Phase Grating Application for Digital Holographic Imaging

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***Abstract* — An application of phase harmonic grating for digital holographic imaging was modeled. The process of digital hologram recording was simulated in off-axis geometry combined by placing a grating in reference or object beam with the subsequent image reconstruction by Local Least Square method. We characterized and evaluated this method by using simulated data of different phase grating parameters (period) and its position and angle in reference or object beam. We show that, by means of a phase grating in reference beam, it is possible to increase the quality of reconstructed image in comparison with holographic recording without grating. This method may find practical applications in three-dimensional digital imaging and microscopy.**

***Index Terms* — digital holographic imaging, phase grating, off-axis holography.**

I. INTRODUCTION

Digital holography and other similar interferometric approaches provide coherent imaging in microscopy for a variety of applications such as Quantitative Phase Microscopy in biology [1-2], characterization of silicon MEMS, three dimensional (3D) imaging [3, 4], particle image analysis [5], and vibration analysis [6]. The potential applications of digital holography have been extended to a wide spectral range, from far IR to deep UV [7]. Recent advances in high-resolution spatial sensors, such as charge-coupled devices (CCD) or complementary metal–oxide–semiconductor (CMOS), have prompted the reassessment, in the new context of digital holography, of several original ideas that had emerged from the seminal work of Gabor [8] and Leith [9]. Digital holography refers to holographic methods that use solid-state detectors, such as CCD or CMOS, and store the hologram in digital form. The main advantage of this method is that it can acquire quantitative 3D data of a specimen at a single shot, in contrast to other methods requiring multiple sequential scans.

The computational image reconstruction from a digital hologram has many advantages compared to the traditional optical holography, including amplitude and phase imaging, 3D imaging and the digital wavefront manipulation. The most methods that aimed at retrieving the complex wave from the hologram were directly inspired by the optical reconstruction process: The chemically processed photographic plate—the hologram—is illuminated, and the image (respectively the virtual image) is generated by the diffracted wave. The translation of this physical process into a numerical algorithm is nearly literal. Simulating the diffraction process boils down to computing the propagation of a complex wave, which can be done using several approximations [10].

The most disadvantages of approaches that imitate the physical process are that the reconstructed image is severely corrupted by interference terms: the zero-order term and the out-of-focus twin-image term. While several techniques have been proposed for removing them [11,12] the presence of these terms still remains a determining factor that limits the quality of the reconstructed image, or at least the field of view.

In [13] Liebling et al. presented a new approach for reconstructing wavefronts from a single off-axis digital hologram. The proposed algorithm is based on a local least-squares estimation of the amplitude and phase by assuming an a priori model of the reference wave's phase. The presented approach overcomes these disadvantages by intrinsically removing the zero-order and the twin-image terms without the need for any pre- or postprocessing.

Recently, Liu et al. [14] demonstrated that super-resolved images can be obtained simply by using the diffraction effect of an appropriate grating. Essentially, their technique allows one to collect parts of the spectrum diffracted by the object, which otherwise would fall outside the CCD array. This was achieved by inserting a diffraction grating in the recording holographic set-up. The basic principle is simple and effective. In fact, the diffraction grating allows one to re-direct toward the CCD array the information that otherwise would be lost. Basically, three digital holograms are recorded and spatially multiplexed onto the same CCD array. Super-resolved images can be obtained by the numerical reconstruction of those multiplexed digital holograms, by increasing three times the numerical aperture. Although the working principle has been demonstrated, it is important to highlight that some limitations wait to be overcome in the approach developed in [14]. The main limitations regard the properties of the grating they used for the recording process.

In order to improve the resolution of digital holography, another kind of space–time digital holography method was proposed by Indebetouw and Klysuban [15]. This method can produce a speckle noise-free image, but its scanning system makes the related setup and experimental procedure complicated. In this letter, we describe another method capable of improving the quality of reconstructed phase images by application of phase grating.

II. MODELING OF THE PHASE GRATING AND OF THE HOLOGRAM RECORDING

The modeled scheme of holographic recording to demonstrate the idea is shown in Fig. 1.

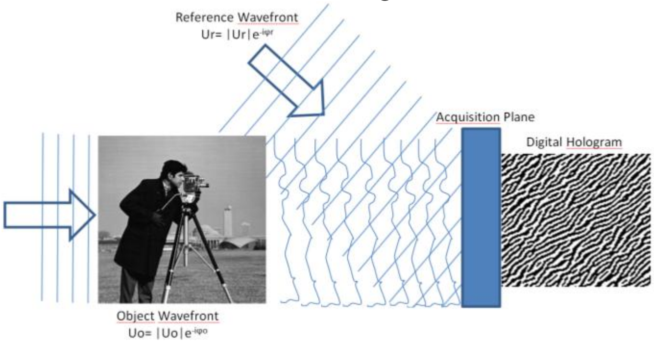
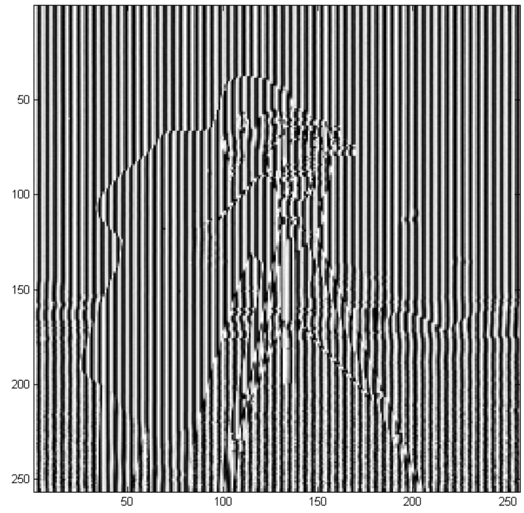


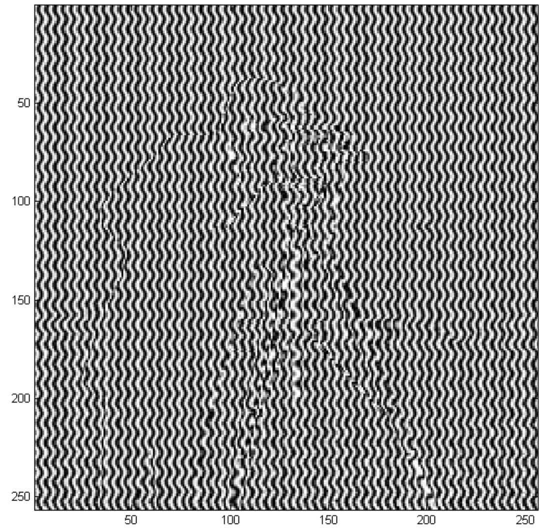
Fig. 1. The modeled scheme of holographic recording.

The object (in our case we selected the test greyscale image Cameraman) is illuminated with a collimated plane laser beam (λ=650 nm) and the complex incident wavefront on the acquisition plane is $Uo=|Uo|e^{-i\varphi o}$, where |Uo| is the amplitude, φ_o – the phase of the object beam. The modulus of the complex object wave is constant over the whole plane of interest while the phase follows a “Cameraman” image. The phase varies between 0 and 1 radian.

A laser beam with plane wavefront $U_R= |U_R|e^{-i\varphi R}$ that makes an angle of Θ=4° with the object beam is used as a reference light. The modulus of the complex reference wave is the same constant. The sampling step was chosen to be 2.2 μm (sampling step of our CCD camera) and wavelength λ=632.8 nm the wavelength (He-Ne laser). A grating, which is the key device in this method, with complex wavefront $U_G= |U_G|e^{-i\varphi G}$ is placed in the reference beam (or in the object beam). The modulus of the phase grating is constant while the phase follows a sinusoidal pattern with given period. The phase varies between 0 and π rad. If we assume that the phase of the grating can be written as $\varphi G=\varphi_0\cos(2\pi/\Delta x)$, where φ_0 is a constant phase and Δ - is a period of grating, the complex wavefront of reference beam (in case of using the grating in reference beam) in the acquisition plane can be obtained by multiplying U_G with U_R. In case of using the grating in object beam the complex object wavefront can be obtained by multiplying U_G with U_O. The reference beam interferes with object wave that traveling perpendicularly to the acquisition plane leads to a hologram formation in the form $I(x,y)=[U_R(x,y)+U_O(x,y)]^2$. The resulting interference pattern has a fringe period $\Lambda=\lambda/2\sin(\Theta/2)$ that corresponds 4 pixels/fringe. For comparison, first we modeled the hologram recorded with the scheme shown in Fig. 1, then placing the grating in the reference beam and recorded another hologram. The two holograms are shown Fig. 3.



a



b

Fig. 3. Two modeled holograms of Cameraman object. a – without application a phase grating, b – with phase grating.

III. RESULTS AND DISCUSSION

Since the holograms of objects were obtained the next step was reconstruction of phase images. First, we estimated the amplitude and phase in the acquisition plane by applying an algorithm [13] that retrieves the complex wave in the CCD plane from the real-valued measurements. This algorithm performs a nonlinear change of variables so that the reconstruction is performed by use of a method that is reminiscent of phase-shifting techniques. The algorithm is based on a local least-squares estimation of the amplitude and phase by assuming an a priori model of the reference wave’s phase. Initial phase image and reconstructed ones without application of grating and with application are shown in Fig. 4.

a

b

c

Fig. 4. Initial phase image (a) and reconstructed ones without application of grating (b) and with application of grating (c).

To compare the reconstructed images and to analyze the contribution of phase grating in quality of reconstruction the parameter root-mean-square error (RMSE) was introduced: $RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2}$, where y_j are the pixels of the original image and $\hat{y}_j$ are pixels of the reconstructed image. Figure 4(b) shows the phase reconstruction of the digital hologram of the object when no phase grating is applied during holographic recording. The phase reconstruction and comparison the obtained image with initial one showed that the RMSE parameter is equal to 0.056. The RMSE values of reconstructed images with phase grating will be compared with this one.

First of all the dependence of RMSE parameter of reconstructed images was studied for different angles of phase grating (angle between the interference fringes and grating fringes).

In fig. 5 the dependence of RMSE on grating angle for grating period 3 Px/fringe and 10 Px/fringe with and without application of phase grating is presented.

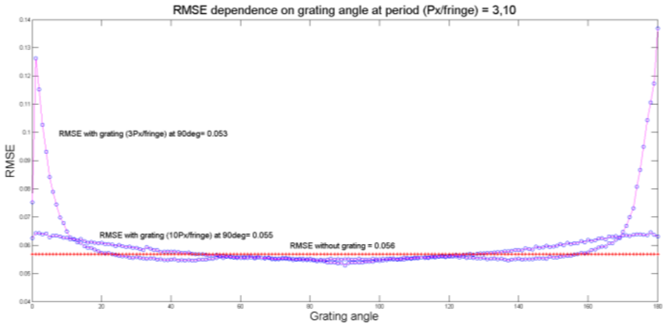


Fig. 5. Dependence of RMSE on grating angle for grating period 3 Px/fringe and 10 Px/fringe with and without application of phase grating.

It was shown that the best angles of grating which provide the minimal value of RMSE are in the range 70°-110° with peak at 90°. At this angle the RMSE is equal 0.053, that is less than RMSE without grating. An improvement of RMSE with application of phase grating was about 5%.

In fig. 6 the dependence of RMSE on grating period for angle 90° grating is presented.

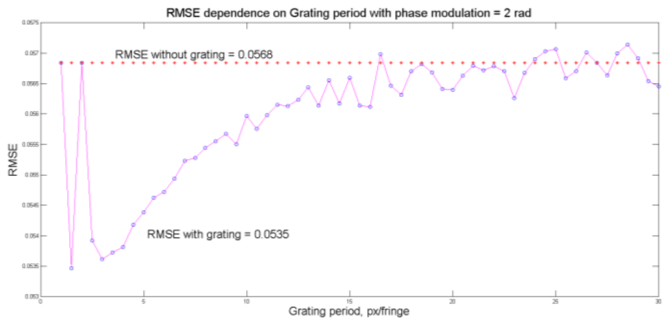
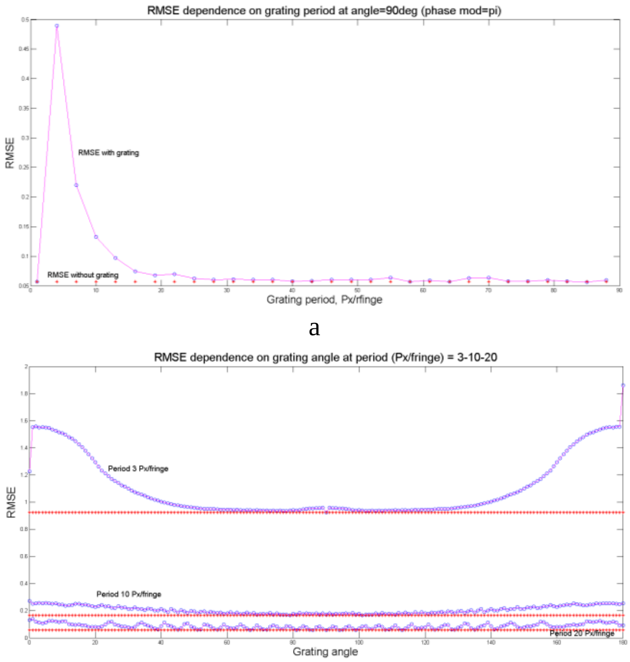


Fig. 6. Dependence of RMSE on grating period for 90° angle of grating.

As it can be seen the best values of RMSE are observed for grating period in the range 3-5 Px/fringe at 90° angle of grating. From the grating period 20 Px/fringe the RMSE is approached to RMSE without grating.

The same calculations were made for the phase grating placing in object beam. As it can be seen from figures 7 (a, b) the RMSE in all cases are above RMSE without grating that shows inefficiency of placing the grating in object beam.



a

b

Fig. 7. Dependence of RMSE on grating period (a) and on angle for grating period 3 Px/fringe, 10 Px/fringe and 20 Pc/fringe.

IV. CONCLUSIONS

It was shown that application of phase grating during the hologram recording by digital holography could enhance phase reconstruction for off-axis holographic configuration. We characterized and evaluated the proposed method by using simulated data of different phase grating parameters (period and angle) and its position in reference or object beam. We showed that, by means of a phase grating in reference beam, it is possible to increase the quality of reconstructed image (up to 5%) in comparison with holographic recording without grating. The optimal grating period was found to be in the range 3-5 Px/fringe at the angles 70°-110°. Contrary to it, application of phase grating in object beam doesn't improve the quality of reconstructed image. This method may find many applications in three-dimensional digital imaging and microscopy.

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