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Compressive sensing sectional imaging for single-shot in-line self-interference incoherent holography

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ABSTRACT

A numerical reconstruction method based on compressive sensing (CS) for self-interference incoherent digital holography (SIDH) is proposed to achieve sectional imaging by single-shot in-line self-interference incoherent hologram. The sensing operator is built up based on the physical mechanism of SIDH according to CS theory, and a recovery algorithm is employed for image restoration. Numerical simulation and experimental studies employing LEDs as discrete point-sources and resolution targets as extended sources are performed to demonstrate the feasibility and validity of the method. The intensity distribution and the axial resolution along the propagation direction of SIDH by angular spectrum method (ASM) and by CS are discussed. The analysis result shows that compared to ASM the reconstruction by CS can improve the axial resolution of SIDH, and achieve sectional imaging. The proposed method may be useful to 3D analysis of dynamic systems.

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1. Introduction

Digital holography [1–3] enables direct access to the reconstruction of the object wavefront. However, coherent illumination can introduce disadvantageous effects into the holographic recording and reconstructing process, such as speckle noise and parasitic interference. Therefore, incoherent digital holography is becoming increasingly attractive for the elimination of these sources of noise [4–7] and has been applied to adaptive optics [8,9], fluorescence microscopy [10,11], ambient light color holography [12] and so on. Usually, the phase-shifting method is employed for the elimination of the zero order and twin image terms, and angular spectrum method (ASM) is applied for the image reconstruction. However, there may be some difficulties for dynamic applications when employing phase-shifting methods which require multiple interferogram recording per complex hologram. Furthermore, by ASM, the in-focus reconstructed image would be disturbed by the out-of-focus section information. These issues limit the application of SIDH in sectional imaging. Compressive sensing (CS) [13,14], a rapidly growing signal acquisition paradigm, has been successfully applied to coherent digital holography for three-dimensional (3D) tomography via in-line holography [15–17], for the recovery of partially occluded object [18,19], and in incoherent digital holography for 3D scene recording by multiple view projection [20]. Sectional imaging based on optical scanning holography is achieved by using inverse imaging [21,22].

Here we propose a numerical algorithm for achieving tomographic imaging by applying CS to SIDH reconstruction. Numerical simulation and experiments demonstrate the feasibility and validity of the method. The intensity distribution along the propagation direction and the axial resolution of SIDH by ASM and by CS are discussed. The axial resolution of SIDH by ASM is typically worse than that of a classical imaging system [23]. However, our analysis shows that the CS method can narrow the axial width of the image spot size and improve the axial resolution of SIDH compared to ASM. Furthermore, it can achieve sectional imaging by significantly suppressing the signals from out-of-focus sections of the object volume.

2. Theory

2.1. Basic theory of SIDH

A basic SIDH apparatus is illustrated in Fig. 1. The two curved mirrors (M_A and M_B) with different focal lengths (f_A and f_B) are equidistant from the beam splitter (BS). The BS produces two copies of the spherical wave emanating from each point-source of a diffuse object, and recombines the reflections from the two mirrors with different curvatures. A Fresnel zone-like interference pattern results from each source point of the object. The intensity

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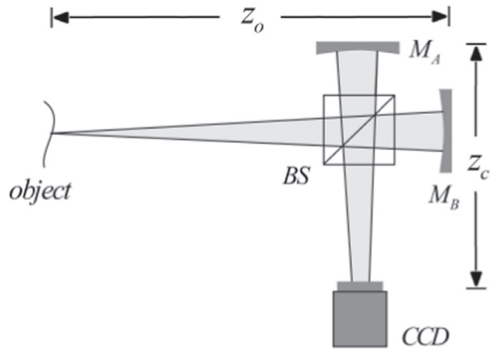

Fig. 1. Basic configuration of SIDH. BS, beam splitter; M_A, curved mirror of focal length f_A; M_B, curved mirror of focal length f_B.

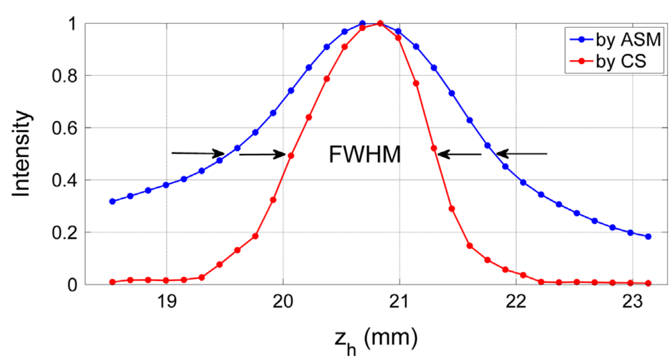

Fig. 2. Intensity distribution by ASM and by CS along z direction, where point-source of $\lambda = 625$ nm at $z_o = 150$ mm and hologram of size 256×256 pixels (pixel pitch 6 μm × 6 μm) recorded at $z_c = 175$ mm with $f_A = 100$ mm and $f_B = 75$ mm.

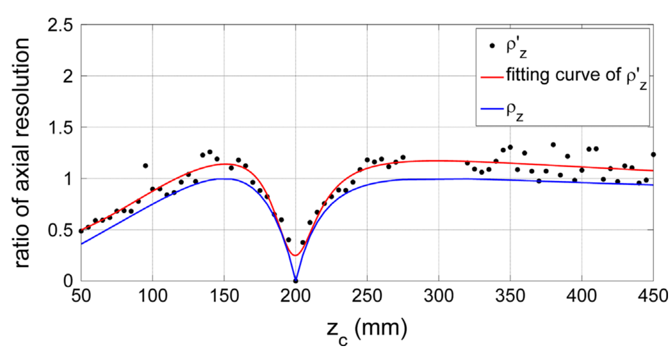

Fig. 3. Axial resolution ratio by ASM ρ_z and by CS ρ_z' vs. z_c, where point-source of $\lambda = 625$ nm at $z_o = 150$ mm and hologram at $z_c \in (50,\ 400)$ mm with $f_A = 100$ mm, $f_B = 75$ mm and $R = 3$ mm. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

pattern at the CCD plane is an incoherent superposition over all the point-sources of the object as:

$$h_c(x_c, y_c) = \iint dx_o dy_o I_o(x_o, y_o)\left\{\left[\left|E_A(x_c, y_c)\right|^2 + \left|E_B(x_c, y_c)\right|^2\right]\right\} + I_o'(x_c, y_c) \odot Q_{z_h}(x_c, y_c) + I_o'(x_c, y_c) \odot Q_{-z_h}(x_c, y_c) \quad (1)$$

where the symbol "⊙" represents the convolution; I_o is the intensity distribution of the object; $I_o'(x_c, y_c) = I_o(x_c/\alpha, y_c/\alpha)$ with $\alpha = -z_c/z_o$; E_A and E_B are the optical fields arriving at CCD after reflection from the two mirrors; λ is the wavelength; $Q_{z_h}(x_c, y_c) = \exp[ik(x_c^2 + y_c^2)/2z_h]$; and z_h is the holographic image distance given by:

$$z_h(z_o) = -\frac{\left[\frac{z_o f_A}{z_o - f_A} - z_c\right]\left[\frac{z_o f_B}{z_o - f_B} - z_c\right]}{\frac{z_o f_B}{z_o - f_B} - \frac{z_o f_A}{z_o - f_A}} \quad (2)$$

For holographic reconstruction, the single-shot in-line self-interference incoherent hologram is back propagated by ASM with the distance $-z_h$ under Fresnel or paraxial approximation as:

$$I = h_c \odot Q_{-z_h} \quad (3)$$

However, the expression (1) includes disturbance of the zero-order and the twin image terms. The reconstructed image also contains mixture of in-focus and out-of-focus contributions.

2.2. Axial resolution of SIDH

The axial resolution of SIDH is discussed in comparison with the classical imaging system. Firstly, according to Eq. (2), we obtain the axial magnification of SIDH as:

$$M_z = \left|\frac{dz_h}{dz_o}\right| = \left|-\frac{f_{AB} {z_c}^2}{{z_o}^2}\left(\frac{1}{\zeta_A} + \frac{1}{\zeta_B}\right)\right| \quad (4)$$

where $\frac{1}{f_{AB}} = \frac{1}{f_A} - \frac{1}{f_B}$, $\frac{1}{\zeta_A} = \frac{1}{z_o} + \frac{1}{z_c} - \frac{1}{f_A}$, and $\frac{1}{\zeta_B} = \frac{1}{z_o} + \frac{1}{z_c} - \frac{1}{f_B}$. The axial resolution of SIDH in the reconstructed image space δ_{z_h} is proportional to $\lambda z_h^2/R_H^2$. The radius of the hologram, $R_H = |R(z_\kappa - z_c)/z_\kappa|$, is given by the smaller of the two projections of the mirrors on the CCD plane, where R is the radius of the mirror and $z_\kappa = z_o f_\kappa/(z_o - f_\kappa)$, with $\kappa = A$ or B. The axial resolution SIDH in the object plane is defined as:

$$\delta_{z_o} = \left|\frac{\delta_{z_h}}{M_z}\right| \quad (5)$$

For the classical imaging system, the axial resolution in the object space $\overline{\delta_{z_o}}$ is proportional to $\lambda z_o^2/R^2$, and the ratio of the axial resolution of the classical system to that of SIDH is:

$$\rho_z = \left|\frac{\overline{\delta_{z_o}}}{\delta_{z_o}}\right| \quad (6)$$

The larger the values of ρ_z the better the resolution of the SIDH system. However, ρ_z of SIDH is between 0 and 1, i.e. it means that the axial resolution of SIDH would be worse than that of the classical imaging system [23]. So, it is disadvantage for achieving sectional imaging.

2.3. Algorithm of SIDH by CS

In order to achieve sectional imaging without the disturbance from zero-order, twin, and out-of-focus components, we apply CS to SIDH reconstruction. Firstly, the nonlinearity caused by the zero-order term $|E_A|^2 + |E_B|^2$ is regarded as model error e, the twin image term $I_o' \odot Q_{-z_h}$ and the other out-of-focus information is considered as n. Therefore, for 3D scene recording, Eq. (1) is re-written as:

$$h_c = I_o' \odot Q_{z_h} + n + e = \Im_{2D}^{-1}\left\{\int \Im_{2D}\left[I'_o(x_c, y_c, z_o)\right]\Im_{2D}\left[Q_{z_h(z_o)}(x_c, y_c)\right]dz_o\right\} + n + e \quad (7)$$

where

$$\Im_{2D}\left[Q_{z_h(z_o)}(x_c, y_c)\right] = i\lambda z_h(z_o)\exp\left[-i\pi\lambda z_h(z_o)(\xi^2 + \eta^2)\right] \quad (8)$$

Here $\Im_{2D}\{\}$ and $\Im_{2D}^{-1}\{\}$ represent the two-dimensional (2D) Fourier transform and the inverse 2D Fourier transform; (ξ, η) are frequency coordinates. The discretized hologram of $N_x \times N_y$ pixels with pixel pitch $\Delta_x \times \Delta_y$ is converted into 1D vector as

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