Optik 126 (2015) 3283–3287

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Scratch enhancement and measurement in periodic and non-periodic optical elements using digital holography

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ARTICLE INFO

Article history:
Received 16 July 2014
Accepted 3 August 2015

Keywords:
Digital holography
Scratch detection in optical elements
Optical inspection
Digital image processing

ABSTRACT

Scratch or flaw detection plays an important role in imaging optics and optical instrumentation. Even a minute scratch or crack can spoil coating and/or scatter incident light which causes irregularities/noise in the signal. Present paper describes use of digital holography for inspection of periodic and non-periodic optical elements for presence of any type of flaws like scratch, dust particles, irregularity etc. Digital image processing on numerically reconstructed wavefronts of the test samples provides enhanced image of the flaw. Various parameters of the flaws are measured. Experimental results of scratch on a glass plate and a lens and a thin hair on a grating and a mirror are presented.

1. Introduction

Optical elements are used in various instruments that play important role in many fields such as semiconductor industry, defense, space, astronomy, medical etc. For imaging applications optical surfaces should be precisely made, finished, handled and kept dust free [1]. Even a minute scratch, crack, irregularity in period or any other type of flaw in the optics will generate noise signal by scattering the incident light and thereby may severely affect the results. The scattered light can generate troublesome ghost interference patterns which may result in incorrect interpretation of the results [2]. Also in case of non-imaging fields, a scratch or dust particle can affect the desired results by generating noise signal. Thus, it is imperative to keep the optics scratch and dust free for obtaining accurate results. Various methods such as spatial filtering [3], Talbot and moiré methods [4,5], diffraction based method [6], interferometric, holographic and digital holographic methods [7–13] etc. are employed to detect these defects. Most of these methods are applicable only for the defect detection of periodic objects. It is necessity of time to develop such a technique which can be used for inspection of periodic structures such as semiconductor wafer or a grating as well as non-periodic components such as mirror, glass plate etc.

Present work describes use of off-axis Fresnel holography to detect flaws in periodic as well as non-periodic components. Interference of object wavefront and reference wavefront is recorded digitally using a Complementary metal–oxide–semiconductor (CMOS) detector. Reconstruction is performed numerically in personal computer and spatial filtering is performed digitally on the reconstructed wavefront. Using spatial frequency filtering one can easily suppress periodicity of periodic components like grating and semiconductor wafers thereby passing frequencies related only to defects/flaws in the observation plane. Further digital post processing of the image results in enhanced information related to defects and flaws making their detection easy. Similarly reconstructed images of non-periodic objects are also digitally processed for efficient detection and measurement of defects present on these elements. Objects used in this work are glass plate, mirror and grating.

2. Theory

Holography, discovered by Dennis Gabor in 1948, is a process for imaging objects without using imaging optics. It records complete wavefront of the test object and provides whole information related to amplitude and phase distribution of the object [14]. In digital holography a hologram is recorded digitally and wavefront from recorded hologram is reconstructed by using numerical methods on a personal computer [15,16]. In present work digital holography in off-axis geometry is used to record the object of interest electronically and reconstruction is performed

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http://dx.doi.org/10.1016/j.ijleo.2015.08.008
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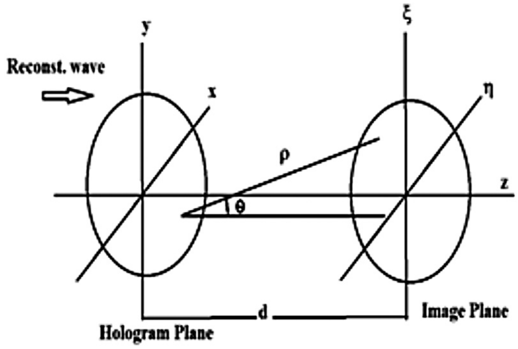

Fig. 1. Coordinate system.

numerically using Fresnel–Kirchhoff integral. A collimated reference wave and the object wave are superimposed at the surface of a CMOS sensor. Object is located at a distance d from the sensor. During reconstruction process, the recorded hologram is numerically illuminated with a computer generated reference beam. This results in diffraction of incident light from recorded interference fringes of the hologram. This diffracted light forms image of the recorded object.

Using Fresnel–Kirchhoff's approximation reconstructed field becomes [15]:

$$\Gamma(\xi,\eta)=\frac{i}{\lambda}\int\int_{-\infty}^{+\infty}h(x,y)R(x,y)\frac{\exp\left(-\left(2\pi/\lambda\right)\rho\right)}{\rho}\mathrm{d}x\mathrm{d}y \tag{1}$$

here (x,y) and (ξ,η) are coordinates of hologram plane and image plane, respectively, (as shown in Fig. 1) z is the direction of propagation; $h(x,y)$ = hologram function, $R(x,y)$ = reference plane wave; $\rho=\sqrt{(x-\xi)^2+(y-\eta)^2+(d)^2}$ is distance between a point in the hologram plane and a point in the image plane. Using Taylor series expansion around ρ

$$\begin{aligned}\Gamma\left(\xi,\eta\right) = {} & \frac{i}{\lambda d}\exp\left(-i\frac{2\pi}{\lambda}d\right)\exp\left(-i\frac{\pi}{\lambda d}\left(\xi^2+\eta^2\right)\right)\\ & *\int\int_{-\infty}^{+\infty}h(x,y)R(x,y)\exp\left(-i\frac{\pi}{\lambda d}\left(x^2+y^2\right)\right)\\ & \times\exp\left(i\frac{2\pi}{\lambda d}\left(x\xi+y\eta\right)\right)\mathrm{d}x\mathrm{d}y\end{aligned} \tag{2}$$

Eq. (2) gives complex amplitude in image plane propagated from CMOS/hologram plane separated by distance d. This field is digitized by sampling the hologram function in hologram plane according to number of pixels and pixel size of CMOS and then converted into samples of image plane. The digitized field is stored in the computer in the form of a digital image which is further used for numerical reconstruction of the recorded object wavefront [17]. The intensity distribution corresponding to recorded hologram field is:

$$I\left(\xi,\eta\right)=\left|\Gamma\left(\xi,\eta\right)\right|^2 \tag{3}$$

The reconstruction process generates a bright patch corresponding to zero spatial frequency in the image known as un-diffracted zero-order term (or DC term). This DC term overlaps the desired reconstructed object image if minimum off-axis angle is not maintained during recording of interference pattern. So this term should be suppressed. To understand this, the intensity $I(x,y)$ of the optically generated interference pattern of reference beam $R(x,y)$ and $O(x,y)$ in hologram plane is given by coherent superposition of the two wave fields:

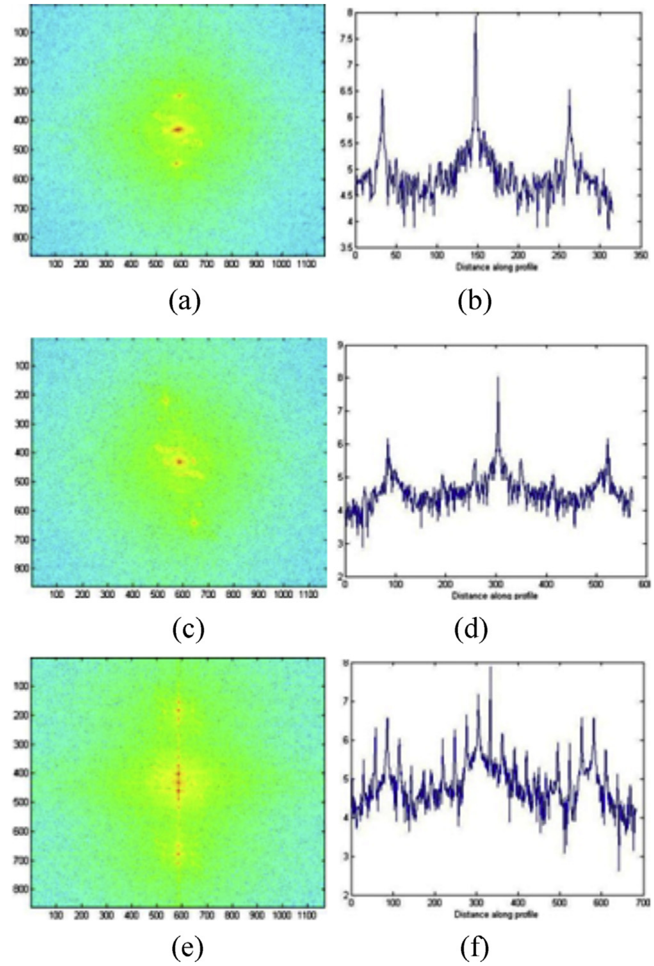

Fig. 2. (a) Fourier transform pattern of glass plate (c) of mirror and (e) of grating and (b), (d), (f) shows their respective intensity distributions.

$$\begin{aligned}I(x,y) = {} & |O(x,y)+R(x,y)|^2=R(x,y)^2+O(x,y)^2\\ & +2O(x,y)R(x,y)\cos\left(\varphi_o-\varphi_R\right)\end{aligned} \tag{4}$$

Here, first two terms lead to the DC term in the reconstruction process. Third term is varying between +2RO and −2RO from pixel to pixel in the CMOS. If first two terms are subtracted from total intensity, we will get the object term undisturbed by zero-term. Since, the average intensity of all pixels of the hologram matrix is

$$I_m=\frac{1}{N^2}\sum_{k=0}^{N-1}\sum_{l=0}^{N-1}I\left(k\Delta x,l\Delta y\right) \tag{5}$$

$R(x,y)^2+O(x,y)^2$ can be suppressed by subtracting this average intensity I_m from the hologram, giving:

$$I'\left(k\Delta x,l\Delta y\right)=I\left(k\Delta x,l\Delta y\right)-I_m\left(k\Delta x,l\Delta y\right) \tag{6}$$

For $k=0\ldots N-1$; $l=0\ldots N-1$

The reconstruction of $I'\left(k\Delta x,l\Delta y\right)$ will result in an image which is free from zero order term. Here, Δx and Δy are the image pixel along x and y directions, respectively. It is also possible to filter the hologram matrix using high pass filter with low-cut-off frequency. For spatial filtering, Fourier transform is taken numerically of the recorded hologram, which generates three terms in Fourier plane (as shown in Fig. 2). The diffracted light having spatial frequency corresponding to object information will be focused at specific