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Long exposure time Digital In-line Holography for the trajectography of micronic particles within a suspended millimetric droplet

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ABSTRACT

Digital In-line Holography is used for the three-dimensional tracking of micronic particles in a millimetric droplet. The 3D location of the inclusions is realized through the digital reconstruction of holograms using the 2-Dimensional Fractional Fourier Transform. The trajectory of the particles inside the droplet is obtained using a long exposure scheme.

1. Introduction

Particle–droplet interactions interest various fields of research. In biology and public health, the particles can be bacterial cells or other foreign bodies which are enclosed by a cell or a droplet [1]. Such bacterials can cause expiratory problems to humans and animals. In the atmosphere, the water droplets containing inclusions are of particular interest for atmospheric studies concerning pollution, particle trapping, and aerosol dispersion [2–4]. In power plants, removing submicron particle from the system is concerned, for example, the micro-particle emitted from power plants and transport vehicles can be removed from the air by charged sprays [5]. The characterization of micronic or sub-micronic inclusions within particles becomes thus essential. Studying the trajectory of particles inside a system is a key point in flow measurements [6,7]. For the analysis of inclusions in droplets, almost all researches concern the visualization of the particle inside the droplet but they cannot give the accurate 3D position of the inside-particle. Using the Digital In-line Holography technique (DIH), a 3D analysis of the position of the particles present inside the droplets can be achieved. This is the aim of the present paper. Using DIH, we show that it is possible to reconstruct the trajectory of trapped micronic particles within a droplet. DIH traditionally gives the 3D position of the particles. Trajectories can then be obtained from multi-exposures. In the present study, we further use a long-exposure scheme in order to trace directly the trajectories of the inclusions. This procedure has been proposed recently [8]. We demonstrate here its possible adaptation to the investigation of droplets with micronic inclusions.

To test the feasibility of the technique, we consider suspended droplets. Inclusions are inserted within the droplets with a syringe. Inclusions are calibrated 20 μm particles, while the droplet's diameter is about 1 mm. This case describes many applications as large droplets in the atmosphere. Holograms are recorded with a conventional CCD camera. The long exposure time evolves from 0.15 s to 0.25 s. The reconstruction of the holograms is ensured using 2 Dimensional FRactional-order Fourier Transforms (2D-FRFT). Section 2 shows the theoretical description of the experiment which allows to predict the fractional orders of reconstruction versus the position of the inclusion within the droplet, and all other parameters of the experiment. It details shortly the principle of our digital reconstructions using 2D-FRFT. Section 3 shows then the experimental results. We present digital holograms that have been obtained with different exposure times, and their reconstructions. The trajectories of the inclusions can be visualized. We demonstrate the possibility to reconstruct trajectories in different planes within the droplets.

2. Theoretical description of our Digital In-line Holography set-up and principle of digital reconstruction

Digital In-line Holography records the pattern diffracted by particles (or other scattering objects) on a CCD sensor. In our case, the diffracting particles are located within a droplet. The experimental setup is represented in Fig. 1. The incident beam is a

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Gaussian beam emitted by a Continuous Wave laser (wavelength $\lambda = 642$ nm). The beam propagates through an optical system and illuminates the suspended water droplet of diameter D. Inside the droplet, calibrated particles of diameter d have been inserted. At the end of propagation, the CCD camera is positioned at distance z from the droplet.

It is possible to predict In-line holograms generated by spherical droplets in the general framework of the Lorenz–Mie Theory [9]. However the scattering properties of droplets with inclusions

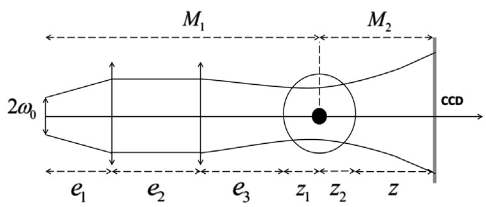

Fig. 1. Experimental setup with $\lambda = 642$ nm, $2\omega_0 = 4.6$ μm, $e_1 = f_1 = 42.8$ mm, $e_2 = 342.84$ mm, $f_2 = 5.5$ mm, $e_3 = 8.7$ mm, and $z = 13.14$ mm.

are so complex that similar codes do not exist in such cases. A paraxial description can however be done if we consider that the inclusions are particles embedded in a global imaging system which includes the spherical interfaces of the droplet itself, and the different lenses of the imaging system. We can then describe the whole system through the definition of appropriate optical transfer matrices. Let us briefly recall the general procedure that we have developed to describe theoretically similar conditions [10]. The incident beam is a Gaussian beam in the incident plane ($z=0$). The propagation of light to the trapped inclusion can be described by generalized Huygens–Fresnel integrals as described in [10], using the optical transfer matrix M_1 (see Appendix A). The amplitude of the electric field is given analytically in the plane where the diffracting element is located (an inclusion within the droplet at distance z_1 in the present study). Then, the beam is diffracted by the particle, and it propagates through the last part of the system (i.e. from the inclusion to the CCD sensor: optical transfer matrix M_2, see Appendix B). The diffracting element is assumed to be an opaque circular object. The transmittance of this 2D opaque object, $\mathbb{T}(\xi, \eta)$, is described by the superposition of

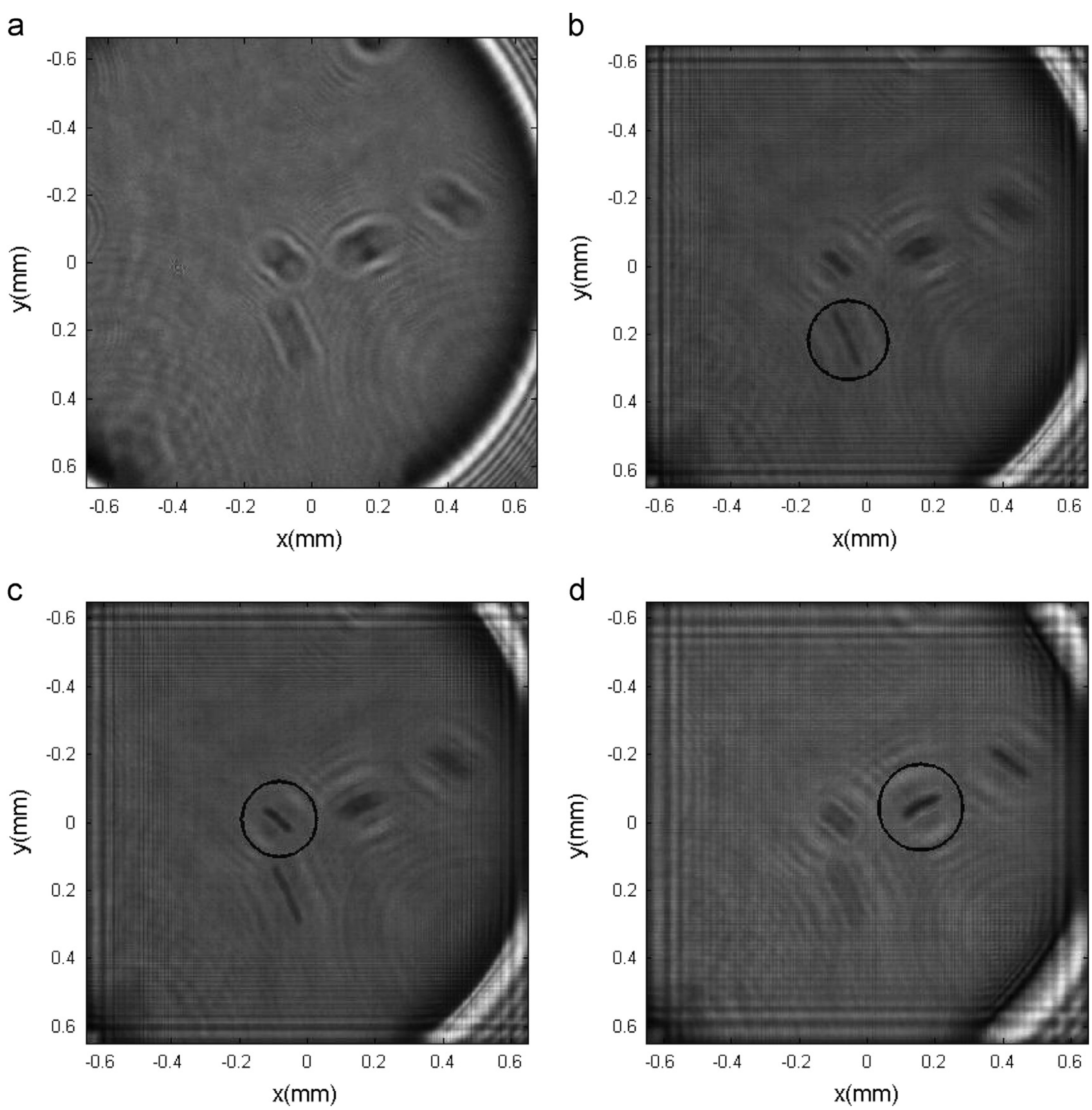

Fig. 2. (a) The diffraction pattern of 20 μm particles inside the droplet with a 0.15 s exposure time. (b)–(d) The reconstructed images in the different planes associated to the fractional orders $0.56\pi/2$, $0.6\pi/2$, and $0.73\pi/2$, respectively. The corresponding distances between the reconstructed particle and the CCD sensor are 14.8 mm, 14.6 mm and 13.2 mm respectively.