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合成孔径同轴数字全息图的相位恢复再现

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摘 要:针对有缝拼接合成孔径同轴数字全息图的再现问题,通过对接缝处预先进行灰度均值填充,利用基于角谱理论的 Gerchberg-Saxton(GS) 加权改进相位恢复算法恢复相位,获得全息图记录面上的完整复振幅信息.仿真模拟了该方法对粒子场的检测,获得的再现像与模拟粒子靶的相关系数较传统方法得到的结果提高 1 倍以上,并可以有效抑制接缝处信息丢失对合成孔径同轴数字全息图再现像的影响,实现有缝拼接合成孔径同轴数字全息图的高质量再现.

关键词:光信息处理;合成孔径;相位恢复;同轴全息图;均值填充;粒子场检测;图像传感器
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Reconstruction Method Based on Phase Retrieval for Synthetic Aperture in-line Digital Holograms with Seams

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Abstract: This paper proposed a reconstruction method for the synthetic aperture in-line digital hologram with seams. The calculated means is prefilled at the seams. By using Gerchberg-Saxton (GS) weighted phase retrieval algorithm based on the angular spectrum, the phase is retrieved and the complete complex amplitude on recording surface is obtained. The particle field detection is simulated with this method. The result indicates that the correlation coefficient between the reconstructed image and the simulated particles target image doubled in contrast to the traditional method. Therefore, the influence of information loss at the seams is effectively restrained and high-quality reconstructed image can be achieved.

Key words: Optical information processing; Synthetic apertures; Phase retrieval; In-line holograms; Mean filling; Particle field detection; Image sensors
OCIS Codes: 090.1995; 100.5070; 100.3010; 110.1220

0 Introduction

Thanks to the development of image sensors (Charge Coupled Device (CCD) and Complementary Metal-Oxide-Semiconductor (CMOS)), digital holography has been deeply studied and widely applied in many fields, such as cell observation[1-2], particle measurement[3-4], multiple-image encryption[5-6] and so on. Relatively to the conventional holography, digital holography can obtain quantitative amplitude and phase information at the same time. However, the lateral resolution and Field Of View (FOV) of the

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digital holographic reconstruction image are restricted by the small target surface size and large pixel dimensions of the existing image sensors. Le Clerc *et al*.[7] were the first to record an object by using the synthetic aperture technique in in-line digital holography in 2001. JH Massig[8] recorded an off-axis hologram in the same way. Comparatively, the in-line holographic set-up is more favourable to the optimal utilization of the spatial bandwidth and more compact. Subsequently, an extensive research using the synthetic aperture technique has been attempted in in-line digital holography. A mainstream method is that multiple sub-holograms are recorded in different positions by moving the single CCD or COMS, and then synthesized into a large-format one[9-12]. Since it is highly time consuming to record all the sub-holograms, the above method is primarily used to record static objects. Therefore, multi-chip CCD or CMOS hardware stitching is utilized to shape the synthetic digital holograms in dynamic test environment[13].

However, some seams will appear between adjacent sub-holograms as the synthetic holograms become larger. The information loss at seams will severely impair the quality of the reconstruction result. Hence, the GS phase retrieval algorithm based on angular spectrum is introduced [14]. It has been modified by several researchers later. Gu Xiang *et al*.[15] gave a new initial phase condition with a weighted average of the intermediate calculated results. In 2013, Peng Jin-meng *et al*.[16] adopted an idea that the amplitude can also be weighted in the iterative process, and the range of weighted coefficient is also given.

In this paper, a new method is proposed which combines the principles of synthetic aperture and phase retrieval to reconstruct the synthetic aperture in-line digital holograms with seams. Firstly, the intensity means of two original digital holograms are calculated, respectively. Secondly, the calculated means are utilized to fill the seams. Thirdly, the weighted phase retrieval of improved GS algorithm based on the angular spectrum theory is applied to retrieve phase, in which the amplitude of seam is figured out through iteration. Finally, the hologram amplitude and retrieved phase are utilized to reconstruct the holographic image. The proposed method is applied to simulate the particle field detection. The simulation result shows that this method can satisfy both the high resolution and large FOV of dynamic measurement, and the quality of the reconstructed image can also be enhanced.

1 Principle

1.1 Recording

As shown in Fig. 1, two synthetic aperture in-line digital holograms can be recorded at the same time. The pulsed converging spherical wave passes through particle target, and then is separated into horizontal and vertical directions by beam splitter prisms. The direct transmission light is regarded as reference wave, and the particle diffraction light is regarded as the object wave. Synthetic aperture digital holograms can be recorded by two CCD arrays in the corresponding directions. The distances from two holograms to particle target are different and each array is composed of 9 CCD sensors with seams.

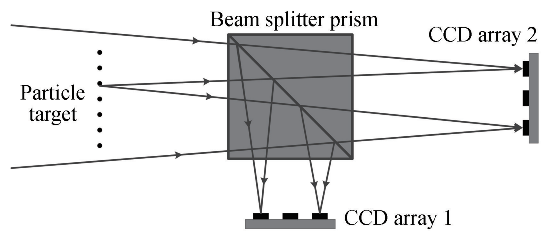


Fig.1 Optical path diagram for recording synthetic aperture in-line digital holograms

1.2 Reconstruction

For convenience, the reconstruction is discussed based on Fig. 2. In Fig. 2, I_1, I_2 represent the intensity recorded on surface 1 and surface 2, respectively. Due to the existence of seams, the low frequency diffraction light of particles in front of seam could be missed out by surface 1, while some of them could be recorded by surface 2. Despite the loss of the low frequency information, most of the high frequency information is still retained . Therefore , iterative

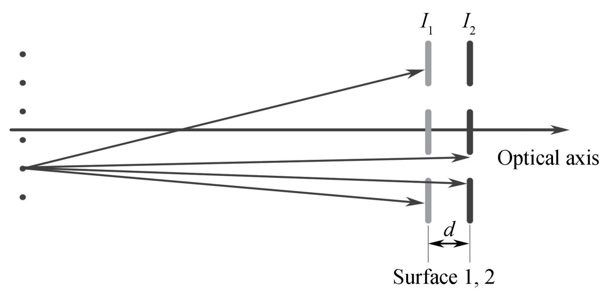


Fig.2 Schematic diagram of the optical path in Fig. 1

operation by using the two groups of holograms can accurately retrieve the intensity and phase information in seams. This idea has been used to reconstruct the synthetic aperture in-line digital hologram with seams in this paper.

The reconstruction with the weighted phase retrieval algorithm based on the angular spectrum theory[16] is shown in Fig.3.

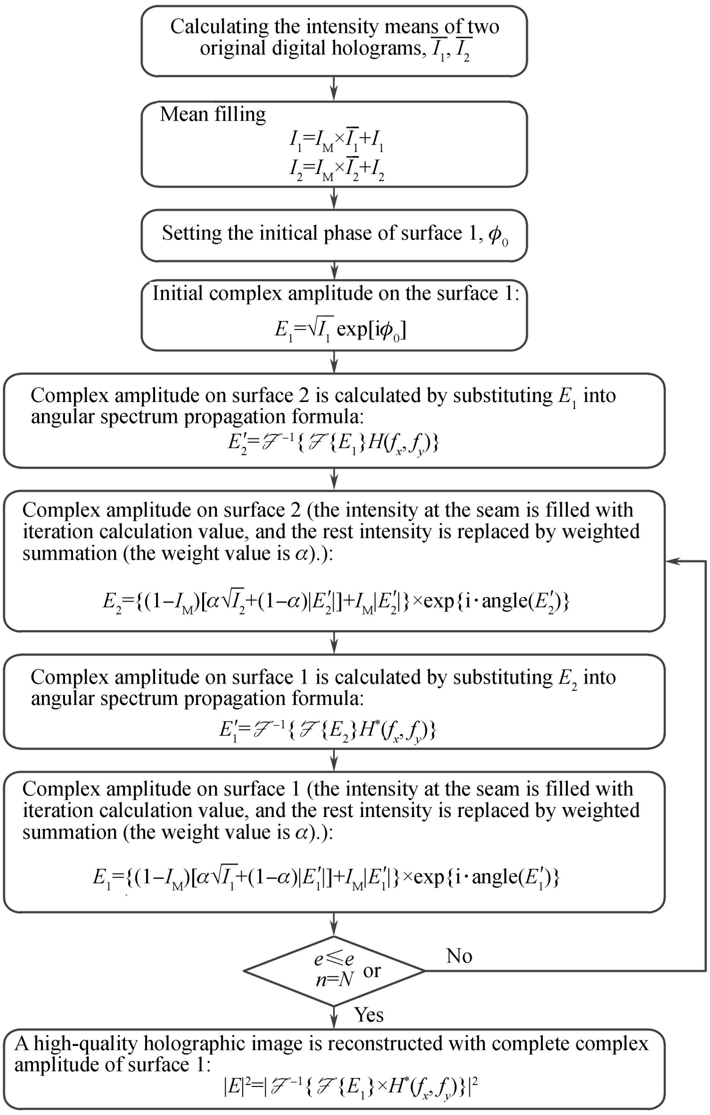


Fig.3 Flow chart of reconstruction

In Fig. 3, $\mathscr{F}\{\}$ and $\mathscr{F}^{-1}\{\}$ represent Fourier transform and inversion Fourier transform, respectively, angle () represents taking the phase of the complex amplitude, I_M represents a template matrix where the seam is 1 and the rest is 0, n is the number of calculation cycles, e is the mean square error between $|E'_1|$ and $\sqrt{I_1}$, N is pre-set number of cycles, ε refers to pre-set error; $H(f_x, f_y)$ represents the angular spectrum transfer function, the specific expression is

$$H(f_x, f_y) = [\mathrm{i}kz\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}] \tag{1}$$

As in (1), k is wave vector ($k=2\pi/\lambda$), λ is wavelength, z represents the diffraction distance, f_x and f_y refer to spatial frequencies in x and y directions, respectively, $H^*(f_x, f_y)$ refers to its conjugate function.

2 Simulation

To verify the proposed method, the simulation experiment of particle field detection is carried out. The size of the simulated particle target is about 18mm square among and the particle diameter is 33 μm, where the particle target is in size of 8 192×8 192 pixels (To accelerate the operation speed of Fourier transform, the number of data should be $2N$, here is 2^13), per pixel size is 2.2 μm, a single particle diameter is 15 pixels, the transverse space is 5 pixels. The partial enlargement of the simulated particle target is shown in Fig. 4. The in-line hologram of particle targets is achieved by the diffraction calculations. Firstly, simulated particle target is illuminated by converging spherical wave with diameter of 20 cm. Next the intensity distribution is calculated at the distance of 6cm away from the particle target to obtain the first hologram I_1. Then keeping other parameters unchanged, increasing the distance by 0.5 mm, and another hologram I_2 is finally obtained. Fig. 5 shows the optical path of the simulation experiment.

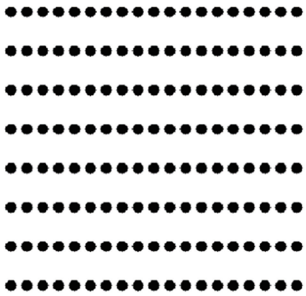


Fig.4 The simulated particle target (partial enlargement)

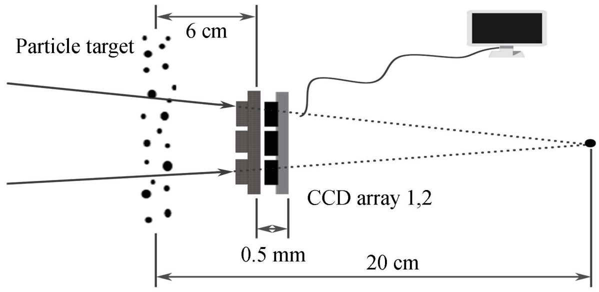
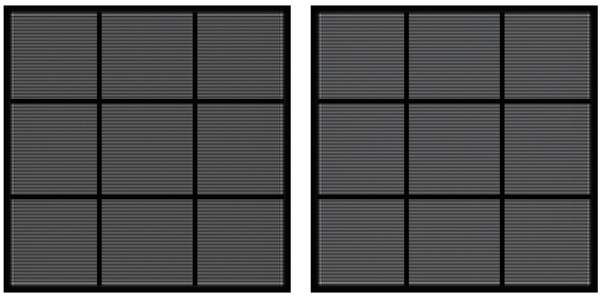


Fig.5 The diagram of simulation experimental set-up

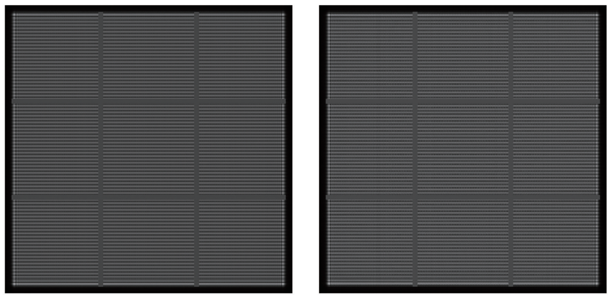
For simulating the impact of seams on the reconstructed image, two original holograms are padding with zero. The padded width is 100 pixels, namely 220 μm. The processed holograms are shown in Fig. 6 (a) and 6(b).

According to the Fig. 3, the intensity mean of non-zero regions are calculated, and then the calculated mean is filled into zero region of two holograms, respectively. Holograms with "mean filling" are shown in the Fig. 7(a) and 7(b).



(a) Hologram of CCD array 1 (b) Hologram of CCD array 2

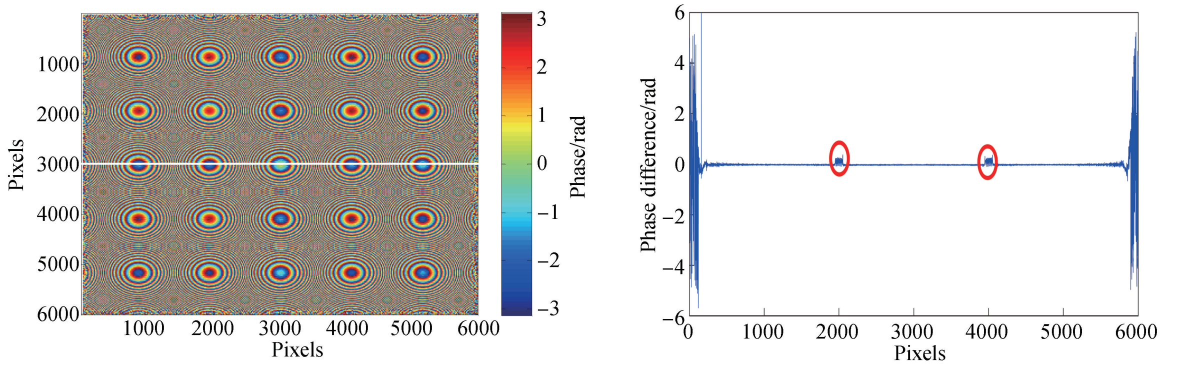
Fig.6 Synthetic aperture in-line holograms without "mean filling"



(a) Hologram of CCD array 1 (b) Hologram of CCD array 2

Fig.7 Synthetic aperture in-line holograms with "mean filling"

Phase retrieval is completed with the two mean filled holograms. In the simulation experiment, cycle index is 500, ε is 3×10^{-6}, the initial phase value is set with the phase of converging spherical wave on CCD array 1 , and weight value α is 1.2. After phase retrieval , the wrapped phase distribution of CCD

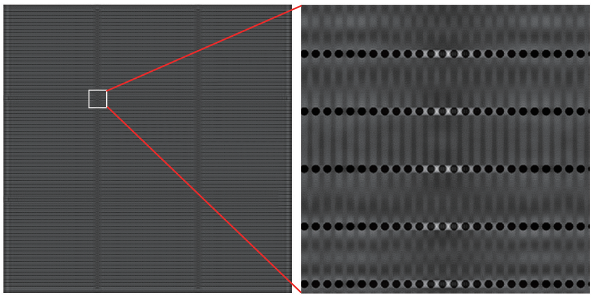


(a) Retrieved wrapped phase (b) Difference between retrieved phase and the original phase

Fig.8 Phase retrieval result

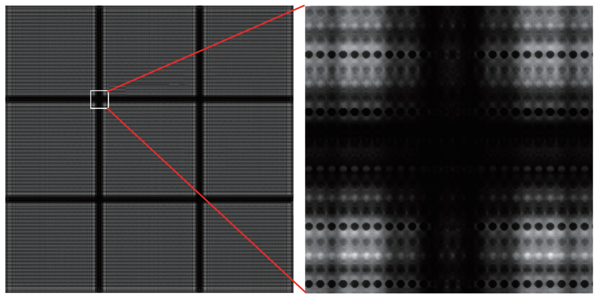
array 1 is obtained, as shown in Fig.8(a). To test the accuracy of phase retrieval, the difference between the retrieved phase and the original phase is calculated. Fig. 8(b) depicts the difference distribution along the white line in Fig.8(a). In most cases, the retrieved phase is in good agreement with the original phase. In seams location (two red circles in Fig. 8(b)), because the received information is less than other regions, the phase retrieval effect is a little inferior, where the average error is less than 0.105 rad.

The complex amplitude distributionis composed of retrieved phase and intensity distribution of CCD array 1. It is used to reconstruct the holographic image with the inverse diffraction calculation. Fig.9 shows the intensity distribution of the reconstruction image. Fig. 9(b) is the enlarged image of the white square in Fig. 9(a). For comparison, Fig. 10 shows the reconstructed image by the traditional methods, and Fig. 10 (b) is the enlarged image of the white square in Fig. 10(a). Obviously, Fig. 10 shows that many particles are submerged in a huge shadow and cannot be distinguished. In Fig. 9, by using the proposed method the lost information at the seams can be well reconstruct, and the particles are clearly visible.



(a) Reconstructed image (intensity)　(b) Enlargement of reconstructed image in (a)

Fig.9　Reconstruction result with proposed method



(a) Reconstruction image (intensity)　(b) Enlargement of reconstructed image in (a)

Fig.10　Reconstruction result with traditional method

To quantitatively analysis quality of reconstructed image, the concept of correlation coefficient of the image is introduced. We adopt the image correlation coefficient (CC)[17] as follows

$$\mathrm{CC}=\frac{\sum_{x=1}^{M}\sum_{y=1}^{N}[g(x,y)-E(g)][g'(x,y)-E(g')]}{\{\{\sum_{x=1}^{M}\sum_{y=1}^{N}[g(x,y)-E(g)]^2\}\{\sum_{x=1}^{M}\sum_{y=1}^{N}[g'(x,y)-E(g')]^2\}\}^{1/2}} \tag{2}$$

As in (2), $g(x,y)$ represents the original image, $g'(x,y)$ represents reconstructed image, $E(g)$ and $E(g')$ represent the average intensity of two images, respectively. The closer to 1 the CC is, and the higher the similarity degree of two images is. The CC calculated with the proposed method reaches 0.830 12, while the traditional reconstruction method is only 0.404 95.

It is crucial to highlight that in the experiment, the intensity of the seams is obtained by each iterative calculation, not obtained by the mean value which is used before iterative calculation. For its rationality, we represent the intensity of the seam by weight sum of the calculated value and the mean value:

$$|E_i|=\beta\cdot \mathrm{mean}[\sqrt{I_i}]+(1-\beta)|E_i'| \quad i=1,2 \tag{3}$$

As in (3), β is weight value, and i represents different surfaces. When β is 0, 0.3, 0.5, 0.7, 1, the convergence with different weights are shown in Fig. 11.

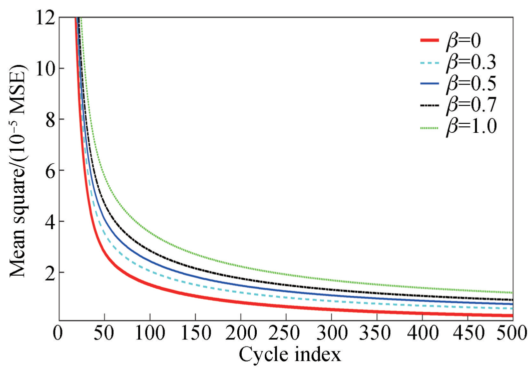


Fig.11　The convergence with different weight value

In addition, Table 1 records the CC with different weight values.

From Fig. 11 and Table1, when β is 0 (the intensity at seams is totally filled with calculated value), algorithm convergence is the fastest, the error is minimum, and the image similarity degree is the highest. Because the estimated value of iterative calculation carries information of two surfaces, its credibility is higher than mean value. Therefore, during the phase retrieval, the intensity of the seam is filled by iteration calculation instead of the "mean filling".

Table 1 CC with different weight value for the 500th times

Weight value (β)	Correlation coefficient (CC)
0	0.830 12
0.3	0.809 16
0.5	0.803 06
0.7	0.798 37
1	0.792 76

3 Conclusion

A new method based on phase retrieval was proposed to reconstruct the synthetic aperture in-line digital holograms with seams. In the simulation, the CC between the reconstructed image and the simulated particles target image is 0.830 12, which is far greater than that of the traditional method, 0.404 95. It shows that the proposed method has three distinct advantages, i.e., 1) the optical field information at the seams has well been retrieved; 2) the interference from conjugate image on the in-line hologram has been avoided successfully; 3) the aperture diffraction effect of the seams and frames have been largely restrained. In summary, the reconstructed holographic image is obtained with high quality, high resolution and large FOV, as well as the estimation of the amplitude in seams with each iterative calculation value has been optimized. The method can be also applied to the combustion field, temperature field and flow field.

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