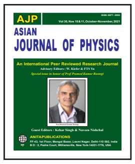

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Digital holographic tomography of cylindrical objects with a conical mirror

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Dedicated to Prof Pramod Kumar Rastogi for his outstanding contributions to Optical Metrology

This paper presents a panoramic holographic reconstruction of a cylindrical object with a conical mirror. This panoramic holographic system has the advantage to obtain 3D information for 360 degrees view in one-shot. We use the phase-shifting method to determine the amplitude and phase simultaneously. This work demonstrates the feasibility of refocusing at different radii inside of the object. Amplitude and phase distributions are presented to validate the tomographic simulation results. These results give the confidence to implement the holographic system to study different quasi-cylindrical objects of importance in areas such as materials engineering and biological science.

Keywords: Digital Holography, Panoramic imaging, Digital Tomography.

1 Introduction

Obtaining a complete 360 degrees view of a general 3-D object has been of increasing importance in topographical measurements. During the last two decades, optical imaging and metrology have found relevant applications in the entertainment, manufacturing industry, arts, medicine, and science [1-4]. Some of the advantages of panoramic vision that make it extremely valuable are obtaining a full view of the object (without blind spots in image), reconstruction of the entire surface of the sample with a single camera from a single view point, thus avoiding time consuming merging procedures that could decrease the accuracy of the measurement, direct reconstruction of the 3D object by using cylindrical-coordinate system, as well as a non-contact technique and, therefore, can be used as non-destructive tests [2]. Panoramic imaging has presented some relevant advances in areas such as industry and medicine [1,2]. Some of the advances in the medical area are the study and evaluation of morphological, muscular and cardiovascular diseases [3,4]. The use of virtual and augmented reality systems in video games, tours of virtual places, and the generation of panoramic videos for different uses in entertainment [5,6] and the arts have been of great interest to people around the world [5,7-9]. Robotics is another area where panoramic visualization has been widely used for autonomous driving and navigation in unmanned systems, mapping of cities and archaeological sites [5-10]. The use of panoramic vision in the industry includes quality control systems [11], fracture inspection, deformation analysis [12], thermal flow changes in the manufacturing process, and reverse engineering [13-15]. The panoramic vision is especially useful in the study of quasi-cylindrical or cylindrical objects [16,17], and displacing commonly used contact techniques such as coordinate measuring machines [18]. Among the acquisition systems used for panoramic vision are those that record the scene or image employing novel optical systems in a single shot and perform a scanning and stitching process in multiple records. The first ones present a lower resolution in the results and are commonly used to study dynamic events [19]. From systems that perform a scanning process, they also need a stitching process where inherently there are

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mechanical displacements. In other work, the development of a Michelson-like white light interferometer to measure both inner and external cylindrical surfaces using conical mirrors was implemented. Scanning of the measured volume was performed in cylindrical coordinates by linear displacement of a flat mirror in the reference arm of the interferometer [20].

The analysis of quasi-cylindrical objects is paramount in different areas of engineering research. For example, the analysis of red blood cell flowing in a microchannel or vein has been studied to determine some biophysical properties of the cell [21]. In addition, some studies on the behavior of the flows in pipes reported interesting characterization [22]. Our proposal allows scanning objects located at different radial distances within a cylindrical sample using digital holography technique. We simulate objects of complex shape, with phase and amplitude distributions, located in different layers of a cylindrical volume. We perform the 4-step phase-shifting method to get four digital simulated holograms recorded at a distance of 50 mm. These holograms were obtained by a panoramic view using a conical mirror. Simulation results demonstrate the feasibility of implementing this tomographical technique to measure engineering structures in quasi-cylindrical objects.

2 Results and discussion

We use a modified Michelson interferometer, as is presented in Fig 1(a). A coherent laser beam with wavelength (λ) of 633 nm is expanded and collimated by a lens. A beamsplitter cube divides the wavefront into an object wavefront $O(x, y)$ and a reference wavefront $R(x, y)$. The reference wave is reflected by the plane mirror that is attached to a piezo-transducer (PZT) system to perform the four-step phase-shifting technique. The object wavefront is produced by the reflection from sublayers of the object not only on the surface but also inside of it. Figure 1(b) shows different views of the simulated complex cylindrical object, similar to a capillary tube, where we can see the letters "P" and "G" on the inner surface located at 70 mm. The outer surface, located at 50 mm, shows the "+" symbol (in green). Inside the wall of the tube, located at 60 mm, the letters "U" and "T" are displayed. That is, we can obtain different reconstructed images with respect to the recording plane. The distances are measured with respect to the position of the CCD plane. The complex object is represented by the distribution $O(x, y) = A(x, y)*exp(i\phi(x, y))$. To get a digital simulated hologram $H(x, y)$, the object wave $O(x, y)$ and the reference wave $R(x, y)$ interfere through the cube beam splitter, and the hologram is recorded by a CCD camera of 1000×1000 pixels and a pixel pitch of 6.7 μm. The simulated hologram is given by:

$$I(x, y) = |O(x, y) + R(x, y)|^2 = |O(x, y)|^2 + |R(x, y)|^2 + O(x, y)\, R(x, y)^* + R(x, y)\, O(x, y)^*. \quad (1)$$

where * denotes a complex conjugate, the first two right-hand terms are DC or zero-order diffraction terms, and the last ones represent the virtual and the real images, respectively.

The 2π phase module is calculated from four π/2 phase-shifted holograms H_1-H_4 with the four-frame algorithm [23]:

$$\emptyset_0\,(x, y) = \tan^{-1}\left[\frac{H_4(x, y;3\pi/2) - H_2(x, y;\pi/2)}{H_1\,(x, y;\,0) - H_3(x, y;\,\pi)}\right]. \quad (2)$$

The amplitude of the optical field $A_0(x, y)$ is calculated as the square root of the object's intensity distribution; which means that the object intensity can be obtained by blocking the reference beam and recording only the object beam in the CCD.

As a result, the object complex amplitude is determined as

$$U(x, y) = A_0(x, y)exp[i(\emptyset_0\,(x, y))]. \quad (3)$$

Figure 2 shows the four $\pi/2$ shifted synthetic holograms of the complex object located at 50 mm from the recording CCD plane (x, y). To simulate the hologram generation and reconstruction process, we use the MatLab™ software with the angular spectrum method to propagate diffraction object and reference plane wavefront.

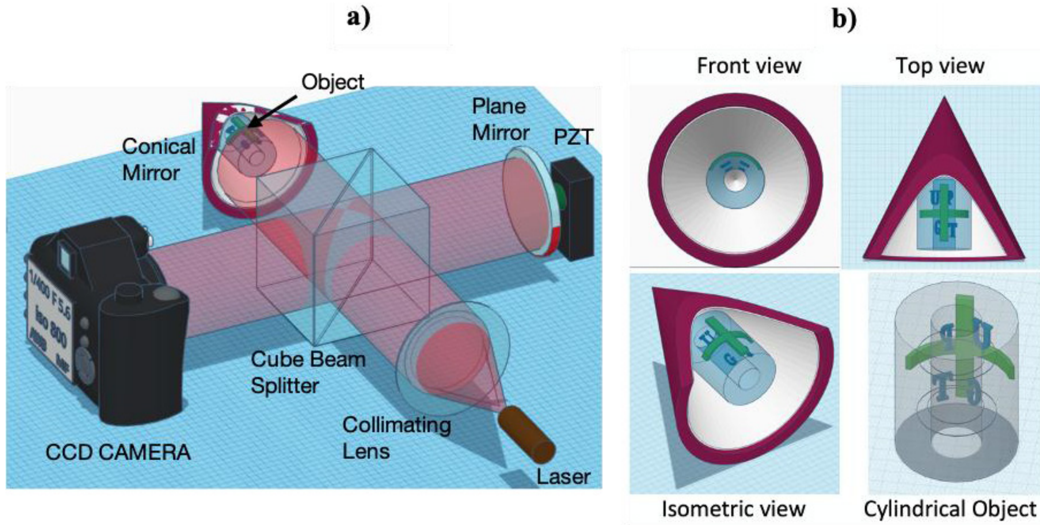

Fig 1. (a) Setup of the panoramic digital tomographic system, and (b) different views of the complex cylindrical object.

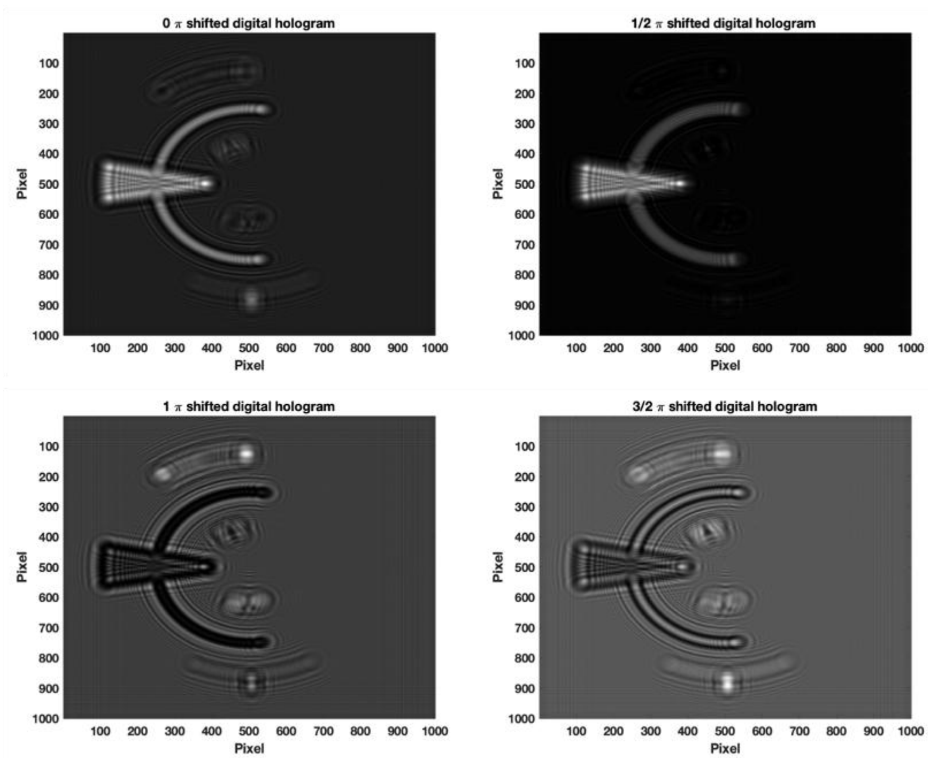

Fig 2. Four π/2 shifted holograms of the cylindrical object.

DH presents a refocusing capability to reconstruct the object wavefront at different planes in the axial direction. In particular, the angular spectrum method (AS) can be used to calculate the object complex amplitude at any other plane (x', y') in order to refocus it [24]:

$$U(x', y') = \Im^{-1}\left\{exp[ikd(1-\alpha\lambda-\beta\lambda)^{1/2}] \times \Im\left[U(x,y)\right]_{(\alpha,\beta)}\right\}_{(x',y')} \tag{4}$$

where $U(x', y')$ is the complex amplitude of the object focused, $k = 2\pi/\lambda$ is the wavenumber, d is the reconstruction distance, (x', y') are the spatial variables at the focus plane, (α, β) are the spatial frequencies, and $\Im$ denotes a two-dimensional continuous Fourier transformation. The reconstructed object wavefront $U(x', y')$ provides the amplitude image $A\,(x', y') = |\,U(x', y')\,|^2$ and the phase image $\phi_0\,(x', y') = \tan^{-1}\big(\text{image}\,(\,(U(x', y'))/\text{real}(U(x', y'))\big)$ of the object.

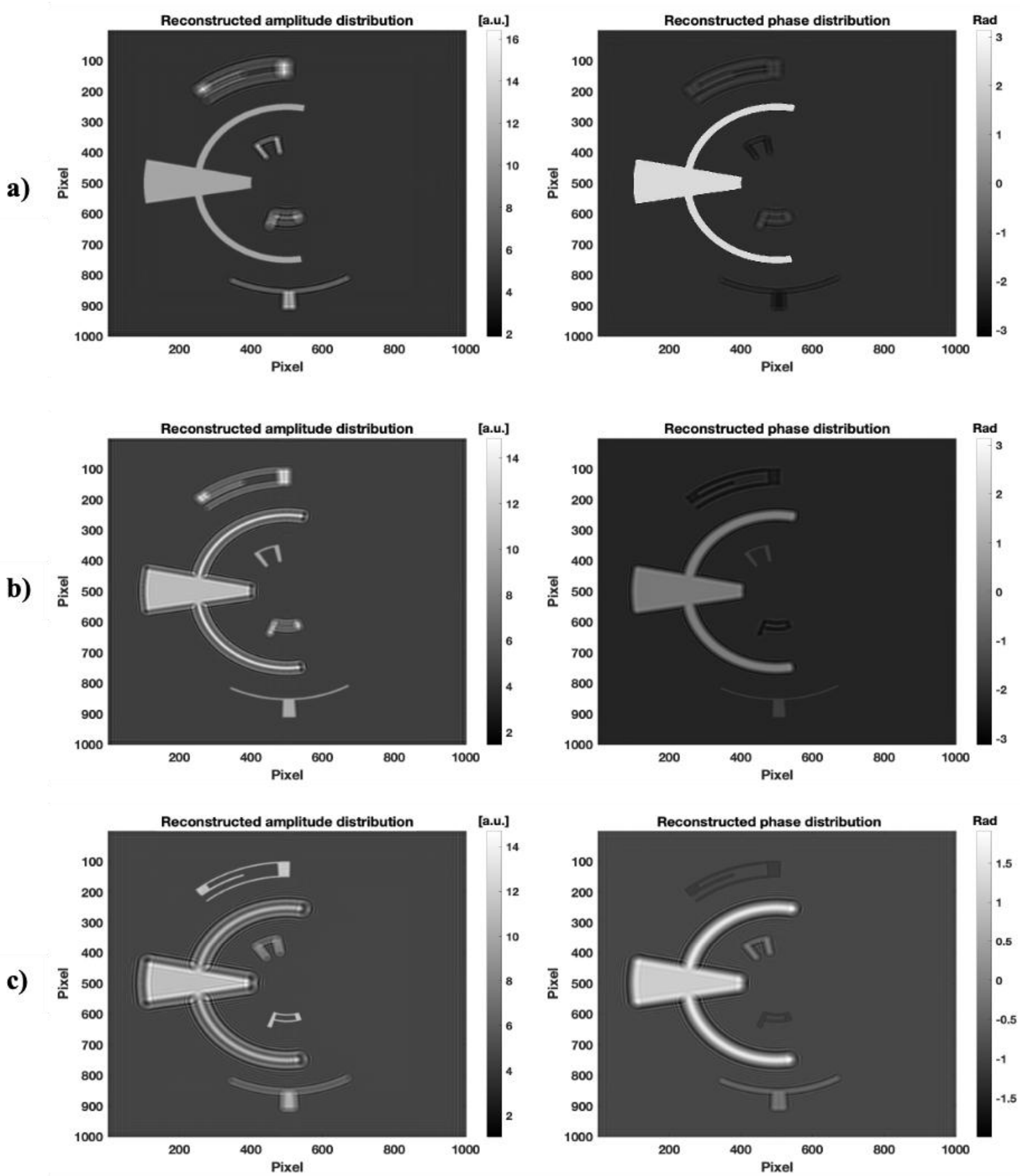

Fig 3. Holographic reconstruction of the panoramic view of the complex object. Reconstruction distances: (a) 50 mm, (b) 60 mm and (c) 70 mm.

Figure 3 shows the reconstruction of the amplitude and wrapped phase distributions with a reconstruction distance *d* of 50 mm, 60 mm, and 70 mm with respect to the CCD camera.

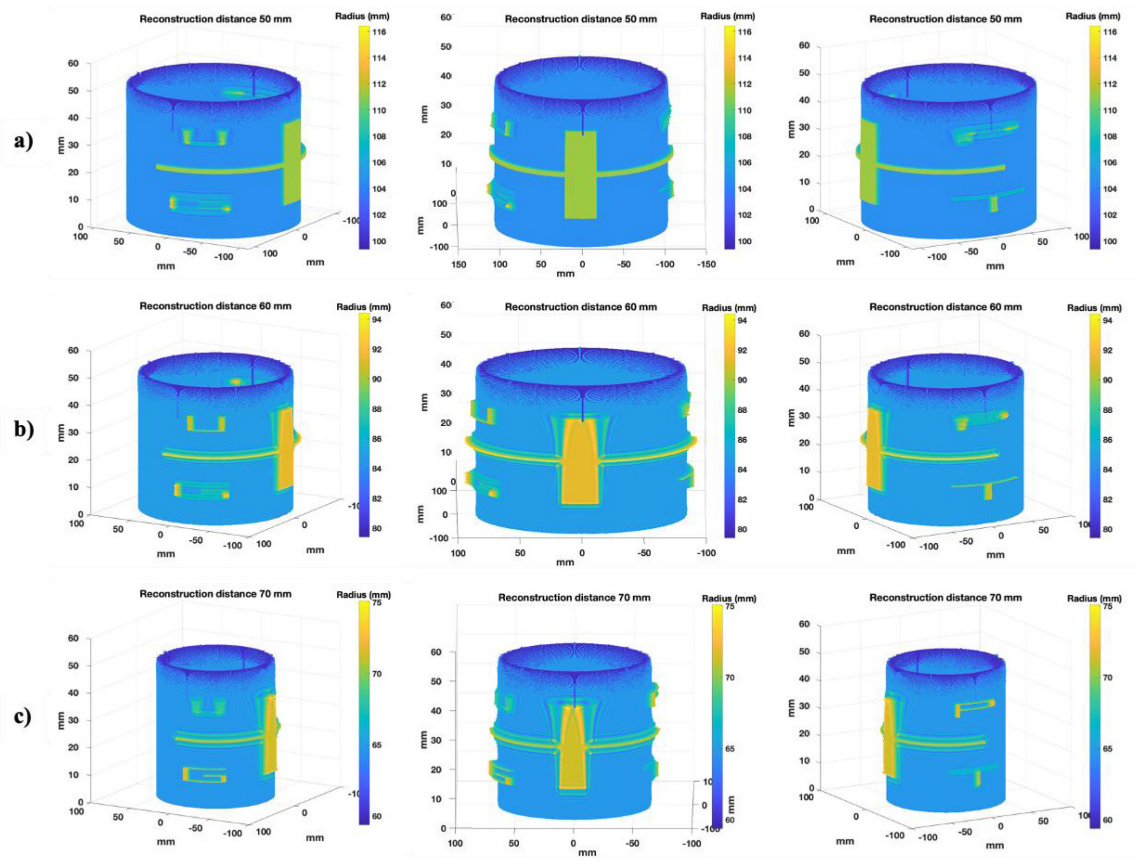

Fig 4. Cylindrical reconstruction shape of the object by the tomographic procedure.

Figure 4 presents a coordinate transformation to reconstruct the cylindrical object shape in the correct focus planes of Fig 3. Figure 4 shows three different views for each of the reconstruction distances in order to show the symbol or letters focused in each layer. Some views are shown in (a) the symbol +, (b) U and T and (c) P and G.

The coordinates transformation is performed using:

$$X = (T + r)*\cos\theta,$$
$$Y = (T + r)*\sin\theta,$$
$$Z = z'. \quad (5)$$

Here r is the initial radius, T is the topographic distribution, θ is the radial angle from 0 to 2π rad, and z' is the height cylindrical coordinate. As we can see in the schematic of Fig 1a, a panoramic view of 360 degrees imaging of the cylindrical object is obtained by using the conical mirror. The maximum size of the objects is limited by the dimension of the conical mirror [25].

Figure 5 shows the reconstruction of the amplitude of the simulated cylindrical object where the feasibility of the tomographic capabilities of our proposal are demonstrated. The ellipses show some focused part of the symbol and letters located at different radial distances. The upper, middle and lower ellipses show sections of U, + and G, respectively.

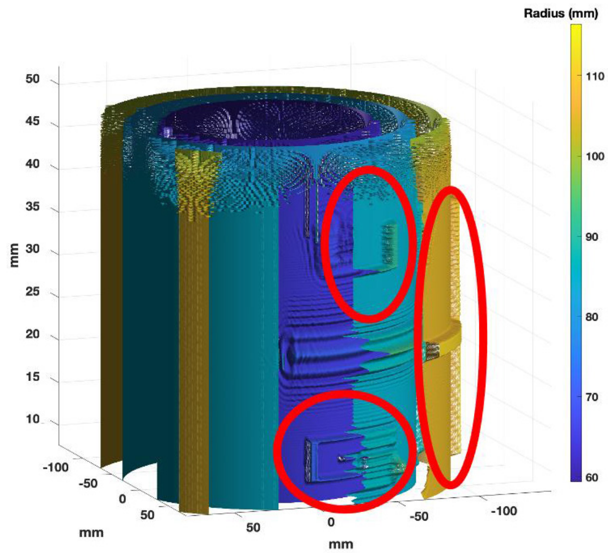

Fig 5. Tomographical representation of the object amplitude reconstruction.

3 Conclusion

In this work, we presented a digital holographic tomography reconstruction of objects (corresponding to symbol and letters) located in different layers of a cylindrical volume. Numerical simulations results were presented in order to show the feasibility for implementing this tomographical technique to analyze engineering structures in quasi-cylindrical objects. In addition, we also show how the conical mirror allows to get a panoramic hologram for a reconstruction of 360º in one shot.

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