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Speckle suppression in off-axis lensless Fourier transform digital holography

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ABSTRACT

Speckle noise suppression in off-axis lensless Fourier transform digital holography by laterally shifting of object is analyzed quantitatively. Speckle decorrelation is directly proportional to the object displacement therefore object is shifted by three different amounts to test its effect on the speckle contrast reduction that is pixel size of camera, averaged speckle size and resolution pixel size of reconstruction plane. Phase-only spatial light modulator (LCOS) is used in object beam path to introduce the lateral shift in its position digitally without mechanical efforts by displaying a grating function. In comparison with the typical methods, the externally input lateral position shifts of object are controlled accurately, which makes the system effective and practicable. Averaged reconstructed results for three quantitative object lateral position shifts are compared and it has been found that the object shift by resolution pixel size of reconstruction plane shows better speckle contrast reduction and is in good agreement with the theoretical prediction.

1. Introduction

The speckle pattern is actually a spatial random intensity distribution, which results when the coherent light either is reflected from a rough surface by random scattering or propagates through a medium with random refractive index fluctuation. Digital holography is a coherent imaging technique due to which the coherent noise known as speckle, is its inherent problem. It obscures the useful object information during reconstruction; therefore many methods have been suggested in literature for the suppression of speckle noise such as digital image processing [1–4], where object information can be extracted from single hologram by using proper filtering methods e.g. wavelet filtering, Fourier transform domain filtering, and non-local mean filtering etc. However these methods suffered from loss of resolution during speckle suppression; therefore another method of superposing multiple speckle patterns was proposed, in which by changing: angle of illumination [5–7], polarization [8,9], multiple wavelengths [10] etc. number of decorrelated reconstructed images are averaged on intensity basis to achieve speckle suppressed object information.

Object translation, rotation or deformation results in the movement and structural changes of speckle pattern in the observation plane. As once the object is displaced in its plane, the speckle pattern also displaces and it is therefore, no more remain identical to the original pattern because the light scattered from a given point in object plane is incident on the CCD at different angle. For small displacement of a solid object, the speckles remain correlated which has been exploited in a well known technique of “double-exposure speckle photography” [11]. For larger displacements or object shift, the speckles decorrelates and changes completely. Change in speckle contrast corresponding to object movement is also reported in literature [12,14], which has been utilized in optical displacement sensors [12,13] and blood flow measurements [14]. Pan et. al., introduced a method, based on the displacement of object/camera for recording number of decorrelated digital holograms in order to suppress the coherent noise for phase image in digital holographic phase contrast microscopy [15–17]. The phase images obtained from different holograms are uncorrelated due to the change of object position but that is not an in-situ investigation method. A similar approach is used in Ref. [18] for deformation and shape measurement by laterally shifting camera. In the above mentioned techniques the displacement of camera or object is arbitrary rather than externally specified input. There is no specific criterion for amount of shift that ensures decorrelation between speckle patterns by laterally shifting along x–axis and y–axis from the centre of recorded pattern. The spatial correlation properties of coherent noise have been examined in Ref. [17] by recording multiple axially displaced blank

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holograms to determine the longitudinal and lateral correlation length, later on, the holograms for coherent noise suppression are recorded with a step more than longitudinal correlation length instead of the lateral correlation length. The pre-determination of correlation length is time consuming. Garcia et. al. reported [19], that averaged patterns will be statistically independent as long as the object is shifted by more than one speckle size on the object surface and therefore two speckle patterns recorded at lateral or axial distances larger than the averaged speckle sizes will be uncorrelated. It is important to know the effect of specific object displacement on the speckle decorrelation which results in its suppression on the final averaged image.

In this study, method of speckle suppression via lateral shift of object in lensless Fourier transform digital holography is proposed where in order to introduce the lateral shift in object information, the object beam is reflected from LCOS that is used to display grating function. Grating function introduces slight lateral shift in object position in the recording plane that is CCD plane. The proposed technique uses the Fourier approach to reduce speckle noise for opaque object where several digital holograms of the object are recorded from different lateral positions of the object with respect to the fixed CCD camera position. The choice of shift distances is in accordance to intensity decorrelation of reconstructed images which in return suppresses speckle in final averaged image. In the proposed analysis we examined three situations of object displacement; (i) of the order of averaged speckle size which is measured from the recorded reference hologram by method of normalized autocovariance function, (ii) displacement less than averaged speckle size that is by an amount equal to pixel size of CCD (as measured averaged speckle size is more than that of pixel size) and (iii) displacement greater than averaged speckle size by an amount equal to the resolution pixel size of reconstruction plane. Finite number of holograms are recorded for all three object shifts where in reconstruction process, the differences between these intensity images due to object shift are corrected by using image registration algorithms. Thus, retrieved intensity images have same distribution, but uncorrelated speckle patterns. Finally on averaging the processed intensity images, speckle is reduced and quality of the reconstructed image has improved. The basic advantage of proposed method is that it can be controlled digitally instead of manual adjustment and it also provides accurate amount of shift in object position which is required for speckle decorrelation and results in its suppression on averaging.

The paper is structured as follows: principle of proposed method is described in Section 2; experimental results obtained for three different quantitative lateral shifts of object are compared and discussed in Section 3; and concluding remarks are given in Section 4.

2. Principle

The coherent illumination introduces irregular diffraction patterns in hologram due to undesired scattering resulted from refractive inhomogeneities, dust particle, multiple reflection, scratches, and rough surfaces etc. Therefore, the object beam can be regarded as the complex amplitude of object modulated by random complex noise (speckle noise) which is actually additive noise and it can distort the object information. A slight shift in the position of object in object plane (x_O, y_O) will result corresponding shifts of the complex amplitude of the object wave in the recording plane (x, y) which is given by

$$O(x, y) = \exp\left[\frac{ik}{2z_0}(x^2 + y^2)\right]FT\left\{O(x_0 + \Delta x_0, y_0 + \Delta y_0)\exp\left[\frac{ik}{2z_0}({x_0}^2 + {y_0}^2)\right]\right\} \quad (1)$$

and

$$O(x_0 + \Delta x_0, y_0 + \Delta y_0) = b(x_0 + \Delta x_0, y_0 + \Delta y_0)s(x_0 + \Delta x_0, y_0 + \Delta y_0) \quad (2)$$

where $b(x_O, y_O)$ and $s(x_O, y_O)$ are the complex profile of reflective object and speckle noise, Δx_O and Δy_O represents horizontal and vertical shifts, k denotes the wave number, z_O denotes the recording distance and the notation FT denotes the Fourier transform operation respectively.

The reference beam $r(x, y)$ is a spherical beam, whose point source is located at the same distance equal to the recording distance of object beam. When object and reference beams are superimposed, the resultant hologram is

$$H(x, y) = |O(x, y) + r(x, y)|^2 = |O(x, y)|^2 + |r(x, y)|^2 + O(x, y)r^*(x, y) + O^*(x, y)r(x, y) \quad (3)$$

In off–axis holography all the three diffracted terms are well separated and we are interested only in third term which is given below

$$O(x, y)r^*(x, y) = FT\left\{O(x_0 + \Delta x_0, y_0 + \Delta y_0)\exp\left[\frac{jk}{2z_0}(x_0^2 + y_0^2)\right]\right\} \quad (4)$$

where constant factors are neglected. During recording, hologram is obtained by using a camera with a finite extent which can be represented by a two–dimensional rectangular function [15] and object information at image plane (x_i, y_i) can be written in a form as follows

$$O_i(x_i, y_i) = \exp\left[\frac{ik}{2z_i}({x_i}^2 + y_i^2)\right]FT^{-1}\left[H(x, y)\exp\left(\frac{-ik}{2z}(x^2 + y^2)\right)\right] * FT^{-1}\left[rect\left(\frac{x}{A}, \frac{y}{B}\right)\right] \quad (5)$$

where A and B are the length and width of the sensor array, respectively. It is clear from the Eq. (4) that hologram is the Fourier spectrum of the object; therefore for the reconstruction of hologram an inverse Fourier transform operation is used where the multiplication of hologram with rectangular function causes the inverse Fourier transform of the hologram to be convolved with a sinc function [18] and the resulted image is

$$O_i(x_i, y_i) = b(x + \Delta x, y + \Delta y)s(x + \Delta x, y + \Delta y)\exp\left(ik\frac{x^2 + y^2}{2z}\right) * \mathrm{sinc}\left(\frac{Ax}{\lambda z}, \frac{By}{\lambda z}\right) \quad (6)$$

As the sample undergoes lateral translation therefore the value of object amplitude remains constant but speckle which is a random distribution is dependent on the object position shift and would be different at different position and will cancel each other on the averaging of number of laterally displaced reconstructed images.

3. Experimental results and discussion

Experimental set up for Lensless Fourier transform digital holography (LFTDH) is as shown in Fig. 1. Linearly polarized light from Cobolt Samba 532 nm laser is passed through half-wave plate (HWP_1) in order to get the same intensity in both arms of the interferometer. Thereafter, the beam is divided by Polarizing beam splitter (PBS) into two beams where each part is expanded and collimated by the beam expander BE_1 and BE_2 respectively. The beam transmitted through HWP_2 and reflected off object “O” (one Yuan Chinese coin) is called the object beam, while the other beam serves as the reference beam. The reflected light from object is made incident on LCOS by beam splitter (BS) whereas the microscopic objective is placed in the path of reference wave to get a spherical reference beam. After reflection from LCOS, the object beam is interfered with reference beam through same BS. Distance of the point source and object, from the CCD should be kept same.

Parallel-aligned LCOS (HED6010XXX Holoeye) is used in the experiment with a resolution of 1920×1080 pixels and pixel pitch of