Digital holography and its application

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ABSTRACT

The theory and the method of digital holography and its application have been studied, and part of the study results mainly involving eliminating zero-order diffraction in digital off-axis holography, analysis of the influence factors of the reconstructed image quality, particle field measurement, etc. are reported, and the experimental results are also given. The preliminary investigative basic research in color digital holography has been done. Multiple-wavelength recording system is introduced in digital holography, and recording of hologram by CCD is no longer a single wavelength one, which is a beneficial tentative research for the development of color digital holography. The research and the results provide the initial theory and experimental basis for the further advancement of digital holography.

Keywords: Digital holography; color digital holography; particle field application

1. INTRODUCTION

Holography, invented by D Gabor in 1948, is a two-step imaging technique based on the principle of optics interference and diffraction. Because hologram can be record not only the amplitude but also the phase information of object wave simultaneously, and the three-dimensional image of the object is obtained through reconstructed hologram. So, Holography, a main metrological technique, has been applied in optical metrology. However holography application is much restricted by its tedious and no real-time hologram plate processing. With the development of holography and the combination of holography with computer, it is possible to transfer either the recording process or the reconstruction process into the computer. Firstly, computer is introduced in the process of hologram produced. This has led to computer-generated holography (CGH) [1], and the computer-generated hologram is then optically reconstructed and the wavefront information of object can be obtained. Secondly, hologram is reconstructed in computer. The on-line hologram or Fourier hologram recorded on a photographic plate is sampled, optically enlarged and then the digitized 'conventional' hologram is digitally decoded by special reconstruction algorithms, and the original field is reconstructed numerically and displayed on computer screen[2].

With the development of high-resolution CCD and fast computer, digital holography, the digital recoding of holograms and the numerical reconstruction of the wave fields, has become possible. In comparison with classical holography, the main advantage of digital holography is that intensity as well as phase information of a holographically stored wavefront can be achieved directly and quantitatively in the numerical reconstruction process, with easy and highly sensitive recording of holograms and quick reconstruction and chemical processing being no necessary, thus increasing the flexibility and speed of the experimental process. So digital holography has been developed and widely applied in various fields of science and engineering, such as microscopy[3-5], interferometry[6,7], 3D object recognition[8], particle measurement[9-13] and the research of deformation measurement and vibrating analysis [14-16], and so on. In this paper, the studies on digital holography recently and the results done in our laboratory are thoroughly reviewed.

2 THE THEORY ANALYSIS OF DIGITAL HOLOGRAPHY

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2.1 Hologram digital recording and numerical reconstruction

The recording optical system of digital holography is the same as the conventional plane holography, as shown in Fig.1.As in classical holography, the two kinds of recording system which are in-line and off-axis setups are used in digital holography. The reference wave may be plane parallel wave or spherical wave as long as the sampling theorem is fulfilled, and may normally impinge onto the CCD or illuminate the CCD from oblique angle. The object wave and a reference wave interfere on the recording plane and form a microinterference pattern. The interference pattern is recorded on photosensitive plate. Supposed that $I(x,y)$ is the intensity distribution of the interference pattern, and the recorded hologram by the CCD is given by[17]

$$I(m,n) = [I(x,y) * rect(\frac{x}{\alpha\Delta x}, \frac{y}{\beta\Delta y})] comb(\frac{x}{\Delta x}, \frac{y}{\Delta y}) rect(\frac{x}{M\Delta x}, \frac{y}{N\Delta y}) \tag{1}$$

wher $rect(x/\alpha\Delta x, y/\beta\Delta y)$ represents a single pixel of CCD, $\alpha, \beta \in [0,1]$ is the fill factor of CCD, $M \times N$ is the number of light-sensitive pixels on CCD, Δx and Δy denote the pixel size in the x direction and y direction, respectively, $comb(x/\Delta x, y/\Delta y)$ represents spatial discrete sampling, $rect(x/M\Delta x, y/N\Delta y)$ specifies the finite width of CCD array, $rect(\frac{x}{M\Delta x}, \frac{y}{N\Delta y}) = \begin{cases} 1, & |x| \le M\Delta x/2, |y| \le N\Delta y/2 \\ 0, & elsewhere \end{cases}$.

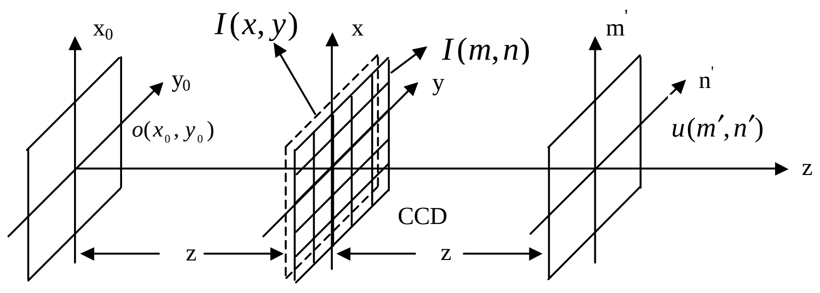


Fig. 1 Coordinate geometry for recording and reconstruction of hologram

The holographic reconstruction, in physical terms, is to reconstruct the wavefront of the object, i.e., to obtain the three-dimensional structure of the object from the two-dimensional hologram. In optical holography, the original object wave is reconstructed by illuminating the hologram in the recording position with original reference wave. The numerical reconstruction of hologram is to perform physical process of optical reconstruction by digital evaluating method, i.e., numerical imitating optical diffraction process. The complex-amplitude distribution in the reconstruction plane of the real image is described as

$$\begin{aligned} u'(m',n') &= \frac{\exp jkz}{j\lambda z} \exp[j\frac{k}{2z}(m'^2\Delta x'^2 + n'^2\Delta y'^2) \\ &\times \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} I(m,n) \exp j\frac{2\pi}{\lambda z}(m^2\Delta x^2 + n^2\Delta y^2) \times \exp - j2\pi(\frac{mm'}{M} + \frac{nn'}{N}) \end{aligned} \tag{2}$$

The intensity $I(m',n')$ and the phase $\varphi(m',n')$ is calculated respectively by

$$I(m',n') = u(m',n') \cdot u^*(m',n'), \qquad \varphi(m',n') = \arctan\frac{\mathrm{Im}\,u(m',n')}{\mathrm{Re}\,u(m',n')} \tag{3}$$

where $m,n;m',n'$ are integers, $m' = 0,1,\cdots,M-1$; $n' = 0,1,\cdots,N-1$, $\Delta x'$ and $\Delta y'$ are the pixel size in the reconstructed image, $k = 2\pi/\lambda$, λ is the wavelength of the incident light, z is the distance between the hologram and the observation.

2.2 Numerical reconstruction method of hologram

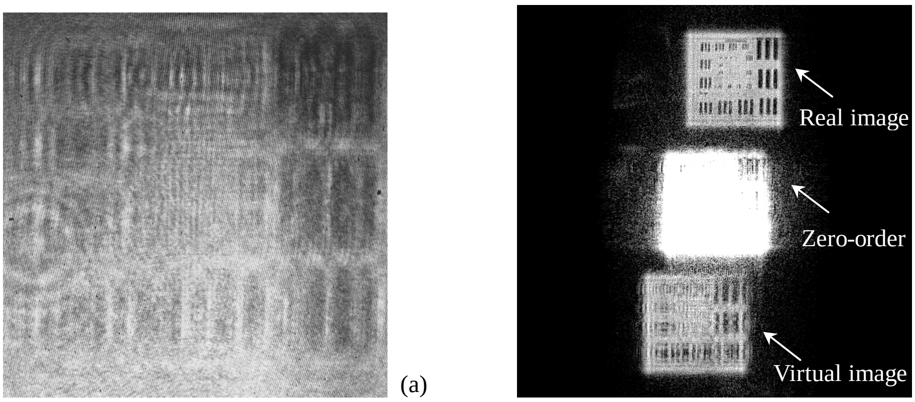
The numerical reconstruction of hologram is in nature that calculate Eq.(2). The several reconstruction algorithms at present have been proposed which are the approach of Fresnel transform, convolution and Fourier transform and the wavelet transform of the real function of amplitude transmission of object[15,10].

Fig.2(a) shows a off-axis digital hologram of resolution target as object, Fig.2(b) shows the reconstructed image obtained by numerical reconstruction of hologram shown in Fig.2(a) using approach of Fresnel transform, located at distance z_r=915mm. Fig.3(a) presents a in-lines digital hologram of resolution target, Fig.3(b) shows the reconstructed image obtained by numerical reconstruction of hologram shown in Fig.3(a) using convolution approach. The reconstruction distance z_r=455mm. The experimental recording of optical system used is shown in Fig.1. The He-Ne laser with the power of 10mw, λ=632.8nm, is used as the light source. The hologram is recorded with a CCD sensor (DALSA 1M30 camera, 1024×1024pixels; pixel size 12μm×12μm).

For Fresnel transform, the relation bewtten Δx , Δy and $\Delta x'$, $\Delta y'$ is $\Delta x' = \lambda d / M\Delta x$, $\Delta y' = \lambda d / N\Delta y$. The pixel sizes in the reconstructed image depend on the recording distance z, the wavelength λ of the used laser light, the dimension Δx, Δy of the pixel of the CCD and $M\times N$ of the number pixels on CCD. With given recording experimental system (CCD and λ), the pixel size in the reconstructed image depends on the recording distance, and the pixel size increases with the recording distance increasing.

For convolution approach, the relation bewtten Δx , Δy and $\Delta x'$, $\Delta y'$ is $\Delta x' = \Delta x$, $\Delta y' = \Delta y$. The pixel size in the reconstructed image is equal to that of the hologram, and is independent of the number of pixels on CCD. The convolution approach is suitable to particle filed analysis and measurement.

The Fourier transform is the approximation limit of the Fresnel trnsform. The wavelet transform is also applied to the reconstructed of hologram. The Fresnel trnsform is suitable to the reocnstruction of off-axis digital hologram and the Fresnel trnsform to the reocnstruction of in-line digital hologram.



(a) (b)

Fig.2(a) The a off-axis digital hologram of resolution target (b)the reconstructed image

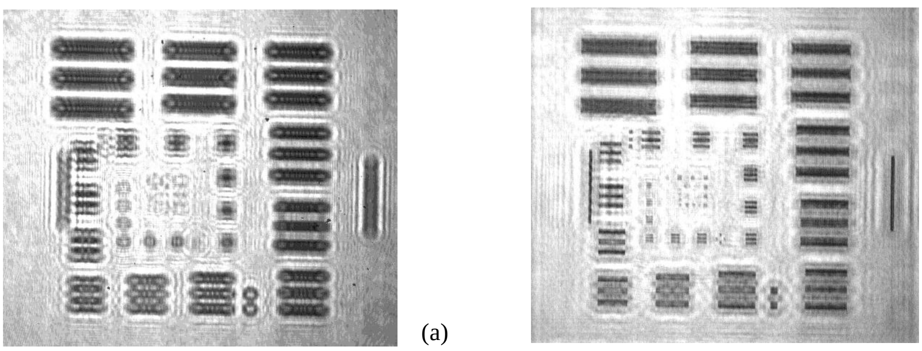

(a) (b)

Fig.3 (a) The a off-axis digital hologram of resolution target; (b)The reconstructed image

2.3 Elimination of zero-order image in digital off-axis holography

The reconstructed image of hologram contains a zero-order image, virtual image and real image. Because the zero-image holds most of the energy in the reconstructed image, as a result, the original image cannot display particular object information because of relative low brightness. In addition, in digital holography, the angle between the reference and the object wave is limited by the spatial resolution of CCD, the various diffraction components of the reconstructed image is not likely to completely separate in space. Even if these three terms appear at different locations in the reconstructed images, the virtual image and the zero-order image need to be eliminated. Because the total number of sampling points of the reconstructed image is equal to the total number of pixels of the image sensor, the virtual image and the zero-order image limit the size of the real image area. Eliminating the two undesirable images results in an improvement of image quality and enhancement of the resolution of the reconstructed image. So the study of zero-order image elimination in digital off-axis holograph is of practical value.

Two kinds of method have been proposed for this purpose. One is based on digital processing method. For example, E.Cuche et.al[18] proposed that zero-order image and virtual image can be digitally eliminated by means of filtering their associated spatial frequencies in the computed Fourier transform of the hologram. In Ref.[19] space-domain modulation of detected hologram was used to suppress zero-order and/or virtual image. The other kind of method based on experimental method was presented by Y.Takaki et.al[20], which eliminates zero-order and virtual image by two shutters and one phase-modulator. This method is substantially based on phase-shifting technique.

We have proposed the experimental method of eliminating zero-order image in the reconstructed image of digital off-axis holography [21]. The diagram of the hologram recording optical system designed is shown in Fig.4. Holographic diffraction grating acts as a beam splitter, and an off-axis holography system is formed. The zero-order diffraction waves propagate perpendicular to CCD, acting as the reference wave and the +1 order diffraction waves illuminate the object and then are reflected onto CCD by reflecting mirror M, acting as the object wave. Assume that the complex-amplitude distribution of the object beam on the hologram plane is denoted by $O(x,y) = |O(x,y)| \exp j\theta(x,y)$ and the complex-amplitude distribution of the plane reference beam on the hologram plane is expressed as $r(x,y) = R$. The intensity distribution of the hologram is given by

$$I(x,y) = |O(x,y)|^2 + R^2 + R|O(x,y)| \exp j\theta(x,y) + R|O(x,y)| \exp[-j\theta(x,y)] \tag{4}$$

where superscript*stands for the complex conjugate, $|O(x,y)|^2$ is the intensity of the object wave and R^2 is the intensity of the reference wave. The third and the fourth terms on the right-hand side of Eq.(4) are the interference terms.

To eliminate the zero order image, we need to eliminate the first two terms on the right-hand side of Eq.(4). In our system, the zero-order diffraction on the right-hand side of Eq.(4) can be eliminated by phase-shifting method of phase-modulated object beams.

Adjust the reflecting mirror M, and change the incidence orientation of the object beam, the complex-amplitude distribution of the object beam on the hologram plane is denoted by $O'(x,y) = |O'(x,y)| \times \exp j\theta'(x,y)$ without losing generality. The intensity distribution of the hologram is described as

$$I'(x,y) = |O'(x,y)|^2 + R^2 + R|O'(x,y)| \exp j\theta'(x,y) + R|O'(x,y)| \exp[-j\theta'(x,y)] \tag{5}$$

Subtracting Eq.(4) from Eq.(5), we obtain

$$\begin{aligned} \Delta I(x,y) = &\{|O(x,y)|^2 - |O'(x,y)|^2\} \\ &+ R\{|O(x,y)| \exp j\theta(x,y) - |O'(x,y)| \exp j\theta'(x,y)\} \\ &+ R\{|O(x,y)| \exp[-j\theta(x,y)] - |O'(x,y)| \exp[-j\theta'(x,y)]\} \end{aligned} \tag{6}$$

Because the adjusted angle of the reflecting mirror *M* is sufficiently small, the complex-amplitude distribution of the object beam on the hologram plane may be taken as unchanged, namely, $|O(x,y)| - |O'(x,y)| = 0$.

Defining $\Delta\theta(x,y)=\theta'(x,y)-\theta(x,y)$, Eq.(6) can be rewritten as

$$\Delta I(x,y)=RO(x,y)[1-\exp j\Delta\theta(x,y)]+RO^{*}(x,y)[1-\exp\{-j\Delta\theta(x,y)\}] \tag{7}$$

If $\Delta\theta(x,y)$=constant, namely, the phase difference between two digital holograms to be subtracted is constant, $[1-\exp j\Delta\theta(x,y)]$ and $[1-\exp\{-j\Delta\theta(x,y)\}]$ is also constant, the reconstructed image has only two terms ($\mathbf{RO}$ 、 $\mathbf{RO}^{*}$) and the zero-order image has been eliminated. The experimental method presented introduces the phase shifting to the object beam through adjusting reflecting mirror, substantially. And the advantage of this method is purely a numerical method with no need of additional phase-shifting equipment, simple in optical structure and easy in operation and data processing. Fig.5 shows the experimental result and the zero-image in the center of reconstructed image has been removed. At the same time, the sharp real image can be obtained.

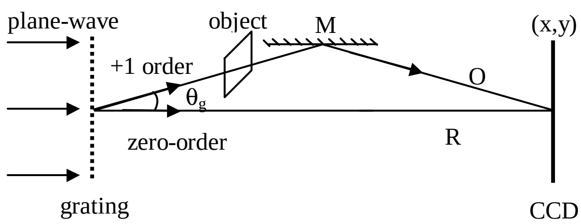


Fig.4 Schematic diagram of the recording system of off-axis hologram by CCD. O: object wave; R: reference wave; M: reflecting mirror

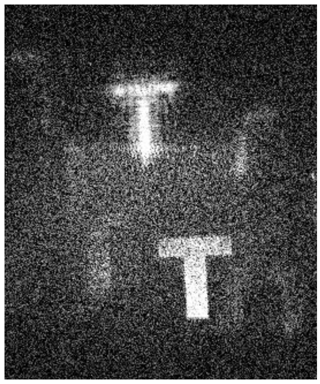


Fig.5 Elimination of the zero-order image in digital off-axis holography

2.4 Several problems of digital recording and numerical reconstruction in digital holography

2.4.1 Recording material

Digital holography is different from classical holography in recording material and storing means of hologram. In the classical holography, the hologram is usually recorded on silver halide plate, and by chemical processing of the exposure, development, fixation, the original object wavefront is obtained by illuminating the hologram in the recording position with original reference wave. In digital holography, the hologram is directly digitally recorded on the CCD and stored in computer, and the object wave is then obtained. The exposure time of CCD recording hologram is shorter than that of the silver halide plate, so it relaxes stability requirement on the recording system, and a moving object or a transient phenomenon can be recorded with a short pulse of light. On the other hand, the numerical reconstruction of hologram differs from optical reconstruction of hologram, achieving intensity as well as phase information of a holographically stored wavefront and extracting the different depth information of recorded object from one hologram by numerical focusing, without any physical reference beam to illuminate onto the hologram in the reconstructed processing. In addition, hologram numerically reconstructed being free of aberrations and noise and the nonlinear influence of photosensitive material in recording processing, the process is simple and flexible, and easy in quantitative analysis and measurement.

Because the spatial resolution of CCD is one order of magnitude less than silver halide plate, the maximum angle between the reference wave and the object wave is limited to a few degrees [22]. This means that only small objects or objects at a large distance from the CCD can be recorded. For a big object, the recording system needs to be modified to fulfill the sampling theorem. At present, two kinds of recording system have been proposed. One is that the hologram is magnified and imaged onto CCD by lens[16]. The other is that the size of object is reduced by optical imaging system[23,,24].

2.4.2 Spatial resolution

Interference pattern between the object and the reference beam is recorded on CCD, this requires that the recording material used to record hologram must resolve the microinterference fringe resulting from superposition of the waves from all object points and the reference wave. The maximum spatial frequency f_{max}, which has to be resolved, for the wavelength λ, is determined by the maximum angle φ_{max} between the reference and the object wave

$$f_{max} = \frac{2}{\lambda}\sin\frac{\varphi_{max}}{2} = \frac{1}{2\Delta x} \tag{8}$$

Due to the maximum spatial frequency f_{max} recorded on CCD is limited by the pixel size of CCD, the angle between the reference and the object wave at any point of CCD must not exceed the maximum value φ_{max}. That the angle between the reference and the object wave at some region of CCD exceeds the maximum value φ_{max}, the interference fringe is undersampled, this result leads to inefficient use the spatial bandwidth of CCD and to the degradation of the resolution of reconstructed image. However, the resolution of the reconstructed image depends on a complete evaluation of all the information that can be gotten from CCD. For the pixel size $\Delta x = 12$ µm and λ=632.8nm, the maximum interference angle is φ_{max} =1.51° . In digital holography, the angle between the reference and the object wave must be less than the maximum value φ_{max} in order that all information of object can be recorded on CCD and the better quality of reconstructed image is expected. For square object and hologram, X=Y，M=N，Δx=Δy，the lowest spatial resolution of the recording material of digital in-line and digital off-axis holographic system should be

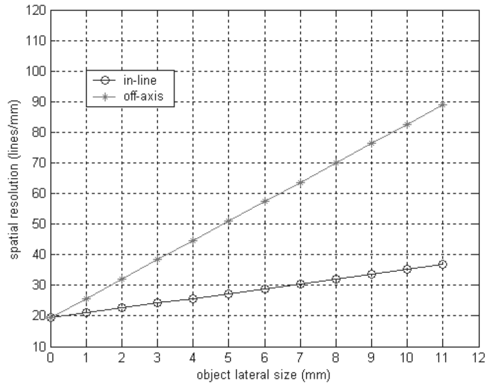


Fig.6 The relation of spatial resolution and the size of recording object (d=500mm)

$$f_{\max:in-line} = \frac{M\Delta x + \mathrm{X}}{2\lambda d_{\min:in-line}} \tag{9}$$

$$f_{\max:off-axis} = \frac{M\Delta x + 4\mathrm{X}}{2\lambda d_{\min:off-axis}} \tag{10}$$

which X×Y stand for the lateral size of object, $d_{\min:\,in\text{-}line}$，$d_{\min:\,off\text{-}axis}$ denotes a minimum allowable recording distance of digital in-line and digital off-axis holography respectively, and its mathematical description is[25,26] $d_{\min:in-line} = (M\Delta x + \mathrm{X})/2\varphi_{\max}$, $d_{\min:off-axis} = (M\Delta x + 4\mathrm{X})/2\varphi_{\max}$. For a digital holography system with given recording parameters (CCD, λ, X) the minimum allowable recording distance of digital off-axis setup $d_{\min:off-axis}$ that is $3X/2\varphi_{\max} = 3X\Delta x/\lambda$ larger than digital in-line setup. As a result, a CCD with much higher resolution is required in the off-axis setup to record the same-size object at the same recording distance, the relationship curves of the spatial resolution as a function of the object size are obtained for two system arrangements, shown as in Fig.6. This conclusion is consistent with the conclusion of optics holography obtained, and can be validated in experiments, shown as in Fig.2and Fig.3.

2.4.3 Resolution of the reconstructed image

The resolution of the reconstructed image depends on the information recorded on hologram. However the information recorded on hologram is influenced by the size and the spatial resolution of recording material and the light source parameter and so on. For digital holography with given experimental system, the information recorded on hologram is determined by the number of pixels and the pixel size and dynamic range of CCD. The resolution of reconstructed image is related to the parameters of CCD, the recording distance and the recording wavelength as well as the size and shape of object. Fig.7 shows the relationship curves of the resolution of the reconstructed image as a function of the object size for two system arrangements.

It can be seen from Fig.7, the maximum lateral resolution of the reconstructed image does not exceed the resolution of CCD, the axial resolution is very low. In digital in-line and digital off-axis system, the lateral and the axial resolution of the reconstructed image decrease along with the increasing size of object. The minimum recording distance d_{min} is, the minimum reconstructed pixel size can be achieved. Therefore the shorter d_{min} in the in-line configuration for a certain-size object helps to acquire higher lateral resolution than with the off-axis system for given CCD and λ.

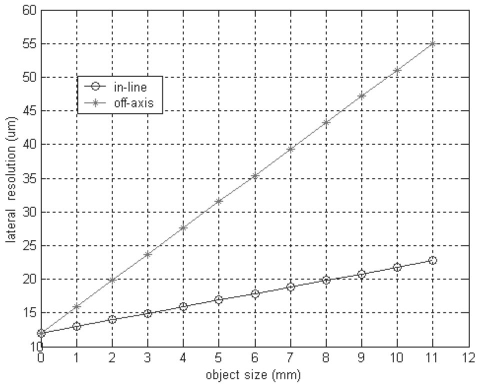


Fig.7(a) Comparison of the recording object size and the lateral resolution of the reconstructed image in different recording system

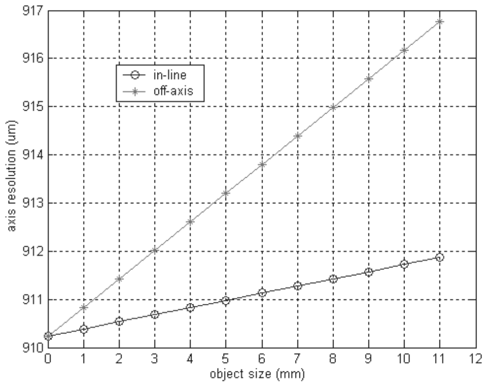
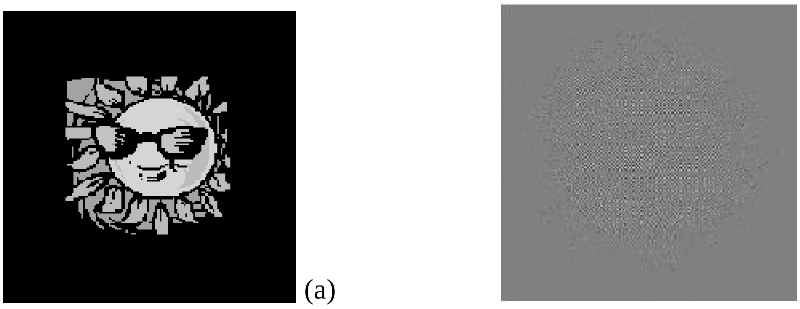


Fig.7(b) Comparison of the recording object size and the axial resolution of the reconstructed image in different recording system

3 COLOR DIGITAL HOLOGRAPHY

Color holography is an important aspect of holographic display. It has good application perspective in rare cultural relic and exhibition of art work, etc. One goal of color holography is to generate a three-dimensional image in natural color. The process of color hologram produced is recording the interference pattern resulting from superposition of RGB three primary object wave and RGB three primary reference wave. The true color image of the original color object can be achieved by superposing precisely the reconstructed image of each wavelength by illuminating the color hologram in the recording position with RGB original primary reference wave. Owing to color cross-talk, the brightness and the color saturation of the reconstructed image degrade and the reconstructed image quality is influenced. Meanwhile, in conventional color holography, materials have to be exposed separately at three wavelengths because of the nonuniform spectral sensitivity of recording materials, color hologram generation is a complex process and several approaches have been proposed, such as one-step copying method and two-steps copying method[27], therefore the application of color holography is restricted. With the development of digital holography, the numerical reconstruction of color hologram will become a direction of holographic display. Multiwavelength recording system has been introduced in digital holography, and hologram of color object is recorded by color CCD, and the original color object can be obtained by numerical reconstruction of color hologram. The color cross-talk of the reconstructed image can be easily eliminated by digital technique, and the high brightness, color fidelity of the reconstructed image can be obtained, free of aberration. On the basis of the theory of digital holography and its experimental study, color digital holography is proposed in our laboratory, and the preliminary research in color digital holography is also done[28,29]. At the same time, I.Yamaguchi research group reported their research result in phase-shifting color digital holography in 2002《Optics Letters》[30].

Fig.8(a)represents a RGB cartoon chosen. Fig.8(b) shows the color hologram of Fig.8(a) generated by computer simulation. The numerically reconstructed results of Fig.8(b) produced by each wavelength are shown in Fig.9. Fig.10 show the color reconstructed image form weighted superposition Fig.9. The original RGB cartoon chosen is fidelity reconstructed by numerical method, as shown in Fig.10. The problems of color cross-talk and color saturation of the reconstructed image in traditional color holography have been disposed, and simple in the color hologram generation and fast and flexible in reconstruction process and free of aberration in the reconstructed image. Fig.11 show the portion hologram of Fig.8(b) and its reconstructed image. Comparing Fig.10 with Fig.11(b), it can be seen that the resolution in the reconstructed image of Fig.11(b) is lower and the resultant reconstructed image is of inferior quality. The reason is that the quality of the reconstructed image is a strong function of the size of the original hologram. The larger the size of hologram is, the higher the resolution of the reconstructed image and the superior the quality of the reconstructed image is. It has been validated from Fig.10 and Fig.11(b).



(a) (b)

Fig.8 (a) Original RGB picture; (b) The color hologram of Fig.8(a) generated by computer simulation

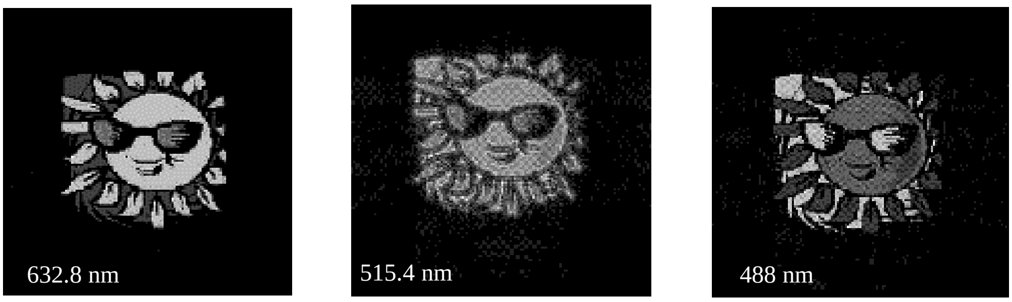
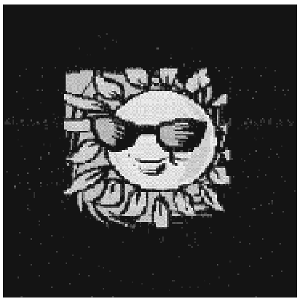
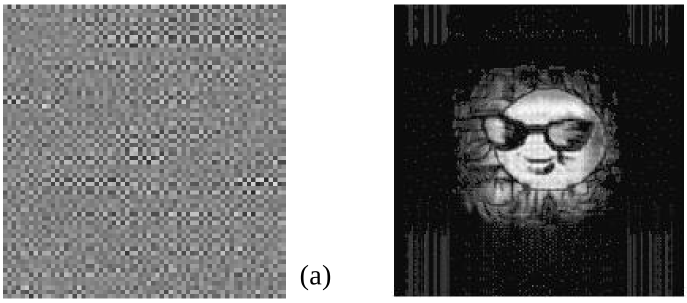


Fig.9 The numerically reconstructed results of Fig.8(b) produced by each wavelength





(a) (b)

Fig.10 The color reconstructed image from weighted superposition Fig.9

Fig.11(a) The section hologram of fig.8(b);
(b) The numerically reconstructed image of Fig.11(a)

4 APPLICATION OF DIGITAL HOLOGRAPHY IN PARTICLE FIELD

Holography is ideally suited for the study of dynamic three-dimensional particle field, and its applications for this purpose are almost limitless[31]. Since B J Thompson research group[32] first applied holography to particle size analysis, holography was widely applied to various particle field of measurement, such as fluid fog field, bubble particle, solid particulate, etc. Holographic analysis technology of particle field has received much attention and acquired development, and gradually realized fully automatic data processing, and become one of the main approaches of tree-dimensional particle field analysis[33-34]. But this method mostly adopts traditional holography which particle fields are recorded on holographic plates or films, the developed holograms are brought back to the reference beams to optical reconstruction the 3D image of the particle fields. A CCD camera then scans the 3D image volume mechanically, plane by plane, and the reconstructed 3D particle field of automatic judgement, analysis, measurement and processing can perform by segmentation amplitude technique. This method is complex, no real-time and the measurement precision low.

One of the applications of digital holography is the analysis of particle field, such as the measurement of size, position, velocity, and distribution of particle. In-line holography is the simplest type of holography and can relax the spatial resolution requirement on the CCD in comparison with the off-axis arrangement. So digital in-line holography perhaps should always be considered first in particle field studies, and is now has been developed into a new tool and applied widely in such various fields as droplet, micro-particle imaging and tracking, polymer crystallization[6,10-14,25,35], etc.

The hologram and its reconstructed image of standard particle field of diameter 90μm are shown in Fig.12. The hologram of particle field is recorded by CCD and shown in Fig.12(a). The diffraction rings of each particle are recognizable from Fig.12(a). When the distance between the particles and the CCD sensor is increased, the spacing between concentric rings belonging to an individual particle also increases. Fig.12(b~d) show the reconstructed real image obtained by numerical reconstruction of hologram shown in Fig.12(a) using convolution approach. The reconstructed distance is 56.5mm, 60.5mm, 64.5mm, respectively. The particle can be seen as dark spots without any diffraction rings. The missing diffraction rings or at least halos show that the particles are in focus. Spheres lying out of the focal plane in Fig.12 are visible as gray patches without sharp features. From Fig.12(b~d), it can be seen that some particles are in focus and some particles are defocused, simultaneously.

The particle diameter can be measured from Fig.12(b~d). Examining the reconstructed particle field in Fig.12(b), the average particle diameter was determined to be 96μm with the lateral resolution of 13.68μm, the average perimeter is 15 pixels and 254.5μm. Fig.13 and table 1 present the reconstructed image of standard particle template and the results of measurement.

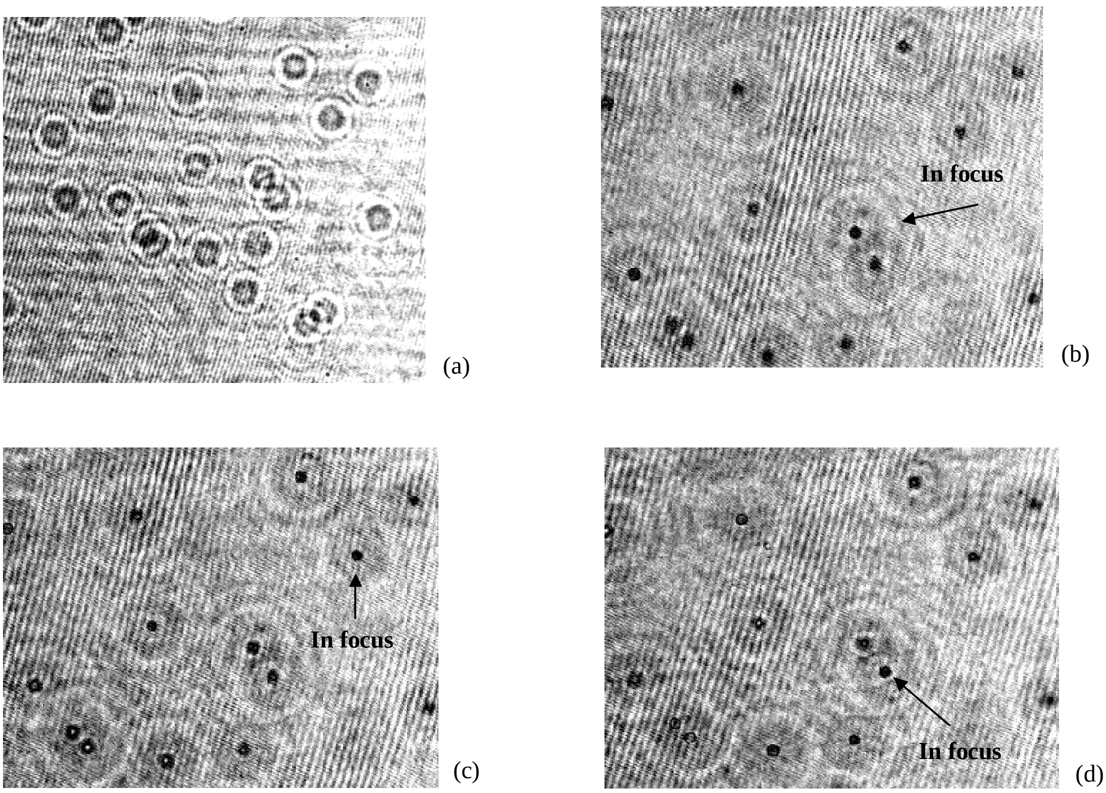
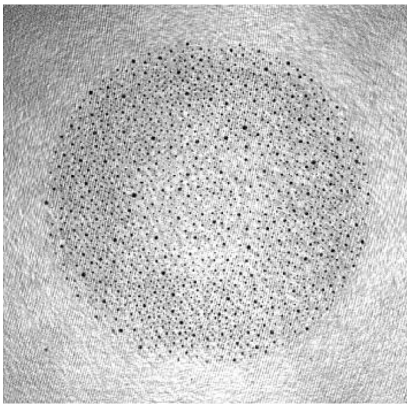
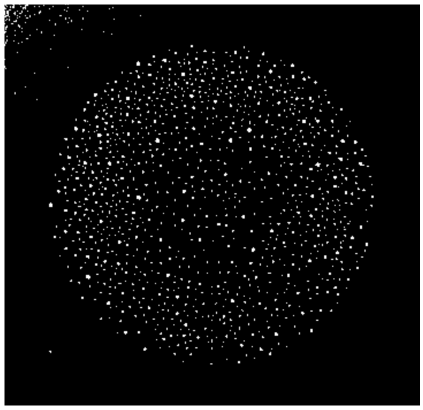


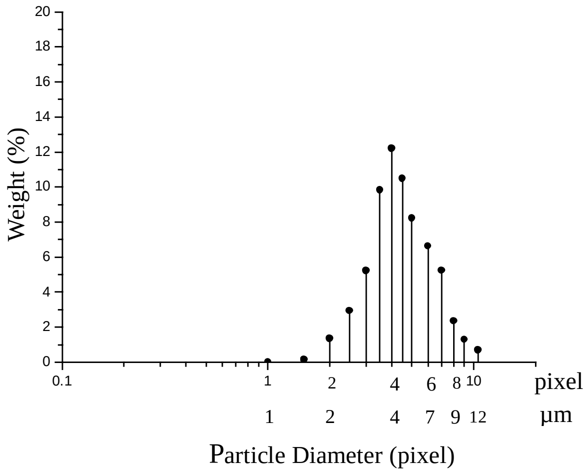
Fig.12 The hologram and its reconstructed image of diameter 90μm
(a) The digital hologram; the reconstructed distance (b)56.5mm (c)60.5mm (d)64.5mm



(a)



(b)



(c)

Fig.13(a) The reconstructed image of standard particle template; Fig.13(b) Binarization of he focus image of standard particle template; Fig13(c) The weight distribution of particle

Table 1 The measurement results of the standard particle template

pixel / parameter	1	1.5	2	2.5	3	3.5	4
	12 (μm)	18(μm)	36 (μm)	30 (μm)	36 (μm)	42 (μm)	48 (μm)
Weight（%）	0	0.154	1.360	2.946	5.232	9.836	12.202

pixel / parameter	4.5	5	6	7	8	9	10.5
	54(μm)	60(μm)	72(μm)	84(μm)	96(μm)	108(μm)	126(μm)
Weight（%）	10.486	8.222	6.639	5.246	2.357	1.298	0.688

5 CONCLUSION

With rapid progress in computers and advancement of CCD, digital holography will be a hopeful replacement of the traditional holography and realize 3D visualization. It will have wide application perspectives in science, engineering, biomedicine and etc.. Besides, digital holography as following field will have very high application value.

- ✧ Data transmission

The inherent advantage of digital holography is producing compressed data and transmiting data. Information of 3D object is recorded in 2D hologram, i.e. the information on complete 3D volume is stored in only 2D images. This process reduces the volume of data and accomplishes data compressed. The 2D data (hologram) will transmit to the reconstruction place by internet, and the original object wave can be obtained by numerical reconstruction in the reconstruction place. Hologram is transmitted on real-time and reconstructed at different place. Due to 3D data can be compressed on 2D hologram, it has the merit of fast uploading and downloading. Digital holography will have great the potential applications in data transmission, especially suitable for space environment experiments. The future data will be transmitted in form of digital holography.

- ✧ Digital color art and display

Color digital holography, the combination of digital technique with color holography, will become another development filed of digital holography. The color hologram of color object is recorded with color CCD and multiple-wavelength lasers; the original color object is also obtained by numerical reconstruction. The problem of color cross-talk of the reconstructed image can be eliminated by digital technique, and realistic 3D object will be shown in virtual 3D. This technology is integration of digitization and 3D visualization and color technique, it will has the potential applications in advertisement, digital museum, work of art and etc.

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