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Reconstruction of apertured Fourier Transform Hologram using compressed sensing

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ABSTRACT

Fourier Transform Holography (FTH) encodes object information as the Fourier spectrum in an interference pattern with the help of a reference point source. Hence, a single Fourier transform (FT) operation is capable to provide a complete object from a digitally reconstructed FTH. However, high intensity values in the central region of the FTH demands central blocking due to the limited dynamic range of a detector in a variety of applications. The central blocking causes the loss of frequency content and hence affects the reconstruction result. Still, it can be properly recovered using signal processing techniques such as Compressive Sensing (CS) or Sparse signal processing. This paper investigates the role of CS for centrally blocked FTH using various kind of beam stops and provide a detailed comparison between usual FT reconstruction and technique equipped with CS. We also provide a detail procedure to apply the CS reconstruction in the FTH and compared the results with and without CS. It is established that an object can be recovered from limited size of a recorded hologram with the constraint that object has to be sparse in known basis. Quantitative analysis has been carried out to compare the quality of reconstruction using inverse Fourier transform (IFT) and CS techniques. Quality of reconstruction is assessed by evaluating measures such as the overall visibility, efficiency and PSNR of reconstruction. The finding highlights that the CS reconstruction is better than that of IFT reconstruction. Both simulation and experimental results demonstrate the effectiveness and robustness of the CS-based approach.

1. Introduction

Holography is an important imaging technique due to its ability to reconstruct the object in non invasive and label free environment. The technique makes use of an interference pattern of the object with reference wave derived from a common coherent source. On axis and off axis position of a reference wave with respect to object can be utilized to make different types of hologram [1,2]. With progress of time, optical recording and reconstruction of hologram is replaced by digital technique referred as Digital Holography (DH). Detail comparison of analog holography (AH), based on optical recording and reconstruction, and DH can be found in Ref. [3–5]. DH allows capture of the hologram by photo detectors and subsequent numerical processing on digital computer [6]. Significant progress of DH was made possible by advancement in detector technology and fast computation algorithms. Since the hologram is directly available in digital form, the object information encoded into the hologram can be reconstructed by simulating inverse propagation of light using computer. Depending on experimental geometry, several numerical techniques have been developed to efficiently reconstruct the hologram, some of these are Fresnel transformation, Convolution approach and Fourier reconstruction etc [7,8]. Among several reconstruction geometry, the FTH attracts significant attention due to its high quality wave-front reconstruction capability and it requires a single Fourier transform operation for digital reconstruction. [9–11].

However, major problem in the FTH is associated with missing signal at the centrally overexposed region of the interference pattern [12]. The whole intensity range of FTH is difficult to capture using a commonly commercially available detector of a fixed dynamic range. Due to this, a beam stop is often desired to block the central region of the hologram [13]. Bhargab et al. [14] have highlighted that it is always preferred to suppress the intensity of the hologram to optimize the storage density. Furthermore, high-intensity X-rays in the forward direction are usually suppressed by a beam stop creating regions of missing data [15]. This has significant impact on the results of existing FTH methods. However, this problem can be resolved by using compressive sensing approach [13]. Compressive sensing (CS) is a popular sparse

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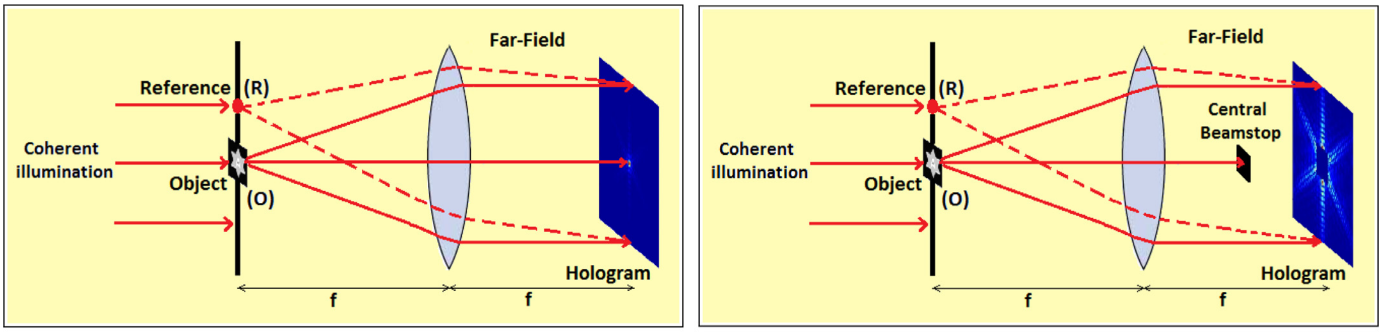

(a) FTH without central beamstop (b) FTH with central beamstop

Fig. 1. FTH recording geometry: (a) geometry of FTH, (b) modification in the geometry with a central beam stop.

signal processing technique for efficiently acquiring and reconstructing a signal, from few measurements, through optimization. Underlying assumption in CS is that the object of interest can be represented sparsely in a suitable basis. Such objects can be recovered from an incomplete set of linear measurements. The basic principle behind the CS theory is, the sparsity of a signal can be exploited to recover it from far fewer samples than required by the Shannon–Nyquist sampling theorem, by finding solution to the underdetemined linear systems [16]. It has been demonstrated that given knowledge about a signal's sparsity, the signal may be reconstructed with even fewer samples than the sampling theorem requires [16–20]. CS has been utilized in a variety of applications to solve missing data problem. In the last few years, there has been significant interests in the application of CS for various reasons and several new techniques have been proposed. Some of these are compressive sensing for digital holographic interferometry [21], compressive holography [22], sampling and processing for compressive holography [23], compressed single pixel imaging in the spatial frequency domain [24], and compressive correlation holography [25] etc.

Recently effect of the centrally blocked FTH on the reconstruction is examined and the role of compressed sensing has been investigated. He et al. [13] have demonstrated that an image can be recovered from high frequencies alone using CS framework. Authors have also implemented CS for coherent diffraction imaging (CDI). However, this work is limited to a specific aperture of size and shape. Similarily, Wild et al. had studied beam stop and vignetting effects in particle size measurements by laser diffraction in [34]

The purpose of this paper is to perform the detailed investigation on reconstruction of the various kind of apertured FTH using IFT and CS technique. Reconstruction results of these two methods are also compared. Quality of reconstruction is also quantitatively evaluated by providing reconstruction efficiency, visibility and peak signal to noise ratio (PSNR). Both simulation and experimental aspects of the work are provided and it is established that CS can be highly useful in reconstructing FTH. Section 2 of the paper provides the principle behind FTH and CS framework for blocked FTH. Simulation and experimental results are explained in Section 3.

2. Principle

The basic principle and the technique applied in the proposed work is as follows:

2.1. Fourier Transform Holography (FTH)

Consider an object O and reference R illuminated by a coherent light as shown in Fig. 1(a). The object and reference is located in the front focal plane of lens and the detector is located in back focal plane of the lens. Let the complex amplitude leaving the object plane be represented as $O(x, y)$, then the field at Fourier plane is given by

$$\varepsilon_O(x', y') = \mathscr{F}\{O(x, y)\}, \tag{1}$$

where $\mathscr{F}\{.\}$ is the Fourier transform kernel and (x', y') represents the spatial co-ordinates in the back focal plane. A reference point R at (x_0, y_0) in front focal plane is represented as $\delta(x - x_0, y - y_0)$. Therefore the captured field at the Fourier plane is

$$\varepsilon_R(x', y') = \mathscr{F}\{\delta(x - x_0, y - y_0)\} = e^{-2i\pi(x'x_0 + y'y_0)} \tag{2}$$

The interference pattern created by object and reference waves is recorded at the Fourier plane and represented as

$$\begin{aligned} I &= (\varepsilon_O + \varepsilon_R)(\varepsilon_O + \varepsilon_R)^* \\ &= |\varepsilon_R|^2 + |\varepsilon_O|^2 + \varepsilon_R^*\varepsilon_O + \varepsilon_R\varepsilon_O^*, \end{aligned} \tag{3}$$

where ε_R^* and ε_O^* are the complex conjugates of ε_R and ε_O, respectively. Numerical reconstruction of the hologram, as in Eq. (3), is possible by a FT operation and represented as

$$\begin{aligned} \mathscr{F}^{-1}\{I\} &= \mathscr{F}^{-1}\{|\varepsilon_R|^2 + |\varepsilon_O|^2 + \varepsilon_R^*\varepsilon_O + \varepsilon_R\varepsilon_O^*\} \\ &= \delta(x, y) + (O(x, y) \otimes O(x, y)) + O(-(x + x_0), -(y + y_0)) \\ &\quad + O^*(x - x_0, y - y_0), \end{aligned} \tag{4}$$

where $\mathscr{F}^{-1}\{.\}$ denotes inverse Fourier transform kernel and $\otimes$ denotes convolution. The first and second term in Eq. (4) represent a dominant term. The third term is proportional to the original object wave field but inverted and shifted by (x_0, y_0). The fourth term is the conjugate of object wave shifted by $(-x_0, -y_0)$ [10].

The limited recording of the FTH due to the fixed dynamic range of camera affects the reconstruction results. Remedy to this lies with blocking intense region of hologram by a central beam stop as shown in Fig. 1(b) [13–15]. This situation corresponds to the recording of hologram WI rather than I. Here, W represents aperture transfer function. Blocking of the central portion of hologram causes loss in the reconstruction as explained by the Fourier transform operation [2]. When frequency information in hologram is lost, it affects the faithful reconstruction of object using usual IFT. CS can be utilized to tackle this problem and basic principle is described below.

2.2. Compressive sensing framework for blocked FTH

Compressive Sensing deals with finding solution of an underdetermined linear system $Ax = b$, where A_{mn} is the product of sensing matrix $\phi_{m\times m}$ with sparsifying matrix $\psi_{m\times n}$, $b_{m\times 1}$ measurement vector and $x_{n\times 1}$ the reconstructed vector. The basic idea is, if there exist a signal sparse in ψ domain which is measurable at ϕ, we can store m values and get back big data information in the sparse basis. It is a rapidly growing signal acquisition method which looks for less number of samples in one domain and its big data reconstruction in the sparse domain of