Research on Experimental Parameters of Reflective Off-axis Digital Holography

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Abstract. Summarized the research status of digital holography microscopy technology. Aiming at the experimental parameters which influences the quality of hologram recurrent image, the recording and reconstruction process of hologram are analyzed, the reconstruction distance are calculated which based on the reflective off-axis digital holographic light path. The experiment records the hologram of standard resolution board and reconstruct it under different light intensity ratio. The results show that the object and reference light intensity ratio have a significant impact on the quality of hologram recurrent image. Besides, it’s the key to determining an appropriate recording distance and object and reference light intensity ratio of improving the quality of hologram. The result would provide theoretical basis and technical conditions for studying the reflective digital holography based on 3-D reconstruction.

1. Introduction
Digital holographic microscopy covers a wide range of fields such as optics, computer science, and image processing (ZHU Yu-liang et al. 2010). It is a new measurement technology with high sensitivity, short exposure time, easy transmission and analog reproduction. However, due to the small size of digital holographic recording components, the image size that can be accepted is also limited. In addition, coherent light imaging inevitably produces speckle noise and other factors, which seriously affects the reproduction image quality (ZHONG Li-yun et al. 2004, Malallah R 2017, Kawatsuki N 2003) In order to improve the image quality of hologram reconstruction, scholars have proposed many solutions, including: optical path structure design, optical path parameter optimization and reconstruction algorithm improvement (TAN Zuo-jun, et al. 2007, MIKHAILOV V N et al. 1998). Based on the transmission digital holography experiment, Wang Huaying pointed out that the reconstruction distance is a major factor affecting the quality of the reconstructed image, and through the gradient experiment of the reconstructed distance within a certain range, the relatively good reconstruction distance is verified (WANG Hua-ying et al. 2013). Wang Xing optimized the reconstruction distance of digital holography by means of average gradient optimization, and realized the automatic adjustment of reconstruction distance (WANG Xing et al. 2017); Song Xiufa proposed that the intensity ratio of ginseng has a certain threshold, when the ratio exceeds a certain range To reduce the reproduction image quality (SONG Xiu-fa et al. 2014). The above research is mainly directed to transmissive digital holography, and little research has been done on the experimental key parameters of reflective digital holography. Based on the Fresnel diffraction integral, the recording and re-synchronization process of the reflective off-axis digital hologram is discussed. The minimum recording distance of the hologram is determined. The holograms of different intensity ratios are observed under the appropriate recording distance.
2. Recording and reconstruction of digital hologram

2.1. Digital hologram recording process

Figure 1 is a schematic diagram of the recording optical path of the off-axis Fresnel digital hologram. $x_0 - y_0$ which is the object plane, $x_i - y_i$ which is the microlens plane, $x - y$ which is the hologram plane, $x_i - y_i$ which is the image plane, $z_i$ where the distance from the object plane to the lens plane is the lens plane to the hologram. The distance of the plane is the distance from the holographic plane to the image plane, that is $z$, the recording distance. Satisfy between the three: $\frac{1}{z_2} + \frac{1}{z_0} = \frac{1}{f}$. Among them $z_2 = z_i + z$, $f$ is the focal length of the microscope objective.

![Fig.1 Digital holographic recording optical path diagram](image)

Let the complex amplitude of the object on the CCD plane be $O(x, y)$, Reference photoresonance amplitude is $R(x, y)$. According to the interference and superposition of light intensity, the total light intensity distribution of the CCD recording plane is:

$$I(x, y) = |O(x, y)|^2 + |R(x, y)|^2 + O^*(x, y)R(x, y) + O(x, y)R^*(x, y)$$

(1)

Where * represents a conjugate operation. The first term represents the intensity of the object light, the second term represents the intensity of the reference light, and the third and fourth terms are the amplitude and phase information after the object light is coherent with the reference light. The hologram recorded on the holographic plane of the CCD can be expressed as:

$$I_D(x, y) = \left[ I(x, y) \otimes rect \left( \frac{x}{\alpha \Delta x}, \frac{y}{\beta \Delta y} \right) \right] \\ \times \text{comb} \left( \frac{x}{\Delta x}, \frac{y}{\Delta y} \right) \text{rect} \left( \frac{x}{L_x}, \frac{y}{L_y} \right)$$

(2)

In the formula, "$\otimes$" the convolution operator symbol, $\alpha$ and $\beta$ the CCD fill factor, $\Delta x$, $\Delta y$ is the sampling interval of the CCD, $L_x$ and $L_y$ the target size of the CCD, $\text{rect}$ is a rectangular function, $\text{comb}$ which is a comb function, indicating spatial discrete sampling (Batenburg K J et al. 2013).

2.2. Digital hologram re-phenomenon process

According to the Kirchhoff diffraction formula, the digital reproduction wavefront of the holographic recording surface is:

$$U(x, y) = C(x, y)I(x, y) = C|O|^2 + C|R|^2 + CO^*R + COR'$$

(3)

In the formula, $C(x, y)$ the computer simulates the reproduction of the light wave, the first two zero-order diffraction terms, the third term is the virtual image, that is, the conjugate image of the object light, and the last one is the re-energy phenomenon of the object light, if the original reference light wave is used as the reproduction light, Accurate reproduction of light is obtained. The wavefront reproduced light obtained by the equation (4) needs to be further diffracted and imaged. According to
different recording conditions and approximation requirements, there are mainly Fresnel diffraction integral reconstruction algorithms, convolution reproduction algorithms and angular spectrum reproduction algorithms. When the object size is small relative to the recording plane, the approximate Fresnel condition \( x_i - y_i \) can be obtained as:

\[
U'(x, y) = \frac{\exp(jkz)}{j\lambda z} \exp\left(\frac{jk(x_i^2 + y_i^2)}{2z}\right) \\
\times 3 \left\{ C(x, y)I(x, y)\exp\left(\frac{jk(x^2 + y^2)}{2z}\right) \right\} \tag{4}
\]

Where \( \mathcal{F} \) is the Fourier transform, \( z \) for recording distance (DING Hang 2011).

3. Determination of recording distance of reflective digital holographic optical path

Figure 2 is a schematic diagram of an off-axis digital holographic optical path, \( R \) is a reference light, and \( L_o \) is irradiated to the CCD target surface at a certain angle, \( L_c \) which is the diameter length of the image plane, the CCD target surface size, the CCD pixel size \( \Delta x \times \Delta y \), the reference light \( R \) and the object light. The angle \( \theta_h \) is the line connecting the lowest point of the detected object and the highest point of the effective size surface of the CCD, and the horizontal angle is \( \theta_{max} \), \( z \) is the recording distance. There are zero-order images and a set of conjugate images in the reconstructed image of the digital hologram. By controlling the angle between the object light and the reference light, the three images are separated to obtain a good reconstruction effect (Shang L et al. 2015, WU Jie et al. 2016).

It can be seen from the figure that if the hologram reproduction image is separated from the conjugate image by the zero-order image, the angle of the object reference light must satisfy:

\[
\theta_h \geq \frac{3(L_o + L_c)}{2z} \tag{5}
\]

Stripe spatial frequency after object interference \( f_1 \) is:

\[
\frac{\theta_h + \theta_{max}}{\lambda} \leq f_1 \leq \frac{1}{2\Delta x} \tag{6}
\]

Where \( \lambda \) is the wavelength of the laser source. From the geometric relationship:

\[
\theta_{max} = \arctan \frac{L_o / 2 + L_c / 2}{z} = \frac{L_o + L_c}{2z} \tag{7}
\]

Then the minimum recording distance of the hologram is:

\[
z \geq \frac{L_o + L_c}{2(\lambda / 2\Delta x - \theta)} = \frac{L_o + L_c}{2(\lambda / 2\Delta x - 3\lambda / 8\Delta x)} = \frac{4\Delta x(L_o + L_c)}{\lambda} \tag{8}
\]

The number of CCD pixels used in the experiment is 1600 × 1200, the pixel size is 7.4 μm × 7.4 μm, and the target size is 11.8×8.9mm². The sample to be tested is the USAF1951 resolution test board, and the area of the fifth pair of pairs is 0.2×0.2mm². When the recording light wavelength is 632 nm, the minimum recording distance of the hologram is calculated to be 426 mm, and FIG. 3 is when the recording distance is 500 mm. The spectral profile of the resolution plate is reconstructed, and it can be seen that the zero-order image and the ±1-level conjugate image are separated.
4. Influence of light intensity ratio of ginseng on reflective holographic experiments

Higher order diffracted light will be produced, greatly reducing the diffraction efficiency. In addition, when the interference occurs, if the reference light intensity is weaker than the object light, a large amount of speckle impurities will be generated in the interference fringes, resulting in a large number of halos around the zero-order diffracted light, thereby affecting the luminous flux during imaging and reducing the imaging quality (JIN Qing-li et al. 2001). The experimental optical path adopted in this paper is an improved reflective holographic experimental optical path. As shown in Fig. 4, a continuous laser is emitted by a HeNe laser, and the beam is transmitted through a mirror 1 (Mirror-1) and a mirror 2 (Mirror-2). Rotate 180°, and then enter the beam splitter 1 (Beam Splitter-1) by Beam Expander. The beam of the beam splitter acts as object light through the microscope objective, beam splitter 2 (Beam Splitter-2) and beam splitter 4 (Beam Splitter-4) eventually enters the CCD. The other beam as a reference light interferes with the object light at the beam splitter 4 (Beam Splitter-4) via the beam splitter 3 (Beam Splitter-3) and the filter, and is imaged on the CCD light-receiving surface. In the optical path, the object light is obviously stronger than the reference light, so an optical filter is added to the light path of the object. In the experiment, the number of the filters in the light path of the object is controlled to control the light of the object and the reference light. Light intensity ratio. The Beam Transmittance 1 (Beam Splitter-1) uses a transflective ratio (the ratio of the transflective ratio to the transmitted light and the reflected light) is 9:1. With this beam splitter, the beam can be collimated to reach the desired control range. The other mirrors of the experimental light path have a transflective ratio of 5:5. It can be seen from the figure that the object light is reflected and enters the microscope objective, and the object light path is larger than the reference light. Therefore, a mirror 3 (Mirror-3) is placed under the beam splitter 3 (Beam Splitter-3) to compensate for the optical path difference (Kato H et al. 2014), so that the distance between the two is approximately equal to the distance of the beam splitter 2 (Beam Splitter-2) to the object plane, to ensure the coherence of the object light and the reference light.

Figure 5 is a physical diagram of the experimental optical path. The experiment uses a HeNe laser as the light source; the microscope objective magnification is 50x, the numerical aperture is 0.55, and the working distance is 13mm. The optical power value is measured by Thorlabs' PM160-T optical power meter. Since the area of the measured area is constant, the optical power ratio is the light intensity ratio. The hologram of the fifth set of line pairs of the resolution plate is adjusted by adjusting the angles of the object light and the reference light in combination with the minimum recording distance obtained above. In the experiment, a filter is sequentially added to the object light path to control the light intensity ratio of the object. 6a-f are intensity reproduction images of holograms taken with light intensity ratios of 1:2.971, 1:3.961, 1:4.952, 1:9.903, 1:14.855, 1:22.282, respectively. It can be seen from Fig. 6a–e that the light intensity ratio is in the range of 1:3 to 1:15, and the reconstruction effect is good. Exceeding the range (Fig. 6f), the reconstruction effect is not good, which is due to the object light and The reference light amplitudes are too different, and the uniformity of the interference field causes the unclear interference fringes.
5. Conclusion

The recording distance and the reference light intensity ratio in the reflective holographic microscopy experiment are studied. The results show that when the distance from the object to the CCD is greater than the minimum recording distance, and the ratio of the light intensity of the object light to the reference light is between 1:3 and 1:15, the image quality of the hologram is better, when the object light and reference When the light intensity ratio exceeds this range, the quality of the re-existing phenomenon is significantly reduced. The resulting minimum recording distance and object-to-light intensity ratio provide important technical parameters for reflective holographic microscopy experiments, which lays a foundation for subsequent three-dimensional reconstruction using reflective digital holography.

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