Creating an extended focus image of a tilted object in Fourier digital holography

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Abstract: We present a new method to numerically reconstruct images on a tilted plane by digital holography in Fourier configuration. The proposed technique is based on a quadratic deformation of spatial coordinates of the digital hologram. By this approach we demonstrate that it is possible to recover the extended focus image (EFI) of a tilted object in a single reconstruction step from the deformed hologram.

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1. Introduction

One of main problems in optical imaging is the limited depth of focus. All optical systems are affected by this limitation that hinder to get in focus in a single image plane objects that are located at different distances, but falling inside the same field of view. This is especially true in optical systems like microscopes where the depth of field is squeezed due to the request of an high magnification. This problem is an important issue in biological applications when a fast analysis for dynamic processes is necessary [1]. In fact, in classical optical microscopes the Extended Focus Image (EFI) is built-up by the optical longitudinal mechanical scanning and by the acquisition of a sequence of images during the scanning, called "image stack". To create an EFI, in each image of the "stack" the in-focus parts are selected and then stitched together in a single image (i.e. EFI). However, the long acquisition time required for digitizing many images prevents it to be used in case of dynamic events. To overcome this problem, some approaches have been developed for incoherent imaging system. One approach is based on the so called "wavefront coding" using an opportune phase plate that introduces a wavefront distortion giving the possibility to have a EFI in a single image acquisition [2]. Recently, the problem to extend the depth of field has been successfully addressed for incoherent imaging system by using a birefringent plate [3], by means of lenses with radial and angular modulation [4], by logarithmic phase mask [5] or by amplitude and phase modulation of the pupil function [6].

The need of an EFI image is also important in 3D optical imaging systems both for incoherent and coherent light sources [7–16]. Of course holographic microscopes allows 3D imaging capability but suffer at the same time of a limited depth-of-focus. Recently various solutions have been proposed to obtain EFI in DH systems [13,16–21]. Some of these approaches use the angular spectrum transformation, others exploit the DH capability to reconstruct image planes at different distances, or image processing during the reconstruction process. The diffraction of a tilted planar object is also studied in ref. 22, where the authors generate a computer-generated hologram of a 3D object composed of planar segment tilted in respect to the optical axis.

Here we show that by means of an opportune coordinates transformation of an hologram recorded in Fourier configuration, it is possible to obtain an EFI image of a tilted object. In our recent work we have shown that in Fresnel holography a linear transformation allows to extend the depth of focus [23]. However, such approach does not work properly for Fourier-type holograms. We extend here the theory about the hologram deformation to Fourier holograms, showing that only a quadratic geometrical deformation allows to obtain a tilted object with all points in focus by a single reconstruction step. Moreover, we report the results of some specific experiments with the aim to demonstrate the validity of the method.

2. Deformation of Fourier-type holograms: theoretical model

In our previous paper we demonstrated how it is possible to change the in-focus distance by stretching holograms acquired in Fresnel configuration [23].

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For holograms recorded in Fourier configuration, the simple linear stretching gives a different result as can be demonstrated by simple calculations reported below. In fact, in the Fourier configuration the numerical reconstruction of the hologram $f(\xi,\eta)$ is obtained simply calculating its spatial FT $\hat{f}(x,y)$.

When the hologram is linearly stretched, we obtained a new 2D matrix, that is

$$h(\xi,\eta) = f(a\xi, a\eta) \tag{1}$$

Because of the Fourier transform properties we have that

$$\hat{h}(x,y) = \frac{1}{a}\hat{f}\left(\frac{x}{a},\frac{y}{a}\right) \tag{2}$$

where $\hat{h}(x,y)$ corresponds to the new numerical reconstruction and it results to be equal to the reconstruction of the initial hologram with scaled dimensions and a scaled intensity.

Therefore, there is no change in reconstruction distance. Consequently by application of a linear transformation to a Fourier hologram no changes can be observed about image focusing properties during reconstruction.

Nevertheless, if, instead of a linear transformation described by Eq. (1), we apply a quadratic deformation, it results that the in-focus distance changes, as will be shown later in this paper, with a linear law given by

$$D = L(1+2\alpha l') \tag{3}$$

where l' is the horizontal coordinate in the reconstruction plane, α is the deformation parameter and L is the reconstruction distance of the recorded (not deformed) hologram. Therefore, by this kind of hologram deformations we can put correctly in-focus the numerical reconstruction of a tilted object recovering its EFI. It important to note that we are considering the possibility to deform the hologram only along the direction of the tilt, that means in our case the x-axis.

To demonstrate how the change of the in-focus distance depends on the quadratic deformation we need to remind some Fourier Transform properties for a composite function $h(x) = g(f(x))$

If we consider the following composite function

$$h(x) = g(f(x)) = \int G(l)e^{i2\pi l\cdot f(x)}dl \tag{4}$$

where $G(l)$ is the Fourier Transform of $g(y)$, we have that the FT of $h(x)$ results to be

$$\begin{aligned}\hat{h}(k) &= \int e^{-i2\pi k\cdot x}\int G(l)e^{i2\pi l\cdot f(x)}dldx \\ &= \int G(l)P(k,l)dl\end{aligned} \tag{5}$$

where $P(k,l) = \int e^{-i2\pi k\cdot x}e^{i2\pi l\cdot f(x)}dx$ .For a quadratic coordinate transformation of the hologram g(x) we have that $f(x) = x+\alpha x^2$

Then, it results that $P(k.l) = \sqrt{\frac{\pi}{2\pi\alpha l}}e^{i\pi^2\frac{(k-l)^2}{2\pi\alpha l}}e^{i\frac{\pi}{4}}$

Therefore

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$$\hat{h}(k) = \int G(l)\,P(k,l)\,dl = e^{i\frac{\pi}{4}} \int G(l)\sqrt{\frac{1}{2\alpha l}}\,e^{i2\pi\frac{(k-l)^2}{4\alpha l}}\,dl \qquad (6)$$

Where $\hat{h}(k)$ is the reconstruction of the deformed hologram, while $G(l)$ is the reconstruction of the initial hologram. If we set $k=\frac{k^{'}}{\lambda L}$ and $l=\frac{l^{'}}{\lambda L}$ in order to change the coordinates from the spatial frequency domain to the space domain, then in Eq. (6) the exponential term $e^{i2\pi\frac{(k-l)^2}{4\alpha l}}$ becomes $e^{\frac{i2\pi}{\lambda}\frac{(k'-l')^2}{2d'}}$ where $d' = 2L\alpha l'$.

Therefore the final reconstruction, i.e. the reconstruction of the deformed hologram, can be interpreted as the reconstruction of the initial hologram at distance L, and further propagated to a distance d' that depends linearly on the coordinate l' (x-axis in the reconstruction plane) and it is a function of the deformation parameter α and of L, that is the reconstruction distance of the not-deformed hologram (see Fig. 1).

Summarizing, we can claim that, if we apply a quadratic deformation to the hologram of a tilted object along the tilting direction, we obtain an all in-focus reconstructed image of the object. In fact the reconstruction distance changes pixel by pixel along the tilting direction l' according to Eq. (3) as will be experimentally demonstrated in the next section.

The quadratic deformation is applied to the original recorded hologram through the coordinates transformation $[x'\ y'] = [1 \quad x \quad y \quad xy \quad x^2 \quad y^2]\,T$ where the operator is

$$T = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ \alpha & 0 \\ 0 & 0 \end{bmatrix}.$$

3. Experimental validation

For the experimental validation, we made an experiment with a Mach-Zehnder interferometer in Fourier configuration as depicted in Fig. 1.

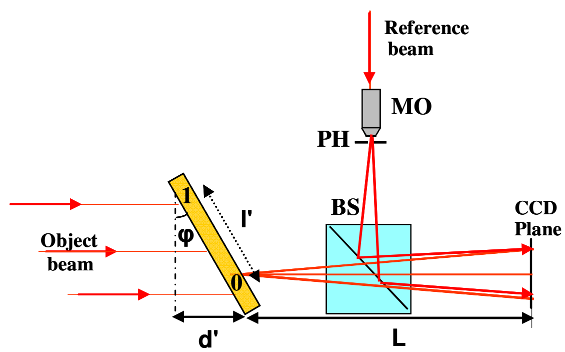

Fig. 1. Experimental set-up: BS, beam splitter; MO, microscope objectives; PH, pinhole.

The object was an USAF target positioned in a tilted way in respect to the laser light illumination direction. The Fourier holographic configuration is such that the curvature of the reference beam matches that of the light scattered by the left side of the object (where is the number "0"), i.e. the part of the target closer to the CCD (at a distance L). Consequently this region results to be in-focus in the numerical reconstruction, that is the hologram Fourier

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Transform. On contrary the right side of the target (where is the number "1") results to be completely out-of-focus in the numerical reconstruction. In Fig. 2 we show the numerical reconstruction of the acquired hologram for an object tilted with an angle $\varphi = 55°$. It is clear that the left part of the object, where there is the number "0", results to be in-focus, while the right part, with the number "1", is out of focus and that the focusing gradually worsen going from left to right side.

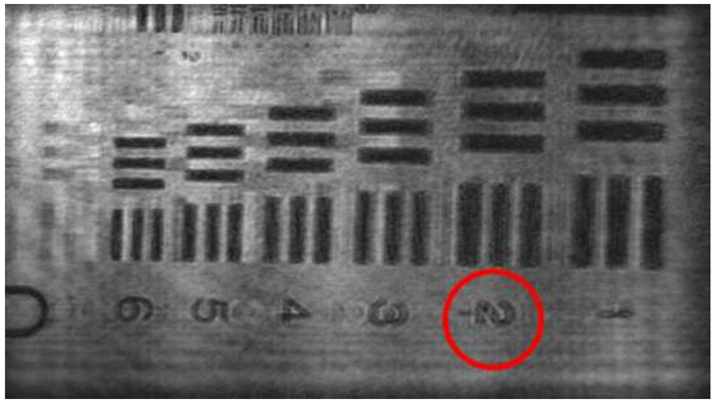

Fig. 2. Numerical reconstruction of the holograms for an object tilted with an angle of 55 degrees as acquired by the CCD (Movie_1).

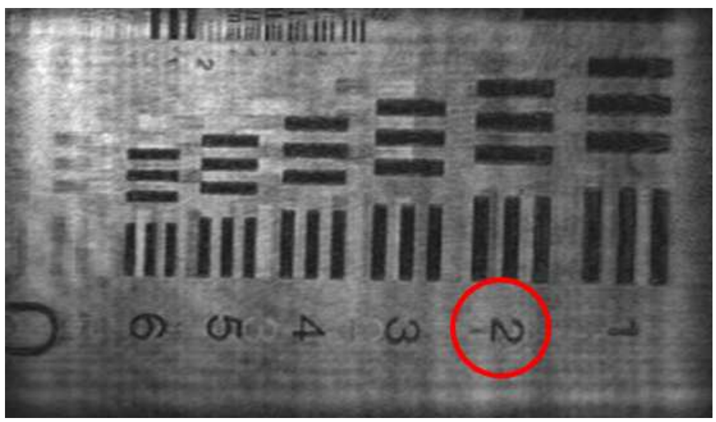

Fig. 3. Numerical reconstruction of the holograms for an object tilted with an angle of 55 degrees after the quadratic deformation.

If we apply the quadratic deformation before performing the reconstruction (with an opportune choice of the deformation parameter α), we obtain the image shown in Fig. 3. In this case the α value is $2.1* 10^{-5}$. Moreover, we show in the Movie_1 how the focus changes varying the parameter α between 0 and the value $2.1* 10^{-5}$ with a step of $2.1* 10^{-6}$/frame.

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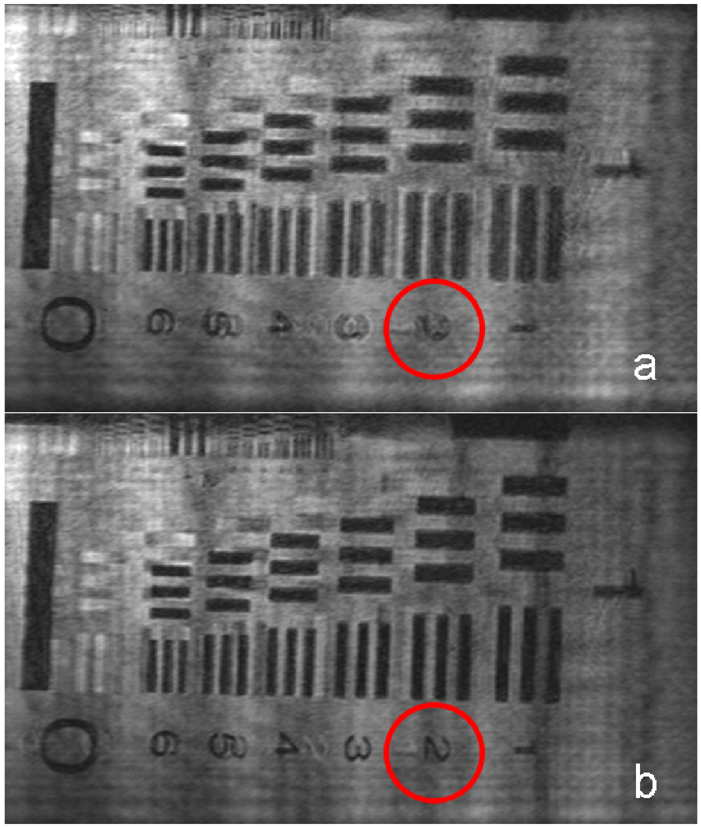

Fig. 4. Numerical reconstruction of the holograms for an object tilted with an angle of 75 degrees as acquired by the CCD (a) and after the quadratic deformation (b).

Finally we performed another experiment for a very high tilted angle of φ = 75°. In Figs. 4(a) and 4(b) are shown the numerical reconstructions of the original and deformed holograms of the same object tilted with the angle of 75°. In the reconstructions of the deformed objects, all details of the target result to be in-focus. We encircled number the number "2" in all the reconstructions to better guide the reader to visualize the comparison between the corrected and uncorrected images. In all the images some replicas of the target elements appear. They are due to the multiple reflections of the laser light on the target surfaces, in fact they are more evident in the image of the object tilted with an angle φ = 75°. Moreover, it is clear that the replicas are not due to the applied deformation as they are visible in the reconstructions of the not-deformed holograms (see Fig. 2 and Fig. 4a).

4. Conclusion

We have demonstrated that by an opportune deformation (numerical transformation) of a digital hologram it is possible to obtain an all in-focus image (i.e. EFI) for tilted objects in case of the Fourier-type holograms. The experimental results are in agreement with the theoretical model. It has been demonstrate that the EFI can be recovered for very high tilted angles. The approach is completely new in respect to the previous methods developed to obtain EFI both for incoherent and coherent imaging systems. In addition, this new approach can open the possibility to make more complex numerical manipulation of digital holograms to correct aberrations. The method is simple because it require just a single recorded hologram dispensing from the need to records multiple images and avoiding mechanical scanning.

The method is easily applied to digital holograms where the coordinate deformation is performed numerically. Moreover for holograms recorded on a specific material (physically

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recorded on a photosensitive media) it is possible to foresight to apply an adaptive mechanical deformation to extend the depth of focus even in that case.

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