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

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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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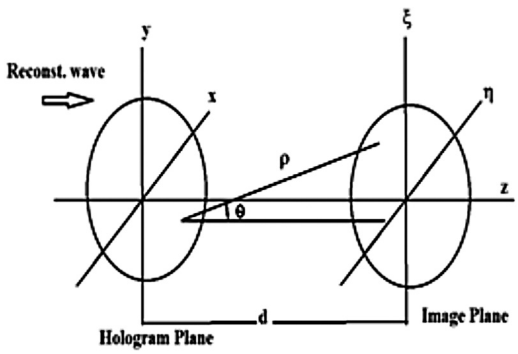

Fig. 1. Coordinate system.

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]:

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

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

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

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:

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

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:

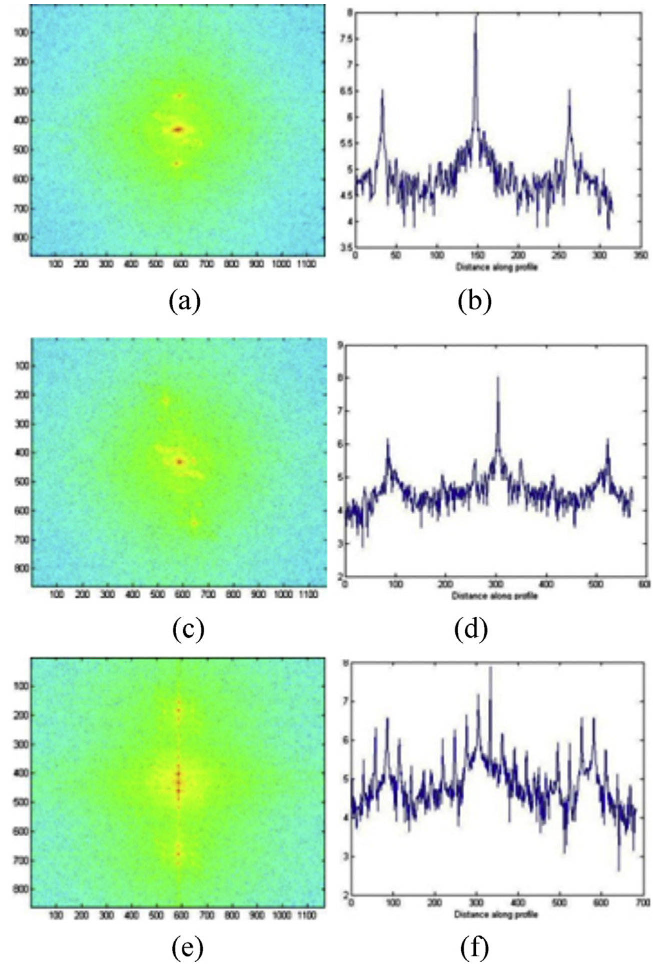

Fig. 2. (a) Fourier transform pattern of glass plate (c) of mirror and (e) of grating and (b), (d), (f) shows their respective intensity distributions.

$$I(x,y)=|O(x,y)+R(x,y)|^2=R(x,y)^2+O(x,y)^2$$
$$+2O(x,y)R(x,y)\cos\left(\varphi_o-\varphi_R\right) \quad (4)$$

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

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

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

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

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

The reconstruction of $I'(k\Delta x, l\Delta y)$ 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

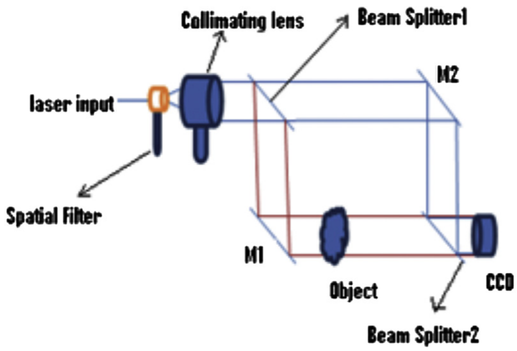

Fig. 3. Holographic recording setup.

points in Fourier plane. These specific points of light are then filtered to get the useful information. Since, intensities of reference beam and object beam are almost equal, as a result diffraction efficiency of periodic pattern is much less as compared to the defect because the spatial frequency components of the defect term are much less than periodic spikes. After taking inverse transform, reconstruction with conjugate reference beam provides enhanced defect out of original object. In case of non-periodic elements, the scattered intensity from defect is different from the object as well as of reference beam so its diffraction efficiency is different from rest of object part. Fig. 2(a, c and e) shows the Fourier transform patterns of glass plate, mirror and grating, respectively. These consists of three frequencies; the central frequency corresponds to DC term and other two are the ±1 diffraction terms. Fig. 2(b, d and f) shows their respective intensity distributions. By selecting accurate spatial frequency filter, other terms except corresponding to defect are suppressed so that defect term gets enhanced. After reconstruction a defect of 1.876 nm depth is found on the optical element.

3. Experimental details

The experimental arrangement of holographic recording setup is schematically shown in Fig. 3. Here, scratch detection is performed through Fresnel digital holography with off axis holographic setup employing Mach–Zehnder geometry having four degrees of off-axis angle between reference and object wave. Light from laser source of wavelength 633 nm is expanded using spatial filter assembly. This spatially filtered beam is then passed through a collimating lens followed by a diaphragm of 9 mm diameter. The collimated beam is split into two beams using a variable beam splitter (beam splitter1). The object on which the defect is to be detected is placed in path of one of the beams now called as object beam. A CMOS camera (1024 × 1280) with pixel size of 6.7 μm is used to record the optically generated hologram. Various objects such as glass plate, mirror, lens and grating are used as test objects to detect their flaws. Recorded hologram is stored into a computer and is further processed numerically.

In order to suppress DC light and to improve signal to noise ratio, average value of intensity is calculated numerically and then subtracted from total intensity of the hologram. Suppression of unwanted terms is achieved by high pass filtering. This pattern is further processed through Fresnel–Kirchhoff integral to get the reconstructed image. The image is processed through some layers of filters. First the image is threshold, which is needed for extraction of the desired image.

Output image now consists of certain rough edges which are smoothened by dilation. A median filter is used to suppress noise from the reconstructed image. The image obtained now is further processed using 'diamond strel' so that we can get a smoothened and higher contrast images. These processes make the defect on

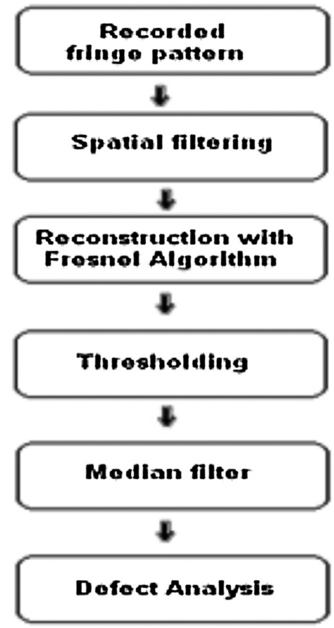

Fig. 4. Block diagram of image processing techniques taken into account during defect detection.

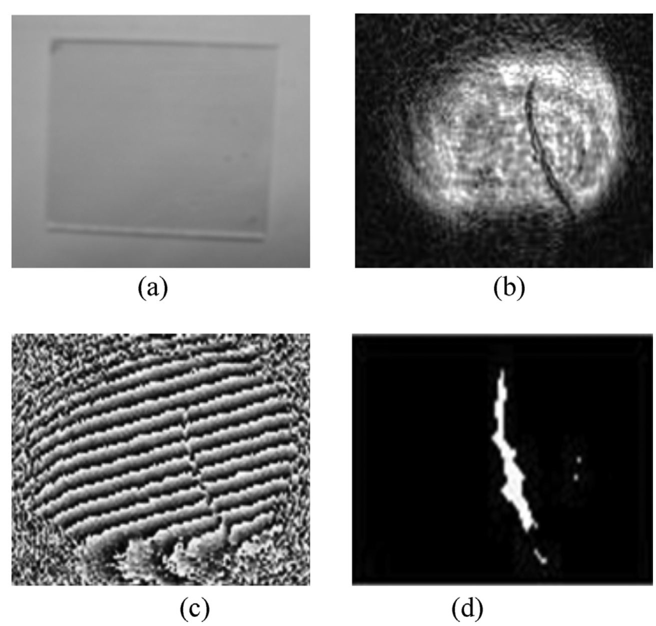

Fig. 5. (a) shows the glass plate on which scratch is detected. Its reconstructed amplitude & phase. Patterns are shown in (b) and (c), respectively, and (d) shows filtered and enhanced image of scratch on glass plate.

test components clearly visible on the computer screen as shown in Figs. 5–8. All the processes are shown via block diagram in Fig. 4.

4. Result and discussion

Experiments are performed on a number of periodic and non-periodic optical components to test their flaws. These flaws are intentionally put on the test components. A scratch was developed on an optical glass plate (60 mm × 60 mm × 2 mm) as shown in Fig. 5(a) and its hologram was digitally recorded. After numerical processing the scratch is found to be 0.27 mm long and covering an area of 2.9 mm^2. The maximum and minimum width of this scratch is 0.05 mm and 0.0067 mm, respectively. The depth of the scratch

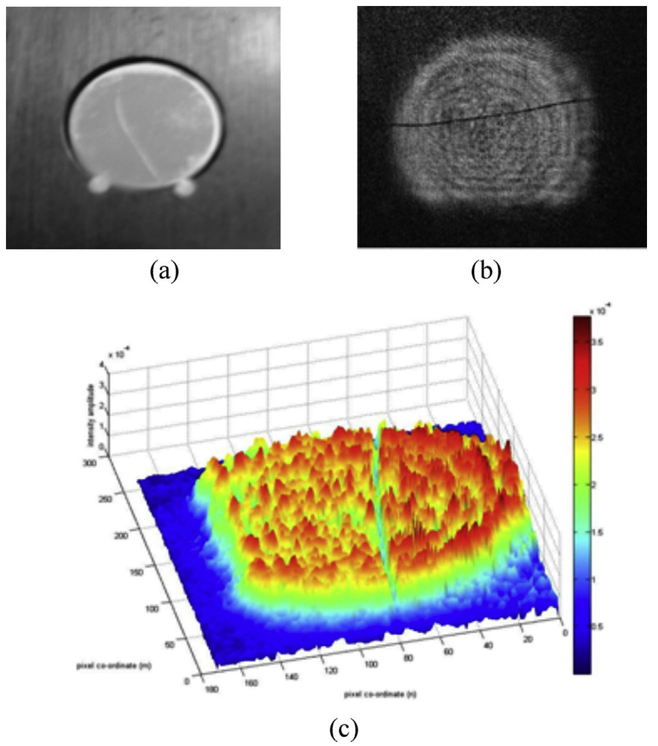

Fig. 6. (a) Human hair sample on mirror; (b) shows the reconstructed amplitude pattern of hair sample & (c) shows the side view of three dimensional amplitude distribution pattern of mirror with defect.

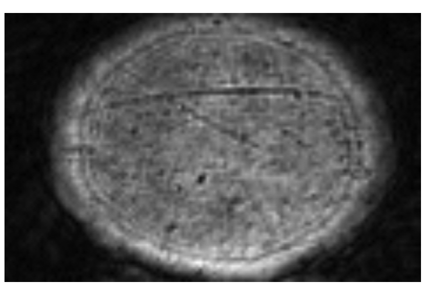

Fig. 7. Reconstructed image of lens containing scratch.

on glass plate is 1.876 nm. Fig. 5(b) and (c) shows reconstructed amplitude and phase images of glass plate, respectively.

Here it may be seen that the scratch on the plate is not visible with naked eye but it become visible in reconstructed images. Spatial filtering leaves scratch stands out clearly as now DC terms has been suppressed. Second experiment is performed on a mirror with a human hair kept on it as shown in Fig. 6(a). The reconstructed amplitude image is shown in Fig. 6(b) and (c) shows its 3D view in which x and y are the image co-ordinates in terms of number of pixels and z coordinate represents amplitude. The measured length of hair on mirror is 1.37 mm with a diameter of 20 μm. Here also the visibility of hair gets enhanced in reconstructed image as compared to seen by naked eye or a camera. A biconvex lens of focal length 4.35 cm at 633 nm wavelength is also tested using this method. During its testing, a converging beam from the test lens is allowed to interfere with the reference beam. The reconstructed image of test lens (Fig. 7) consists of two main scratches and numerically measured maximum length of scratch is 0.516 mm. The measured depth of the scratch is 1.34 nm.

A periodic optical element in the form of an optical grating having 6 lines/mm is also tested through this technique. Fig. 8(a) shows a hair sample on grating; (b) shows its reconstructed

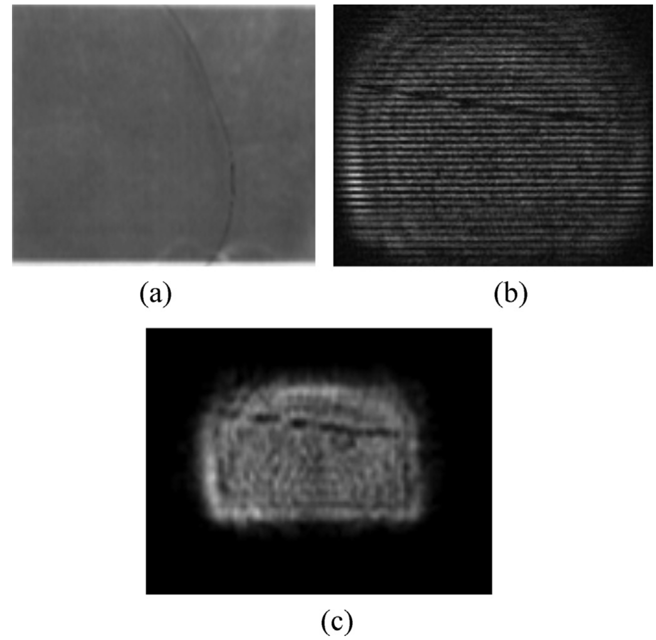

Fig. 8. (a) Hair sample on grating; (b) Reconstructed hologram of grating & (c) Spatial frequency filtered reconstructed image of grating.

amplitude image. This image consists of both flaw as well as periodic pattern. To enhance the defect and to suppress periodic pattern spatial filtering is performed before reconstruction. Fig. 8(c) shows the spatial frequency filtered reconstructed image of grating. The measured length of flaw on grating is 1.62 mm and width 20.1 μm.

Here also spatial filtering of the reconstructed hologram enhances defect present in the periodic pattern. These results clearly show that digital holography can be effectively used for quality testing related to flaws and scratches of periodic as well as non-periodic optical components with high accuracy and fast speed.

5. Conclusion

Digital holography is a non-contact and mostly non-invasive method for recording and reconstruction of three-dimensional information of the test objects. It offers advantages of fast, parallel and dry processing, numerical analysis and compactness compared to other techniques. In present work, use of digital holography is demonstrated for inspection of optical elements for scratches and dust/foreign particles. The system is tested for detection and measurement of scratch on an optical glass plate and lens and dust/foreign particles on a mirror and a grating. The spatial filtering is used to enhance the defect and a median filter is used to suppress the excess noise. Experimental results demonstrates applicability of this technique for inspection of periodic as well as non-periodic components and thus may prove useful in optical and semiconductor industry for quality testing of fabricated optical components and masks and/or circuits.

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