the reconstructed speckle patterns are independent of each other, combining Eq. (5) and boxcar approximation theory, Eq. (7) is rewritten as

$$I_a(i,j) \approx \frac{1}{TA_D}\sum_{q=1}^{Tm} A_0 I_q \tag{8}$$

Since $I_q$ follow the same negative function, the characteristic function of each $I_q$ is written as

$$M_q(\omega) = \frac{1}{1 - iw\langle I_S\rangle} \tag{9}$$

where $\langle I_S\rangle$ is the average intensity of the single speckle pattern. Because these holograms are recorded in the same condition, the mean intensity of every speckle pattern can be approximately equal. Therefore, the mean intensity of single speckle pattern is identical to the mean intensity of averaged speckle pattern. From Eq. (9), we can obtain the characteristic function of the averaged speckle at a pixel as

$$M_{I_a(i,j)}(\omega) \cong \prod_{k=1}^{Tm} \frac{1}{1 - iw\frac{A_0}{TA_D}\langle I_a\rangle} = \left[\frac{1}{1 - iw\frac{1}{Tm}\langle I_a\rangle}\right]^{Tm} \tag{10}$$

where $\langle I_a\rangle$ is the mean intensity of the averaged speckle field. By Fourier transformation, the PDF of $I_a(i, j)$ is described by the Gamma density function

$$p\left[I_a(i,j)\right] \cong \frac{\left(\frac{Tm}{\langle I_a\rangle}\right)^{Tm} I_a(i,j)^{Tm-1}\exp\left(-Tm\frac{I_a(i,j)}{\langle I_a\rangle}\right)}{\Gamma(Tm)} \tag{11}$$

where $\Gamma$ is a gamma function of argument $Tm$. When $m$ is assigned an appropriate value, the approximate density function will closely match the true density function. According to Ref. [7], $m$ can be approximated as

$$m = \left[\langle I_S\rangle/\sigma_S\right]^{1/2} = \left[\frac{1}{C}\right]^{1/2} \tag{12}$$