Errors in Determining Coordinates in the Digital Holography of Particles

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Abstract: Based on the approach applied to diffraction-limited optical systems, the study evaluates the measurement errors of transverse and longitudinal coordinates of particle images reconstructed from digital holograms. The paper shows the experimental results of testing the above estimates.

Digital holography is used to identify and measure particles of different nature in various media, including to study plankton and marine particles in situ, visualize and detect volumetric defects (inclusions) in nonlinear crystals [1, 2]. The DHC technology (DHC – Digital Holographic Camera) was developed for these applications, and includes the following: registration of an in-line digital hologram of the volume of the studied material (medium) with particles; subsequent layer-by-layer numerical reconstruction of volume cross-sectional images with a predetermined step and fixation of the longitudinal coordinate of each cross-section; detection of sections with focused images of particles – longitudinal focusing, as in microscopy, and determination of longitudinal coordinates of particles; determination of transverse coordinates, sizes, shapes of particles and their recognition.

For a number of tasks, it is fundamentally important to estimate the error in determining the longitudinal and transverse coordinates of particles according to their reconstructed images. For example, this is important when cutting non-linear crystals and rejecting defective materials.

In a number of works, the longitudinal coordinate of a particle is determined by the position of the best-focus plane, while the transverse coordinate is determined by the center of gravity of this image in this plane [3], alongside with the development of methods for automatic detection of the best-focus plane with an accuracy of 100-200 μm. However, there are uncertainties in the position of the reconstructed particle image that significantly deteriorate this accuracy and, depending on the distance, may be essential. They are associated with the diffraction of light at the aperture of the particle hologram [4] and are significantly dependent on the distance to the reconstructed particle image.

This issue is well studied and described for diffraction-limited optical imaging systems [4, 5]. Besides, it is shown in [5] that an element (pixel) may be presented as a volumetric body – "cigar", in some sources – as a "specklon". This pixel has a transverse size of the Airy spot:

$$2\rho = 1{,}22\frac{\lambda}{A}, \qquad (1)$$

and longitudinal extension

$$2\Delta z = \left(\frac{\lambda}{A^2}\right) \approx \frac{(2\rho)^2}{\lambda}, \qquad (2)$$

where λ – used wavelength, A – numerical aperture of the optical system (on the image side) used to form the image.

For the DHC system $A = \frac{D_h}{2L}$, where D_h – diameter of the area occupied by the particle hologram (plankton individual, drop, gas bubble, etc.), L – distance from the hologram to the particle image numerically reconstructed therefrom. For example, for a circular opaque particle, the area occupied by the hologram in the far field is the Airy pattern of diffraction on that particle. The work [6] presents the calculation of hologram sizes required for the reconstruction of the image of particles of different shape corresponding to the specified quality criterion.

The relations (1) and (2) allow determining the dimensions of the "specklon" in the image space when reconstructing the holographic image. The corresponding dimensions and coordinates in the space of objects may be determined taking into account the refractive index of the medium in which the particles are physically located.

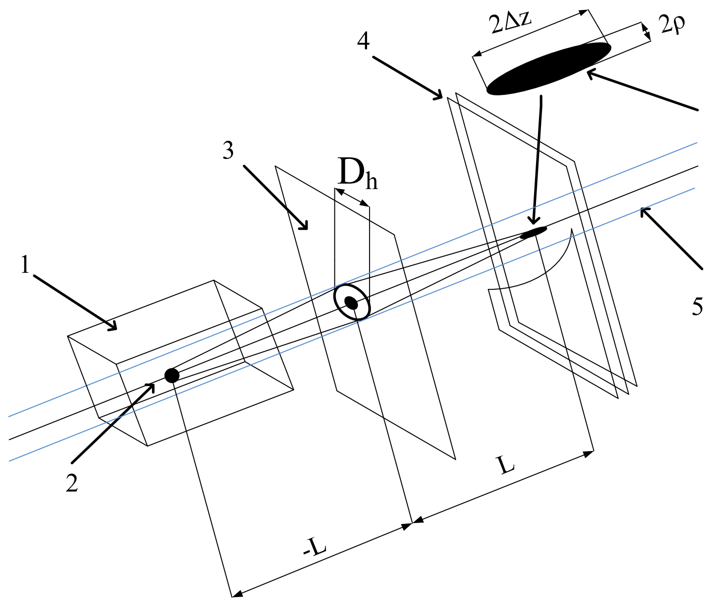

Fig. 1. Recording of a digital hologram of a particle and reconstruction of its image. 1 – analyzed volume with a particle (2), 3 – digital hologram, 4 – best image plane, 5 – recording (real) and reconstructing (numerically simulated) beam, 6 – resolution elements of the digital holographic system ("specklon").

Numerical experiments that included the registration of the digital hologram of test objects were performed to check the given estimates. Test particles in the form of opaque squares, placed photolithographically on a glass plate, were used as test objects. A good correspondence between the results of the numerical experiment and formulae (1) and (2) was obtained, confirming, among other things, significantly different quality of images in the near and far planes of the analyzed volume from the hologram.

Besides, the digital holography of volumetric defects of single crystals at a wavelength of 1.06 µm showed the possibility of determining characteristic transverse coordinates and sizes of defects with a measurement error of ±3 µm, and longitudinal coordinates and sizes with an error of up to ±100 µm (for defects with characteristic transverse dimensions of ≤60 µm), which is acceptable for practical tasks (in particular, when cutting non-linear crystals and rejecting defective materials).

Thus, formula (1) may be used to estimate the measurement error of transverse, while formula (2) – longitudinal dimensions and coordinates of reconstructed images in the practical implementation of the DHC technology to study particles.

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