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Micro-structure measurement of digital holography

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ABSTRACT

Miniaturization is a development trend of electronics, machinery and information systems, while micro structure brought a large amount of new development for industrial and research applications, whereas, slow measuring speed and two-dimensional results of traditional micro-measurement could not meet our needs, it's urgent to find a matching testing techniques with more sensitivity, more effectiveness and better to have a real-time three-dimensional display. Digital holography applied to the measurement of micro-structure, it made up for the lacking of traditional micro-structure measure systems of too much time consuming, poor immunity, easily damaging samples with its simple structure, high accuracy, non-contact features and three-dimensional reproduction[1]. This paper analyzed the key factors of digital holographic recording and reproducing process. In order to solve the low quality of holograms captured by traditional recording system, holograms and pre-processing algorithm was combined for real-time, by observing the holograms and delicate adjusting the system, to ensure that the collected holograms with full use of CCD width while convenient for subsequent processing. In the processing of reproduction, the influence of spectrum choice, reconstruction wavelength and algorithms and unwrapping algorithm was been studied, and finally obtained an accurate three dimensional topography of the object. The improved rerecording system and reconstruction algorithm mentioned above solved the low holography quality, much noise and not clear shortcomings of the reconstructed image. Experiment on a raster, compared with traditional system and algorithm results, results showed that the recording system and determine algorithms can reproduce the three-dimensional topography of the object with high precision and has a broader applicability.

Keywords: Micro-structure measurement, Recording light path, Reproduction algorithm, three-dimensional topography

1. INTRODUCTION

Miniaturization is one of the important directions of current technical developments, and has expanded to areas such as micro-electro-mechanical with the growth of electron technology. Owing to the big differences of MEMS between the characteristics in macro-scale and in the area of micro-operation, a measuring method proper for miniaturization to obtain its properties and precise geometric dimensions is urgently needed. Meanwhile, the sophisticated miniaturization and high integration request the measuring method to be non-intrusive and with high resolution. Digital holography also has many important applications in the field of biological research. Live cell micro-deformation and its movement can be tested and monitored by digital holography to achieve the study of morphology. Relative to Confocal microscopy and Mutiphoton microscopy, digital holography is completely a nondestructive testing technology due to the low use of light

source. this allows the configured live cell samples could own many hours or even days of life, thus to get a possibilities to study the long-term evolution of the development of cells.

2. ANALYSIS OF DIGITAL HOLOGRAPHIC RECONSTRUCTION

Digital holography is an optical information storage and information reproduction technology along with the development of opto-electronic devices and high-speed computers, it has two processes of recording and reproducing the same as optical holography, only the implement of recording and reproducing are different.

2.1 Analysis of digital holographic recording conditions

Opto-coupled device CCD is used in digital holographic as the recording medium, due to its small image surface and magnitude smaller resolution prepared with traditional silver plate[2], digital holography could not record the high frequency information and it was restricted in the recording information in small aperture and small field.

Figure 1. Diagram of off-axis digital holographic recording path

From the figure, the maximum θ can be expressed as:

$$\theta_{\max} = \frac{L_{\text{CCD}} + L_0 + 2b}{2Z_{\min}} \quad (1)$$

The minimum recording distance could be described as:

$$Z_{\min} = \frac{L_{\text{CCD}} + 4L_0}{2\theta_{\max}} = \frac{L_{\text{CCD}} + 4L_0}{\lambda} \Delta x \quad (2)$$

In order to make accurate three dimensional information of things to be recorded and reproduced, experiments must be conducted to set several limited experiment conditions to decrease the CCD defects caused effects.

2.2 The angle between the object and the reference beam

Digital holographic recording and reproducing process are affected by CCD pixel size, photo size and other factors[3]. On the one hand, the bigger the pixel size, the lower resolution of the reproduced image. On the other hand, due to the small size of photosensitive surface, the angle between the object and the reference beam is limited to be small, it could only record the low frequency information and lead to a difficult separation of ± 1 image. therefore, its only suitable for small objects and long distance record. The angle between the object and the reference beam should in a proper range, the zero-level image and first level image will depart with the increase of the angle, but if the angle is too large, CCD will not

satisfy the sampling theorem, and the recorded holographic interference fringe will be with a high spatial frequency[4].

Assuming an angle θ between the object and the reference in the 'u' direction has a high spatial frequency spectrum that is W , CCD pixel size of Δx_H , λ represent the laser wavelength. According to the angle between object and reference wave deduced above which should satisfy the spectrum separation conditions and CCD resolution, the proper valid angle should be represented as

$$\arcsin(3W\lambda) \leq \theta \leq \lambda / (2x_H) \quad (3)$$

In the above range, CCD can record the maximum object wave frequency band width, a best value of angle θ is determined. As shown in the figure 1.2.

Figure 2. Holographic frequency spectrum under the optimum angle

Assuming the recorded largest frequency spectrum is $f_{cx}=1/2 \Delta x_H$, the wave band will reach its maximum when $W_r=3f_{cx}/4$, as shown in figure 2, meantime, there exist the equation:

$$\arcsin(3W\lambda) \leq \theta \leq \lambda / (2x_H) \quad (4)$$

There are zero-order image, original image and conjugate image in the reproducing light field, while the original image and the conjugate image symmetrically distributed on the sides of the center of CCD[5]. To avoid the overlapping image of +1 order, -1 order and back lighting leading to the increase of noise, the angle between object and reference should be proper, meantime, the record stripes should be moderate. Therefore, during the actual operation, multiple manual fine tuning is needed.

3. EXPERIMENTAL DEVICES SELECTION AND PLATFORM BUILDING

3.1 Devices selection

Based on the above calculation, devices are selected while experiment system is built. This article uses a fiber coupled laser with a wavelength of 632.8nm, it has the advantage of : (a) use fewer components, optical components, with the function of beam transmitting and expanding. (b) uniform illumination of a variety of objects, including complex shape objects. (c) the record could be at a long distance. (d) holographic testing is also suitable for closed system. The CCD

model in this experiment is DM×41BU02, with a function of progressive scanning. Essential parameter: pixels:1280×960, pixel size:4.65μm×4.65μm, field range:4mm×4mm.

3.2 platform structures

Figure 3. The experimental system light-path diagram

The measuring system and major device are shown in figure 4.

(a)The recording system

(b)The angle adjustment device

Figure 4. The system and major device

4.THE EXPERIMENTAL IMAGES AND THE RESULTS

4.1 Measuring objects and recorded holography

(a) the tested object

(b) the recorded holograph

Figure 5. The object and holograph

4.2 Frequency spectral selection effect

During the process of digital reproducing ,it is necessary to select spectrum, generally the regular level spectrum was selected while the zero-level and pseudo first level were filtered out to eliminate the interfere from background light and conjugate image, thus ,only the object image was reproduced[6].While in the selection of first level spectrum ,different size of it lead to different results, the analysis are as follows:

Figure 6. The experimental results

The selection of frequency spectrum is closely related to the measurement of surface morphology, for different samples, the size of filter window need to be constantly adjusted, combined with the processing algorithm at the same time ,to obtain the reproduced results real time .To get an accurate surface information ,the filter window should be adjusted so that the reproduced results obtained from the filter selected spectrum could include the superficial details while removing the effects of details smaller than the needed message.

4.3 The results of different reconstruction algorithms

Fresnel algorithm is based on the Fresnel diffraction integral formula, with the proviso that approximation of Fresnel conditions, combined with the sampling theorem, using FFT method to obtain the amplitude of reconstructed wave.

$$U_1(x_1, y_1) = \frac{\exp(jkZ_1)}{jkZ_1} \exp[j \frac{k}{2Z_1} (x_1^2 + y_1^2)] \times \Im\{I(x_H, y_H) C(x_H, y_H) \exp(jk \frac{x_H^2 + y_H^2}{2Z_1})\} \quad (5)$$

Different recording distance will yield different reproduction results,only when the reproduction distance is strictly equal to the recording distance, we shall get the accurate result.

Figure 7. Different result of different reconstruction distance

From the above diagram, it is obvious that different distance produces different images of different resolution. Therefore, Fresnel is not quite suitable for the reproduction of three dimensional objects, especially for the objects with significant levels, it will be partially distorted.

Convolution method is another classical method in the reproduction of holography:

$$U(x, y) = \int \int_{-\infty}^{\infty} U_0(x_0, y_0) h(x - x_0, y - y_0) dx_0 dy_0 = U_0(x_0, y_0) * h(x_0, y_0) \quad (6)$$

This equation indicated that the diffracted light field and the original light field has a relationship been described using convolution integral. the convolution kernel is :

$$h(x_0, y_0) = \frac{1}{jkz} \exp[jk\sqrt{z^2 + x_0^2 + y_0^2}] \quad (7)$$

During the calculation of convolution, Fast Fourier transform method been used could significantly shorter the operation time.

Figure 8. the intensity image of convolution method

For the Fresnel method, it will change the spatial coordinates of it into the frequency domain coordinate during reproducing. whereas, for the convolution method ,the holography is still in the spatial domain, the coordinate of it did not changed. the reconstructed image has the same pixel size as the recording surface[7], these characteristics makes it suitable for the measurement of different level particles.

4.4 The results of different unwrapping algorithm

The main theory of Goldstein is to use branch-cut to connect the adjacent poles, it first identifies the positive and negative residuals, and then connect them to realize the 'charge' balance, meantime, generate the optimal tangent, determine the path to prevent error passes, the result is shown below:

Figure 9. Goldestein unwrapped phase

Quality mapped unwrapping method is a kind of unwrapping method that set modulation as a parameter, thus to better suppress the regional propagation of shade and steep changes. While the orientation algorithm set the packaged phase second derivative mode value for parameter could unwrapping along the highest continuity direction, the result is shown in figure 6.

Figure 10. Quality mapped unwrapped phase

The results of these two different unwrapping method shows that the Quality mapped unwrapping method is more suitable for the surface that distributed like grate due to its basic principles, whereas, in the measuring of other object surface, the unwrapping method of Goldstein plays an important role always. The unwrapping method should be studied more to meet the urgent needs of optical measuring.

4.5 The effect of reproduction light on the results

Coherence properties of light determines the interference fringes quality of the recorded hologram. Temporal coherence and spatial coherence are together called coherence, only when the coherence length and area of the coherence is large enough that can record high quality holograms[8]. The source light will be used twice in the process, one is the recording, that the actual laser illuminated to the object, second is the imitation process, in the process of reproduction, use the simulated light to illuminate the recorded hologram, thus to realize the reproduction of three dimensional object.

The light source in this experiment is opto-coupled lasers, with a wavelength of 632.8nm, the reproduced light is simulated, so the properties of it should be studied to detect the infect of it.

Figure 11. The different results of various wavelength

The wavelength of the reproduced light would affect the quality of the reproduced image. When the wavelength of it is longer than the reference wavelength, the more longer of it ,the quality of reproduced image is worse.

From the diagrams above, the Horizontal and vertical size of the grate can be got:

Figure 12. The width and depth of the tested object

The data is already has a high accuracy actually,to get a more accurate data of the width and depth , it is requested to adjust the system and collect more data, and then take the average of them.

5. CONCLUSION

This system combines the pre-treatment system and the experimental image capture in real time, by observing the results of pre-treatment ,to adjust the measuring system, so that the state of object will be in a good mode, thus lead to a good recording quality of the image.The system improved the traditional recording system, makes it easier to record holography and convenient for the processing of reproduction. For a given tested object, through the analysis of the influencing factors in the reproduction process, optimized theories are selected separately in the steps of reproduction,an accurate profile information was got, and the system is with a wide range of applications.

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