

Numerical study of density fluctuations of suspended particles in a volume of optical medium

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Abstract. This paper is devoted to the numerical study of density fluctuations of scattering particles suspended in a volume of the optical medium. Two spatial distributions were considered: random distribution and normal distribution. As a result of statistical processing of the focused images of scattering particles normalized distributions of density in the image plane, which characterize the fluctuations in the volume of the optical medium were obtained.

1. Introduction

The necessity for statistical accounting of particles in the volume of the medium arises in many scientific and practical problems, for example, in problems of atmospheric optics in the study of gas dynamics of particle fluxes [1], in oceanography and biology in the study of particles or small organisms suspended in the fluid [2] and in the study of transparent media. [3] There are several methods by which it is possible to quantitatively and qualitatively examine the distribution of particles in the optical medium. Methods of processing of images of particles obtained by coherent illumination currently became more widespread. Depending on the concentration of the particles contained in the volume, scattered laser radiation forms two distinct structures, which in turn leads to two possible approaches to image processing: processing of images of individual particles carried out by means of PIV (particle image velocimetry) [4] or processing of speckle patterns using DSP or ESP-methods (digital/electronic speckle photography) [5]. Formation of a speckle pattern leads to serious limitations: even a relatively small movement of the particles outside the illuminated plane can lead to a serious change in the speckle pattern between exposures.

The aim of this work was to study density fluctuations of scattering particles suspended in the volume of optical medium by numerical simulation. Using statistical accounting of particle images, normalized density distributions of particles in the image plane that determine their fluctuations in the volume of the optical medium were obtained.

2. Statistical study of scattering particles suspended in the volume of optical medium

In this paper the propagation of electromagnetic radiation through the volume of the optical medium with different statistical distributions of particles in it is simulated. Figure 1 shows a schematic illustration of an optical system that forms the image of a volume of optical medium with particles. The electromagnetic radiation passing through the volume of the medium which is previously broken into segments (a, b, c - in Figure 1) is diffracted by the particles. The concentration and the size of particles may vary for different experimental implementations. Such spatial distributions of particles as random (equiprobable in each segment) distribution and normal distribution, which is realized in



the numerical model using the Box-Muller transform (random variables are normally distributed with respect to the optical axis) are considered in this paper. The method of distribution of the angular spectrum of plane waves was used to calculate the electromagnetic field propagation through the volume of the optical medium and optical system.

Image of particles in a certain volume segment (segment b), is transferred to the recording plane by a lens. Recorded image of the particles (3 – Figure 1) is the result of a coherent superposition of the particles located in different volume segments. In the numerical experiment, it was possible to obtain focused images of different planes of the volume of the optical medium by changing the distance on which the propagation of the wave field from the plane of volume segment to the lens plane is calculated. In this case, the images of the neighboring planes take on the form of defocused spots.

Figure 2 shows the results of the simulation of the focused images of particles with different concentrations of N in one transverse volume segment for random and normal distributions of particles. Simulated volume of the medium $0,768 \times 1,536 \times 1,536$ mm during the numerical experiment was divided into five segments, grid size $\Delta x = 6$ μm , wavelength $\lambda = 632,8$ nm, focal length of the imaging lens $f = 29,1$ mm.

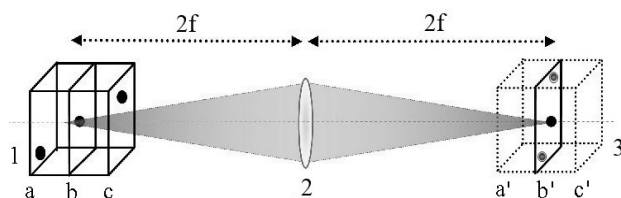


Figure 1. The intensity distribution of a wave field diffracted by three particles in the volume of optical medium is recorded in the segment b': 1 – volume of the medium divided into segments (a, b, c), 2 – lens, 3 – focused images of particles a', b', c'.

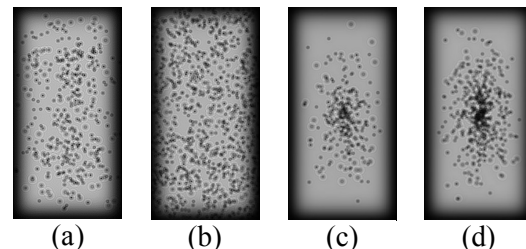


Figure 2. Focused particles images, (a)-(b) – random distribution, (c)-(d) – normal distribution, (a), (c) – $N=50$, (b), (d) – $N=100$.

In this paper the statistical analysis of the focused particle images is carried out. For automatic image recognition of focused particles the following algorithm was developed and implemented in the code: in the first stage, approximate regions with focused particle images are obtained; in the second stage, the program finds double brightness jumps from light to dark by scanning the selected image fragment and determines the coordinates of the particles; in the final stage, on the basis of the data obtained, the radial and density distributions of particles in the image plane are constructed, which determine fluctuations of density in the volume of the optical medium (Figure 3).

If the density of particles in one segment of the medium volume is low, then all focused particles can be detected. With increasing number of particles per segment of the volume, the effect of coherent superposition of the particle images of the adjacent planes begins to appear strongly, which leads to a partial loss of information about the particles in the test segment of the volume. After reaching the threshold value under certain specified parameters, we obtain not the individual particle images but the speckle pattern in the image plane. In this case, as in the case of studying the particles which are transparent to the probing radiation, but introduce the phase retardance (phase objects), the detection (contouring) of the particles using the method of analysis of singles image becomes problematic. As shown in Figure 3, random distribution of detected particles (a,b) at $N = 150$ is well approximated by Poisson distribution compared to normal distribution at the same concentration (c,d). On the normalized distribution of the mass fraction of particles for normal distribution (Figure 3-d), the additional peaks of the distribution function appear, which can be explained by the formation of clusters of particles near the optical axis as a consequence of the specifics of used distribution law.

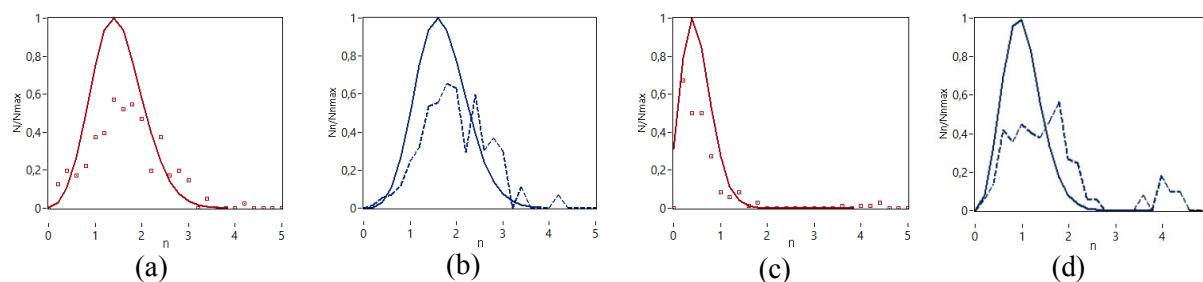


Figure 3. (a), (b) – random distribution, (c), (d) – normal distribution ($N=150$); (a), (c) - calculated according to Poisson statistics (solid curve) and experimental (indicated by dots) normalized density distribution of the particles in the image plane; (b), (d) - calculated according to Poisson statistics (solid curve) and experimental (dashed curve) normalized distribution of the mass fraction of particles.

3. Conclusion

In this work, the density fluctuations of the scattering particles in the volume of an optical medium were investigated. As a result of applying method of statistical accounting of particle images, based on the contouring of particles and thresholding technique, normalized density distributions of particles in the image plane that determine their fluctuations in the volume of the optical medium were obtained. At low particle densities in the volume of the medium, recognition of images of particles in the particular segment is lossless. With the increase of the amount of particles per segment of the volume, the effect of coherent superposition of the images of particles in adjacent planes becomes apparent. Reaching the threshold concentration of particles per segment results in the inability to obtain complete information about the statistics of the particles in the test segment of the volume.

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