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Record and Reconstruction of Digital Holograms of Dispersed Microparticles

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Abstract: The paper describes how to record dispersed microparticles in the fast processes using the digital holography and following mathematical treatment with recovery of microparticle spatial distribution. The reconstruction of microparticle images is analyzed based on cross-correlation between holograms and point scattering function at the given distance.

Keywords: Digital holography, Fraunhofer holography, Dispersed microparticles, Reconstruction images, Fast processes.

1. Introduction

Research of material destruction processes under the impact of intensive impulsive loads is of great interest with regard to applied problems. Hydrodynamic instabilities develop in a material exposed to strong shock waves, and its fragmentation takes place including formation of a dispersed phase. This process is named ejection [1]. The essence of the ejection effect is in material destruction processes and dispersed phase generation when a shock wave arrives at the free surface of a sample [2]. Dispersed phase particles move at a speed exceeding that of the free surface, and the particle number density may achieve the value sufficient for complete shielding of the free surface against probe optical radiation. Detailed understanding of the phenomenon physics is needed to seek possible ways to neutralize negative effects of ejecta. The availability of high-precision instrumentation and methods that enable to record dispersed phase parameters during blast experiments is a necessary condition for attaining this goal.

One of the methods to record ejecta is digital dynamic holography. Holographic methods allow information about 3D distribution of objects to be saved in the form of a 2D image. A hologram contains information both on the phase and amplitude of waves diffracted by an object, due to which it becomes possible to reconstruct accurately the dimensions and spatial distribution of the objects under research [3]. Saving of reproducible information about the phase is a unique feature of the holography method. Photography allows saving only spatial distribution of light intensity forming the object image. The intensity does not contain information on phase distribution of light wave. And in the holography method information on the amplitude and phase of the recorded wave coming from the object is coded using the reference wave even before the hologram recording [3].

Analog holography has higher depth of field and resolution versus digital holography due to coarse resolution of pixels of CCD or CMOS cameras in comparison with holographic films. This problem seriously degrades digital holography usefulness,

especially in densely filled fields of particles [4-6]. However, holographic plates assume chemical decomposition and fixation; the process that is more and more often considered as undesirable for a user. In addition, a labor-intensive 3D mechanical scanning of the reconstructed image volume is required for optical reconstruction – the process that takes most data processing time [5].

When using the digital dynamic holography method, the object under research is lighted by a short laser pulse (less than 10 ns), and the amplitude and phase of the scattered radiation are recorded by a digital array in the form of an interference pattern.

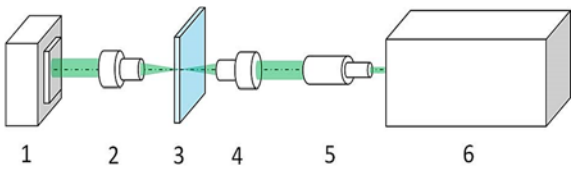
Digital processing of the recorded image by means of computing Fresnel-Kirchhoff integral enables to obtain information on 3D location of microscopic objects within the limits of the volume explored. Reconstruction of a 3D scene is executed by mathematical processing of the interference pattern recorded. The source image can be reconstructed by simulating the interference of the reference wave on the hologram. So, the 3D scene is reconstructed of how those particles were situated when they were shot. The quality of image restoration depends on the quality of hologram recording. Limited resolution of optical system leads to the fact that the low-contrast part of interference rings can remain unrecorded, which negatively affects the contrast of the reconstructed image. The second requirement for the developed equipment follows from this fact – provision of high resolution and consideration of its influence on the recorded holograms.

Holographic method of information recording and reproducing, where a hologram is information-carrying medium, has two stages. At the first stage information recording is carried out, including the formation of interference pattern with the specified object wave, and its recording – obtaining of a hologram. The second stage is information reproduction (reconstruction, conversion) when restoration (reproduction, conversion) of the object wave takes place.

The paper addresses digital Fraunhofer in-line holography where an interference pattern obtained is recorded using a digital camera. The paper also speaks about a reconstruction method that allows quick reconstruction of images from digital holograms, which in its turn enables to obtain 3D distribution of objects in space based on the interference pattern of radiation scattered on them.

2. Techniques

One of techniques to record the dispersed microparticles in the fast processes is a digital dynamic holography. The most widely used experimental setup is in-line Fraunhofer holography [7-11]. A laser beam propagates through the volume of interest and some of the light scatters from the microparticles. The other light travels through the volume as unscattered. Both wavefronts interfere so that the scattered light is a signal wave and the unscattered one is a reference wave. (Fig. 1).



1 – camera, 2 and 4 – lenses, 3 - investigated object, 5 – telescope, 6 – laser

Fig. 1. Schematic of experimental setup.

Fig. 1 illustrates the components of holographic setup. The setup operates as follows: the laser (6) beam is collimated by the telescope (5) and directed to the lens (4). The investigated object (3) is placed between the lenses (4) and (2) in the waist. The holograms are recorded by the camera (1).

The in-line Fraunhofer holography implies that the signal wave and the reference wave propagate in one direction while the traditional holography provides for the signal wave to be transmitted to the recorder apart from the reference wave. Fig. 2 shows Fraunhofer hologram.



Fig. 2. In-line Fraunhofer hologram of dispersed particles [13].

In this case the hologram is a micropattern from concentric rings formed by each particle separately. This hologram woks as Fresnel-zone plates.

An optic holography is based on recording of holographic images of moving particles and on particle image reconstruction through a numerical processing of holograms applying Fresnel-Kirchhoff integral [7].

3. Results

In order to reconstruct a digital hologram, the mathematical simulation needs to be used to distribute the reference wave, diffract its hologram and generate the reconstructed wave front. The Huygen's principle states that every point on the hologram is a source of secondary spherical harmonics expressed by:

$$U(r,t) = \frac{A}{r}\exp(i\omega t - ikr), \quad (1)$$

where r is the distance from the source to the investigated object; $\frac{A}{r}$ is the falling amplitude of oscillations; ω is a radian frequency; i is the imaginary unit; k is a wave number.

The reconstructed image is formed from the total wave front in the reconstruction plane and is made as a superposition of all point sources of spherical harmonics propagated from the hologram. The superposition is described by the Fresnel-Kirchhoff integral expressed as:

$$U_{obj}(x_1, y_1) = \iint_{-\infty}^{\infty} U_h(x,y)g(x_1 - x, y_1 - y)\,dxdy, \quad (2)$$

where $g(x_1 - x, y_1 - y) = \frac{ia_r}{\lambda}\frac{\exp(-i\frac{2\pi}{\lambda}\rho(x,y,x_1,y_1))}{\rho(x,y,x_1,y_1)}$ and $g(x_1 - x, y_1 - y)$=$g(x - -x_1, y - y_1)$, i.e. the function is symmetric.

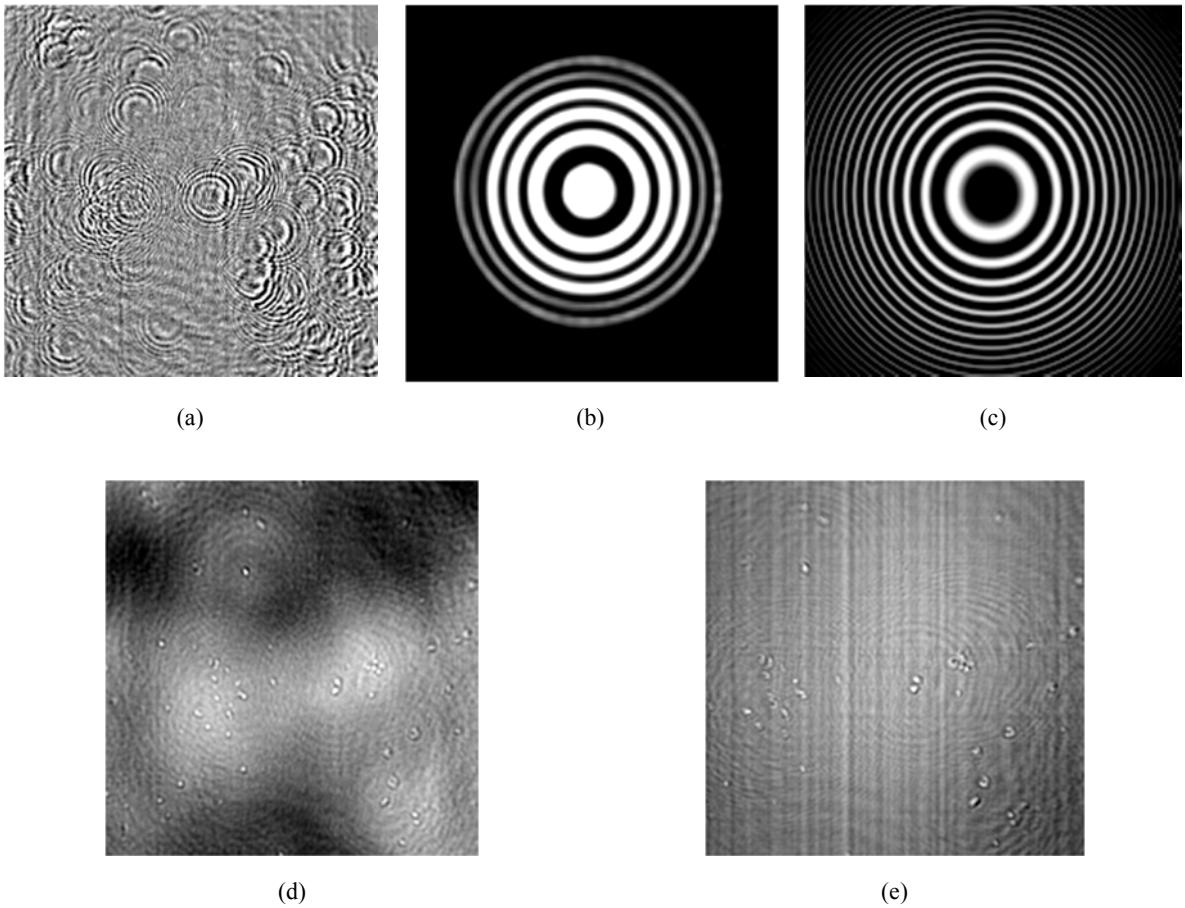
The integral can be interpolated as a convolution integral or an intercorrelation integral which do not differ in this case due to the symmetric function $g(x_1 - x, y_1 - y)$.

The cross-correlation of two holograms is quite fast found by point-to-point multiplication of their Fourier transforms followed by the Fourier inversion [12].

Pre-simulation of the scattering function from one point of the particle for different distance from the focal spot makes it possible to acquire a library of so called "patterns" for reconstruction of the recorded holograms.

The similar pattern can be experimentally obtained. If a quite small (less 1μm) single object is placed instead of the sample in the experimental equipment, the recorded image will be a convolution of point scattering function h(x, y), dependent on the optics quality, with the function $g(x_1 - x, y_1 - y)$. During the practical experiment the image also has a speckle noise and the parasitic interference patterns from the optics elements. To select the useful signal, the axial averaging is performed over the center of the ring system. As a result we have a reconstruction pattern based on holograms of objects at the prescribed distance. Moving the point object along the system axis, we will acquire the patterns consistent with the distance.

Fig. 3 demonstrates the master holograms and the holograms reconstructed using the above procedure. About 90 holograms were obtained provided that the object was successively shifted along the optical axis within an interval from 0 to 330μm with a step of 50μm. The region was selected so that the clear image of particle could be formed when the object is shifted up to the half interval. Two different techniques for the hologram processing were investigated.



(a) (b) (c)

(d) (e)

Fig. 3. Master holograms and the holograms reconstructed.

Both of them applied the convolution approach to the recorded hologram (Fig. 3(a)) and the point source hologram (Fig. 3(b) and Fig. 3(c)). In the first case (Fig. 3(b)) the point source hologram was a result of experiment under the same conditions as for particle hologram. In the second case (Fig. 3(c)) the point source hologram was a product of computation. Fig. 3(d) illustrates the reconstruction from the experimentally formed pattern. Fig. 3(e) shows the reconstruction from the calculated pattern.

4. Discussion

The results of reconstruction when compared prove that both ways to reconstruct an image from a hologram enable to obtain the same shape and relative position of reconstructed particles. However when the experimental pattern is used, the reconstructed background is blurred and there is a diffraction ring around the reconstructed particle hence the signal to background ratio is worse. Fig. 4 reveals the brightness profiles for two particles reconstructed from a hologram using both methods. The profile reconstructed from the experimental pattern has a visual diffraction ring.

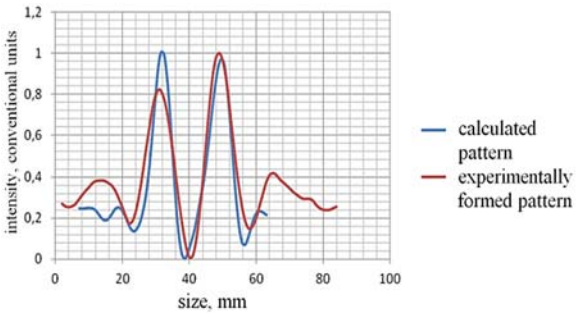


Fig. 4. Brightness profiles for two particles reconstructed from a hologram.

The calculated pattern mainly differs from the experimental one in having the ring structure at its periphery. As the calculated pattern ensures a sharper reconstructed image, the peripheral rings are crucial for the image to be formed. The blurred background of the image based on experimental pattern can be interpreted as a convolution of the pattern on the peripheral ring structure of particles.

5. Conclusion

The experimental patterns are different from the calculated ones in a lack of rings of high orders. There are two causes for it. First, when the interference pattern is distributed all over the large area with the distance to the object getting longer, the signal intensity drops in proportion to the square of distance. The rings of high orders have less brightness than the central rings, therefore their intensity fast drops below the noise level. Secondly, as the order number of the ring is incremented over the pattern center, its thickness gets less. The restricted optical resolution of the system lessens a contrast of thin rings and reduces the amplitude of their signal below the noise level.

Fig. 5 shows the reconstructed image contrast as a function of the distance to the focal spot.

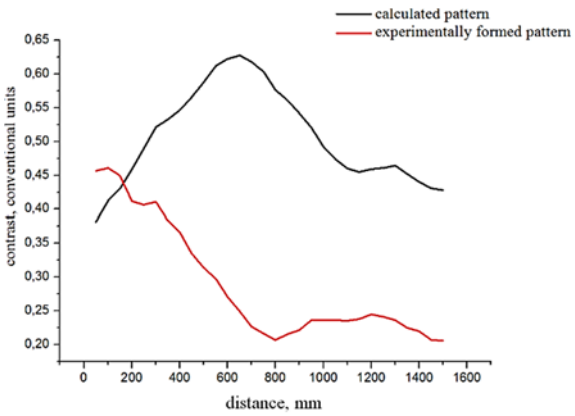


Fig. 5. Reconstructed image contrast as a function of the distance to the focal spot.

The contrast of the calculated reconstructed image for the most part of the observed distances exceeds twice or threefold the contrast of the experimental reconstruction. The contrast for the calculated pattern first gets up as the distance from the focal spot increases, and then starts falling. The low contrast for the short distance is caused by the fact that the rings of low orders are thin at the short distance and the optical resolution does not enable to detect them provoking the contrast degradation. As far as the distance from the focal spot becomes longer, the rings become thicker and the contrast improves. However, the total intensity of the hologram drops proportionally to the square of distance from the focal spot. At the definite distance the above factor is getting more and more crucial and the contrast degrades. The experimental reconstruction pattern at the short distance offers the more effective image since unlike the calculated reconstruction it has no rings of high orders which are not recorded on the hologram. However, as far as the distance from the focal spot extends, the brightness of the useful signal drops faster below the noise level and it worsens the quality of the experimental pattern and as a result, the contrast of the reconstructed image decreases.

The offered technique contributes to fast reconstruction of images from digital holograms. The successive reconstruction of images at different distance from hologram results in 3D distribution of objects based on interference pattern of beams scattered onto the objects. Comparison of two reconstruction techniques, i.e. using experimental pattern and calculated pattern, demonstrates a higher quality of reconstruction when applying the second technique.

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